Solar Photovoltaics:
Fundamental Technology and Applications
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Lecture-11
Current Voltage Characteristics of Solar cells

Welcome everyone to our week 3 module 1 course last few weeks we have introduced you the concept of solar photovoltaics and we have learn that how a basic solar cell work. We also learnt that is solar cell is nothing but a p n junction semiconductor diode, where n side is very narrow and heavily doped. But in many occasions we can represent this solar cells by an equivalent model.

Equivalent model means you represent the solar cell in terms of resistance, capacitance which also control the behavior of the solar cells. Today we will learn that in details and different parameters associated with the solar cell technology and the sources of loss for efficiency in a solar cell.

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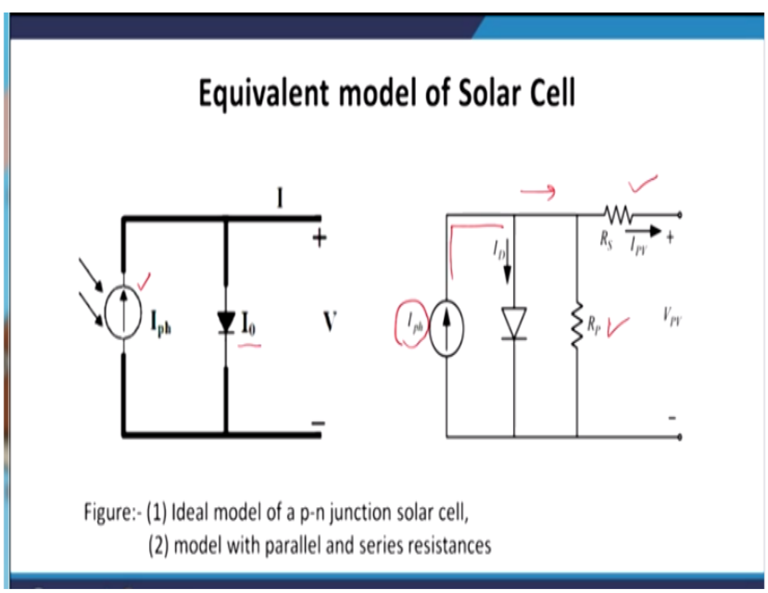

Here we are showing the equivalent model of a solar cell as you can see the first diagram the equation the figure1 is the ideal model of a pn junction solar cell. Here we have a current source Iph is this one which is connected in parallel with a diode. And then since this is an ideal model, so there is no resistance but in real cell or in practical solar cell there are difference source of resistance it can come due to the metallic contact of the solar cell with the semiconductor.

Or it can come due to the crystallographic defects which originates due to the semiconductor growing. So because of all these there can be difference source of resistance in this circuit, so we can put the resistance in the circuit either as a series as shown it here or either as a parallel or as a shunt resistance as shown it here. So if we connect this series resistance and shunt resistance along with this photocurrent source and the diode current source.

Then it makes the equivalent circuit of a real solar cell, now this equivalent model of a real solar cell has the following parameters. The first one is a current source or current generator which is generating a amount of current Iph. Now this amount of current is coming through here now it sees there are 2 different paths, one path is through the diode an another path goes through this way. So the amount of the diode current is ID which is in the absence of the light.

And then the rest of the current it flows through here, now it can divided through Rs and it can divide through Rp. Finally the total photovoltaic current Ipv that goes to the outside load, now as you can see from this circuit diagram that series resistance as small as possible that will be good for us. Similarly since this Rp or the parallel resistance connected as a shunt resistance here it is value as high as possible that will be good for us.

But what comes from this series resistance or what contributes to the origin of series resistance and shunt resistance.

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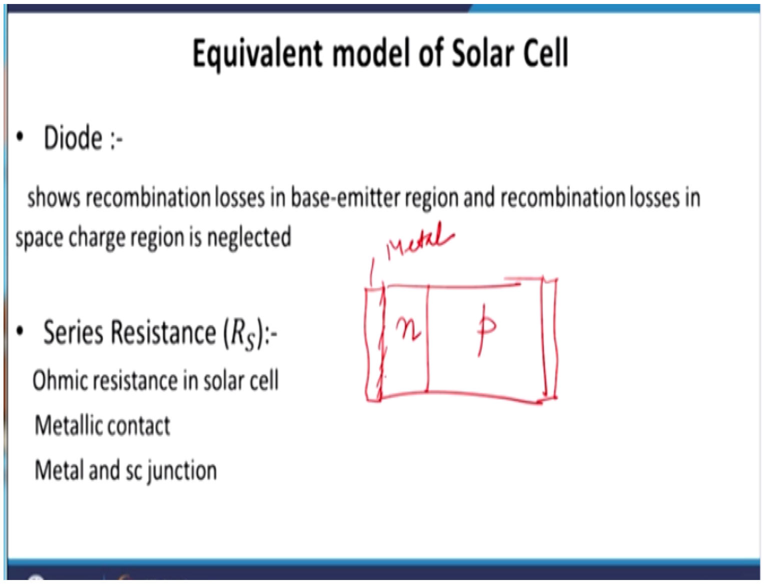

So series resistance is a ohmic resistance in a solar cell it is comes due to the metallic contact or more precisely metal and semiconductor. Let us consider this is our solar cell where the n side is narrow and heavily doped, so that the depression regions extent inside the p regions, to compute a solar cell we put a metallic contact on the front end and ohmic back contact at the back end. Now this metallic contact made as schottky kind of barrier at this metal semiconductor interface.

Now this schottky kind of barrier like they contributes to some kind of resistance and that resistance is the series resistance.

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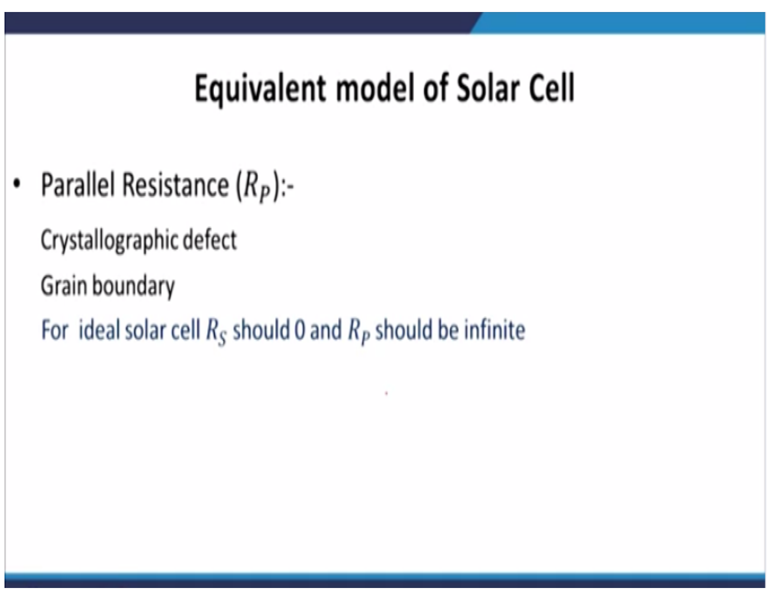

On the other hand we have parallel resistance or shunt resistance which is mainly due to the crystallographic defect. Now let us for example we have a silicon solar cell, now when you grow this silicon crystal there can be lot of defects or crystallographic defects can originate during this growth process. And that defects actually behaves like a charge carrier recombination sides. In addition to that during the growth of this crystal there can be lot of grain boundary which appears in the circuit.

Now this grain boundary also acts like a charge carrier recombination sides. So because of this crystallographic defects and the grain boundary we get some kind of resistance in the solar cell and that resistance is contributing to the shunt resistance. So as we can see now for an ideal solar cell the series resistance should be 0 and shunt resistance should be infinite. In many of the cases for an ideal solar cell does not behave in a practical way as we get the power from them.

Or in more precisely the behavior of a practical solar cell in many times different than in solar cells. For example if we draw the iv characteristics of a solar cell then it should looks like a perfect square. But we do not get that perfect square in the real life when we record the IV characteristics. Now this deviation of the real solar cell from an ideal solar cell is described in terms of a quality factor and that quality factor is called fill factor. So for comparing maximum obtain power and maximum theoretical obtained power we define the fill factor.

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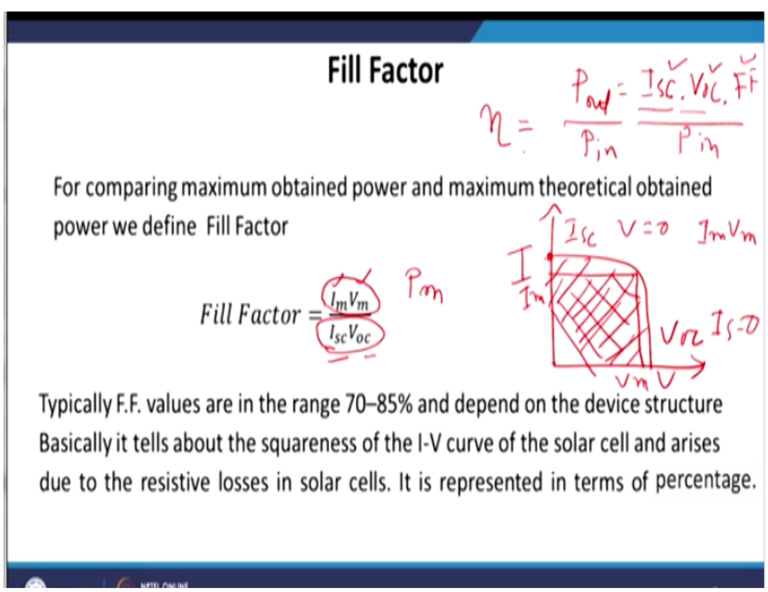

By definition fill factor is the maximum power that is the Im times Vm the maximum current times the maximum voltage/maximum theoretical power which we get from the circuit that is short circuit current and open circuit voltage. So ImVm that is the maximum obtained power from the device which is like you know the maximum power which we can get from the device, if the device is an ideal solar cell.

But in reality what we get is that Isc times Voc that is short circuit current times the open circuit voltage. So **the the** the maximum current and the maximum voltage we cannot record, what is record is the short circuit current and the open circuit voltage. If we draw an IV characteristics here, so if this is my current axis and this my voltage axis, so we know that this looks like this. The point where the IV curve intersects the I axis that is gives the short circuit current.

Obviously at the short circuit current voltage v = 0, whereas this IV curve where it intersects the V axis that is gives as the open circuit voltage. At that open circuit voltage or Voc the current I short circuit current I is equal to instead of short circuit we can just call it as a current that current I=0. So the power delivered from the solar cell can be obtained by integrating the area under this IV curve or we can get the power p output by multiplying the y coordinate that is Isc times Voc or short circuit current times the open circuit voltage.

Now typically this fill factor values are in a range from 70 to 85% and depend on the device structure. Now if this curve is a perfect square not like this but it rather imagine this curve have a shape like a perfect square. And now this perfect square they intersects the I axis at this point Im and on the V axis at a point Vm. So what will be the power obtained in the ideal case that is the area under this perfect square or I can draw it in other direction like this.

So what will be the maximum power in that case that will be Im times Vm. But we do not get the Im times Vm because of the series resistance and the shunt resistance we get a deviation from the maximum power output what you really get is the Isc times Voc. So to quantify this deviation from the ideal solar cell we define the fill factor. Basically it is about the squareness of the IV curve of the solar cell and arises I just due to the resistive loss in solar cells, it represented in terms of percentage.

So as the square curve deviates from a square nature we get more and more value from the fill factor. So like let us say we got a curve like this IV, so it is not a perfect square, how much deviation I got. I got a deviation that I quantify in terms of fill factor which is Im times Vm/Ioc * Voc that expression quantifies this deviation from a square or ideal square curve IV curve. Now if I multiply my output power which is I short circuit times V open circuit into the fill factor.

So then what I get is the power output from a real solar cell, so the power output from a real solar cell, now if you divide by power input that is the how much amount of power I have put in the solar cell which is coming from the solar radiation. So then I have to divide this Ioc * Voc * fill factor/p input but what is this, output power/input power this is nothing but the efficiency of a solar cell.

So the efficiency of a solar cell eta is defined as the output power to the input power, we will come to this point later on in details. And as you can say that this efficiency is equal to the short circuit current times open circuit voltage times fill factor divide by p input. So if we have been given the input value from the IV characteristics we can calculate what is Isc value, what is Voc value and what is fill factor value and in principle we can calculate the efficiency of a solar cell.

Now p input or the amount of power we are putting inside a solar cell that can vary significantly even as we have learn that sun moves across the earth the intensity which reach on the earth surface that varies over the day times. So if somebody wants to define the efficiency of the solar cell one has to be very consistent about how much input power he or she is using. Let us say somebody is measuring the solar cell efficiency for an input power of 500 watt/meter square.

And another person is measuring for 1500 watt/meter square, obviously even if we keep Isc, Voc and ff as the same. Since now p input is different for the same values of the IV curve for different values of the input power my efficiency will be different. So to remove this inconsistency people have come to a conclusion that whenever we will report the efficiency of a solar cell.

We will report that for a particular input power and that is called the M1.5 solar radiation, M1.5 solar radiation corresponds to 1000 watt per meter square input power. So if we put that value of the p input in the input value and from a solar cell if we measure the short circuit current, open circuit voltage as well as fill factor then we can calculate what is the efficiency of a solar cell, and this job more often is done by an instrument which is called solar simulator.

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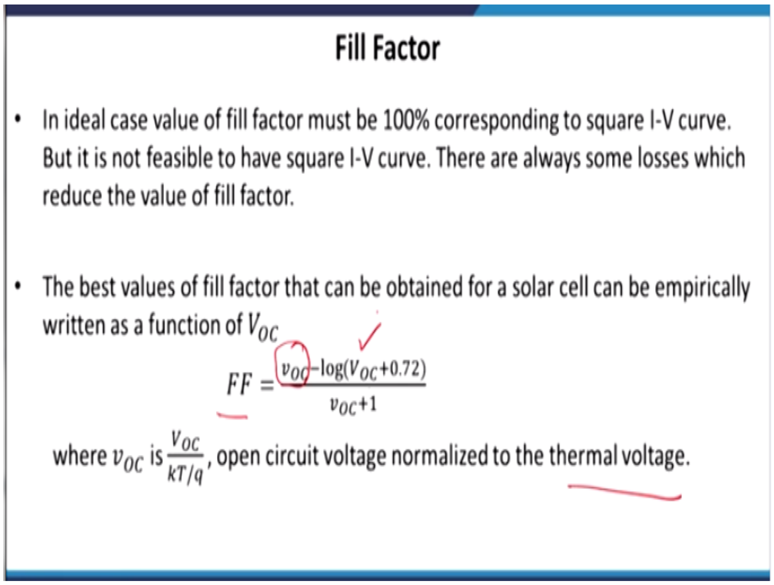

It is also worthwhile to mention that like the fill factor value can tell you how good the quality of the solar cell. In ideal case the value of fill factor must be 100% that means there should not be any deviation from the square nature. But in real solar cell there can be deviation and where this deviation is coming from due to the resistance, what kind of resistance, it can be series resistance or it can be shunt resistance what contribute to the resistance.

It can be metal semiconductor contact or the defect states which comes during the growth of the semiconductor. Now this is all the experimental parameters or the experimental efficacy, so because of that we very often we get a series resistance or shunt resistance in the circuit and that contribute to the deviation of the iv curve from a ideal iv curve. But it is not visible to have a square IV curve always, there are always some losses which reduce the value of fill factor.

Significantly if the fill factor values is very very less than the efficiency of the solar cell will also be very less. The best value of fill factor that can be obtained from a solar cell it can be empirically written as a function of the open circuit voltage. So you can write the fill factor as the v open circuit or open circuit voltage-log of V open circuit + 0.72/V open circuit + 1. So that means if we know the open circuit voltage we can calculate what is the value of the fill factor.

Where V open circuit voltage is Voc/Kt/q it is the open circuit voltage normalized to thermal voltage. So this utilized Voc is not the open circuit voltage but it is normalized open circuit voltage, with which we have normalized it we have normalized it with thermal voltage. And what is the value of thermal voltage it is the Boltzmann constant time temperature divide by the charge of an electron. So if we know what is the value of the Voc or the open circuit voltage then we can calculate, what is the value of a fill factor.

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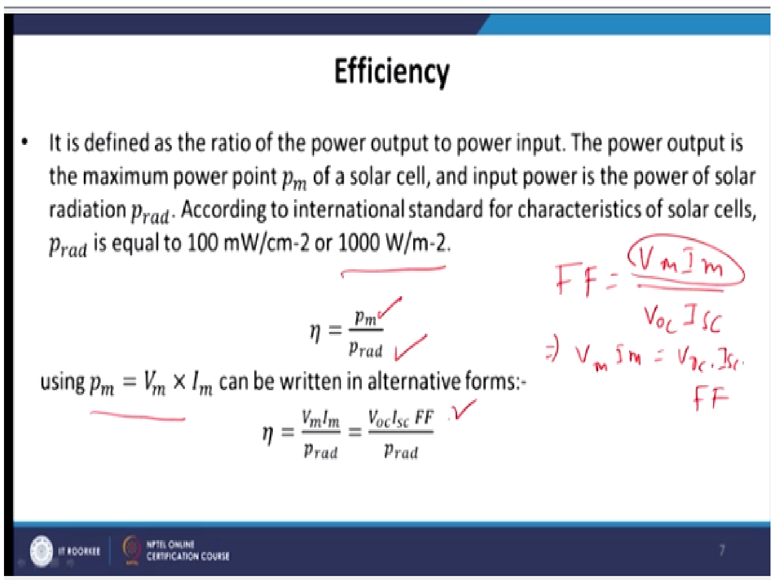

So as we said like efficiency it is defined as the ratio of the power to power input like all engines they provide some kind of power output when you put some power input. Solar cell also take this power input from the solar radiation and it what it does like you know it converts the light energy to the electrical energy. And this electrical energy is nothing but comes in a terms of the current and voltage and this product of current and voltage we call it as a power.

The power output is the maximum power point Pm of a solar cell and input power is the power of solar radiation P radiation. According to international standard for characteristics of solar cells P radiation is equal to 1000 milli watt/centimeter square or 1000 watt/meter square. Now as I have also mentioned before that if the input value of the power is not same while reporting the efficiency of a solar cell there can be several inconsistency.

For example if somebody make a solar cell and measure the efficiency per 100 watt/meter square like M 1.5 and some other person make the same solar cell but report the efficiency for 500 watt per meter square, then this 2 value will be significantly different. To avoid this inconsistency we always keep the input power as 100watt/meter square. So eta or the efficiency of a solar cell is defined as the maximum power/the input power which is nothing but the P solar radiation.

Now what is Pm, Pm is Vm times Im that is the maximum voltage times maximum current and we can write this maximum voltage time maximum current as open circuit voltage times short circuit times fill factor/P radiation. Because we have last learn that fill factor equal to Vm Im/Voc * ISc. So Vm Im this is this part can be written as Voc time Isc times fill factor that exactly what you have written here, open circuit voltage*short circuit current*fill factor/the P radiation if we multiply by 100 we will get the efficiency in 100.

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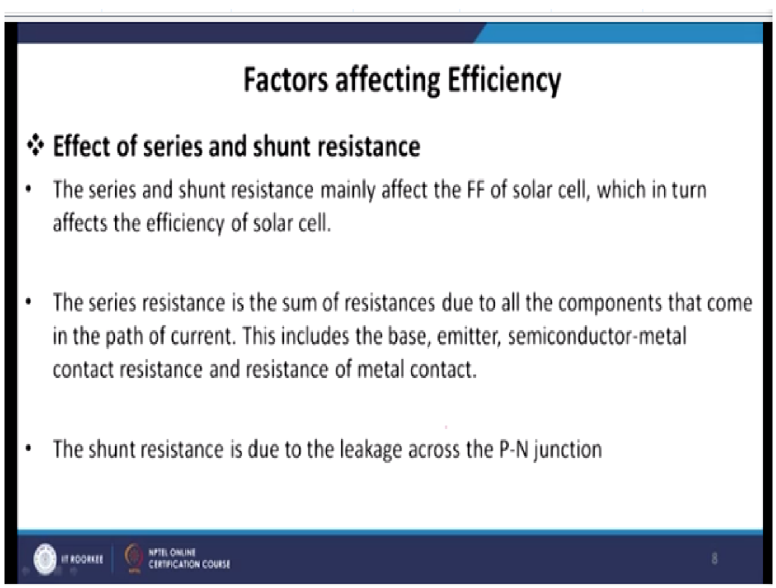

Now because of the series resistance and sun resistance fill factor value can change significantly. Now the series and shunt resistance mainly affect the fill factor of the solar cell which in turn affects the efficiency of a solar cell. The series resistance is the sum of the resistance due to all components that come in the path of the current. So whenever current flows in a circuit whatever the source of resistance it fills while going to the electrode that is acts as a series resistant.

This includes the base, emitter, semiconductor metal contact and resistance of the metal contact. So that is why some times we make a finger electrode to minimize the series resistance as much as much as possible, the shunt resistance is due to the leakage current across the p-n junction.

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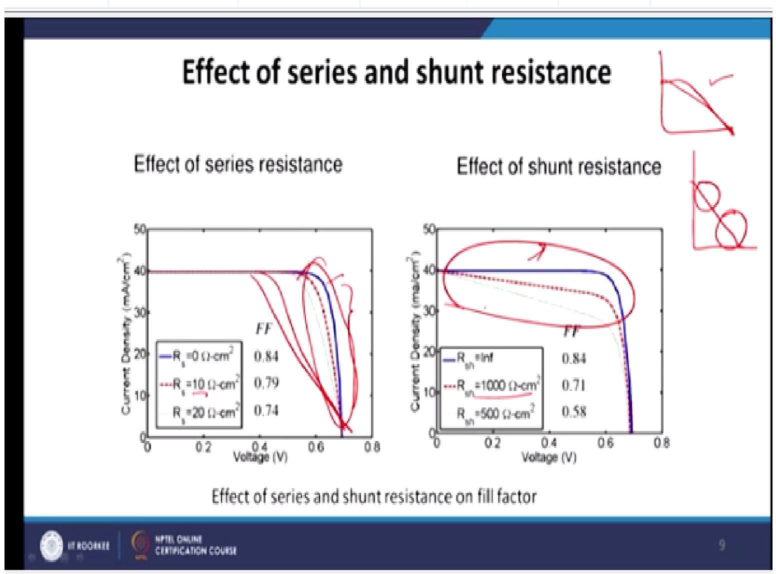

Now what will happen if the series resistance changes and if the shunt resistance changes, so that will directly affect the IV curve. As you can see here the IV characteristics like the fill factor value is showing for series resistance value 0, when the series resistance value is 0 then you see that this curve is this blue curve this one. When the series resistance is 10 ohm centimeter square then this portion of the curve is changing.

So the you see that the red curve is bending before a perfected knee, while like it is a 20 ohm/centimeter square it has bended like this. So if it is high like let us say 50ohm/centimeter square it will be like this, if it is too high, so then it will be like this. So if we get a solar cell where the IV characteristics is like that. So we mean that the series of this device is very very high, now what will be the contribution of the shunt resistance.

So if the series resistance is modulating this part, so we can consider the shunt resistance obviously it will contribute to the other part. So for a infinite shunt resistance the IV characteristics should be like a blue curve, like this. But if I have the shunt resistance value like 1000 ohm/centimeter square then it is a red curve like this. So it falls off rapidly from the ideal curve, then if it is 500 ohm/centimeter square then it falls off more rapidly.

So as you go lower and lower values of the shunt resistance the **x** axis near about part of the IV curve falls off very quickly. So in this same curve here if the shunt resistance is very very low, so this graph will be like this. So if somebody recorded a solar cell IV curve and this is like that, so what do you mean from that, that series resistance value is very very high and shunt resistance value is very very low, what we need very very low series resistance ideally 0 and very shunt resistance ideally infinite.

If the series resistance value anything more than 0 then we have learnt that this part of the curve is going to change and if the shunt resistance values is less than the infinite value or as small at as it will be this part of the curve is going to change. So by looking an IV characteristics an engineer can comment that whether the series resistance or shunt resistance is contributing to the performance of the devices and they can take precaution measures to take care for that.

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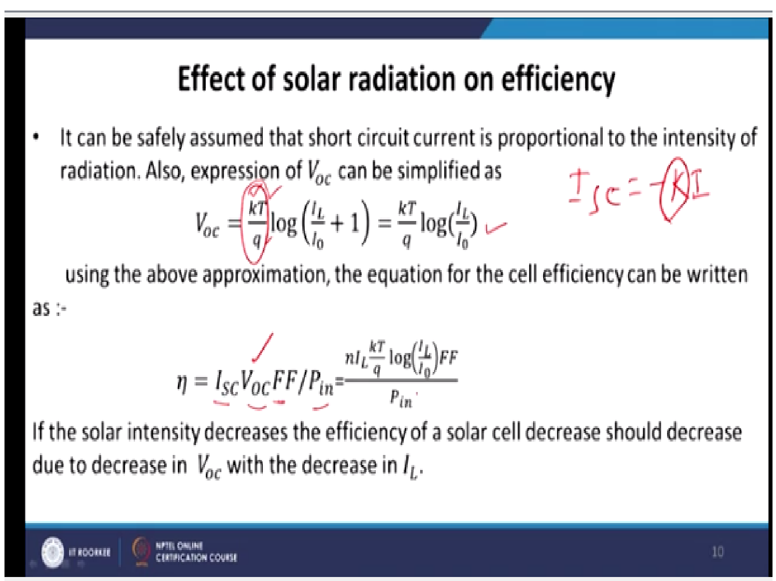

Now what is the effect of solar radiation on efficiency, it can safely be assumed that short circuit current is proportional to the intensity of radiation that we have learned earlier, that I short circuit equal to – k * I where I is the intensity of the radiation and k is a geometric factor. Also the Voc or the open circuit voltage we can write as open circuit voltage=kT/q logIl/I0 + 1 = kT/Q log Il/I0. Now what is k, k is the Boltzmann constant, T is the temperature and q is the charge of the electron.

So this part is the thermal voltage times log Il/I0 that is the load current/I0 + 1 or one can simplify if the Il very very greater than Io, so we can write it is kT/q log Il/Io. Using the above approximation the equation for cell efficiency can be written as eta = I short circuit*open circuit*fill factor/the input power. Now if we plug in the value of the open circuit voltage from here what I will get it is kT/q log Il/I0 * fill factor into the short circuit current/P input.

If the solar intensity decrease the efficiency of a solar cell decrease so decrease due to the decrease in the Voc with the Il. So if Voc changes or the open circuit voltage changes then the efficiency of the solar cell also changes.

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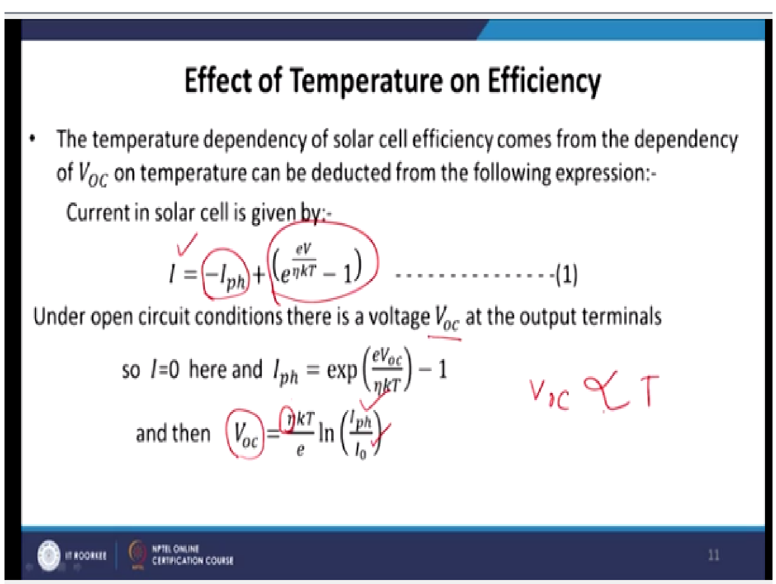

Now temperature also plays a very important role in measuring a efficiency of a solar cell. For example the temperature dependency of solar cell it comes due to the changes in the Voc as you change the temperature. And we can reduce an expression for that, so as you know that current in a solar cell that can be retain as **as** a combination of 2 part, one is the photocurrent minus Iph and another is the diode current, I0 e to the power ev/eta kT - 1.

Under open circuit condition there is a voltage V open circuit at the output terminals, so when I = 0 here then Iph = exponential eVoc/eta kT - 1 because we have consider this term is equal to 0 when we are considering the open circuit condition. Open circuit conditions means the voltage developed across the device is V of oc but what is the current, current is 0. Now if I put I = 0, so this will this terms will come on the left hand side giving you Iph is exponential eVoc/eta kT -1.

And then the value of Voc comes out to be eta kT/e lan of Iph/I0. So we know what is the photo current we know what is the like diode current. So what all we use to know like you know the efficiency of a solar cell. So or in other way if we know the Voc we can find the efficiency we can if we find the efficiency we can know the Voc. So for a given photocurrent and for a given temperature the value of the open circuit voltage and the efficiency they are proportional.

Now if we put it in some different way the open circuit voltage depends on the temperature. So from here we can write that Voc is proportional to T. so that means if Voc changes then T will changes and if T changes then the efficiency will also be changes.

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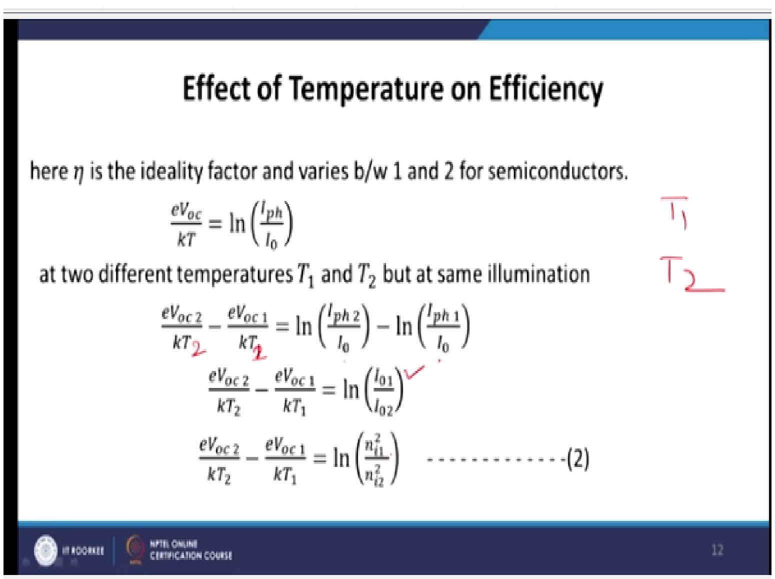

So here eta is the diode ideality factor and varies between 1 and 2 for semiconductors. So eVoc/kT is log Iph/I0 at a 2 different temperatures let us say 1 temperature is T1 another temperature is T2 but the illumination is same or the intensity of the solar radiation is same but the temperature is different. Now what will happens in this case in one case it will be T2 another case it will be T1, so we can write it eVoc2/kT2 - eVoc1/kT1 = lan Iph2/I0-lanIph1/I0. Now if I write this eVoc2/kT2-eVoc1/kT1 so since this term and this term is same say we can divide the term inside the bracket of the lan and get lanI01/I02 or I1/I2 right.

So e**V V** Voc2/kT2 - eVoc1/kT1 = log, we can also write this what is Io, what is the diode reverse situation current that is proportional to the intrinsic carrier concentrations. So we can also write in terms of intrinsic carrier concentration. So instead of this I we can also write in terms of the ni square, so that is what we have written here lan ni1 square/ni2 square. Now intrinsic carrier concentration heavily depend on temperature.

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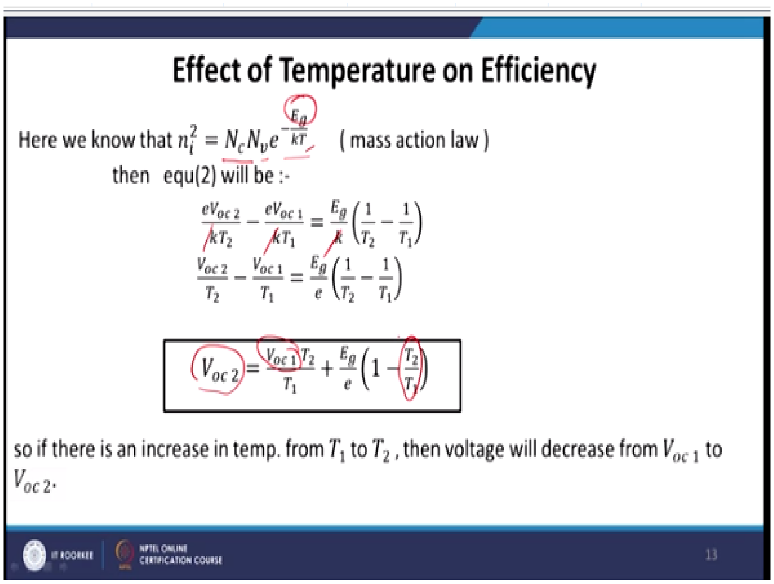

We know that ni square is Nc times Nv * e to the power –Eg/kT law of mass action if we remember where Eg is the band gap and T is the temperature. So then eVoc2/kT2 - eVoc1/kT1 = Eg/k 1/T2 - 1/T1 or if we take k as a common from here this k and this k and this k cancels out giving you Voc2/T2-Voc1/T1 = Eg/e so this e we are taking out in the right hand side into 1 over T2 - 1 over T1 or you get Voc2=Voc1T2/T1 + Eg/e 1 - T2/T1ok.

So if we measure the temperature T1 and open circuit voltage at Voc1 and if we measure the temperature T2 and the corresponding open circuit voltage is Voc2. So Voc2 is related to Voc1 by this equation, so what it depends on, it depends on the temperature ration and depends on the band gap. So if we keep the band gap fixed, that is for a same material it depends totally on the temperature T2/T1 ratio.

So if there is an increase the temperature from T1 to T2 the voltage will decrease from Voc1 to Voc2. So if we increase the temperature open circuit voltage decrease, if the open circuit voltage decrease since the efficiency is proportional to the open circuit voltage the total efficiency of the solar cell will decrease if we increase the temperature. That is why it is sometimes said that solar cell operates best at low temperature.

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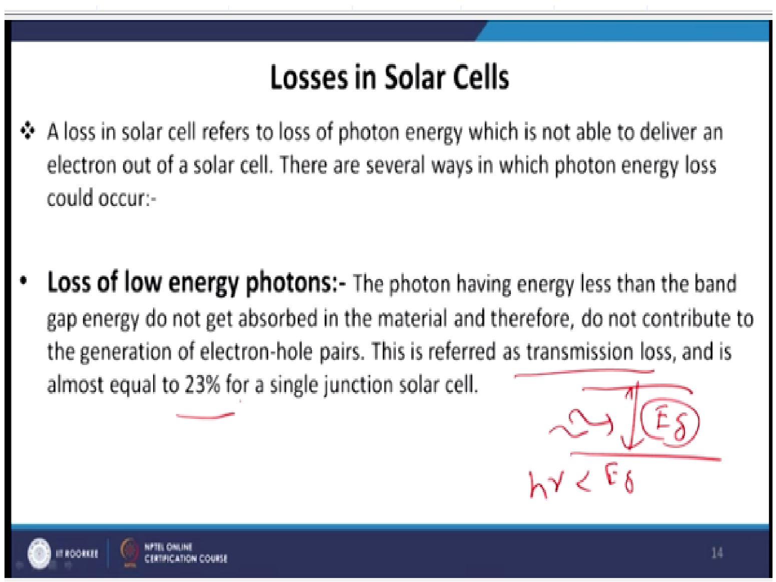

Now what can be the loss of the source of loss in a solar cell which contributes to the lower efficiency in a solar cell. A loss in a solar cell refers to the loss of photon energy which is not able to deliver an electron out of a solar cell. So that means a solar radiation is falling on a solar cell but it is not giving of an electron that usual job is solar cell. So there are several ways in which photon energy can loss, one is that loss of low energy photons.

The photon having energy less than the band gap energy do not get absorbed in the material and therefore do not contribute to the generation of electron hole pairs. So let us say like a material which has a band gap like this Eg, now a photon which is falling on this material which like you know energy if it is less than Eg or the band gap. So if H mu is less than Eg, so then this material will not be able to absorb this photon energy, so that photon will get lost.

So this is referred to as a transmission loss and this almost equal to 23% for a single junction solar cells. So to utilize a solar cell for an maximum efficiency we need to design a material which can take care for the solar radiation both in the visible range but both in the UV range and also in the IR range. Because most of the light let us say which are in a UV range and if I have a material which is which has a band gap in a visible range.

So then they will be not be able to absorb this UV radiation, so what it will do that it will heat the solar cell eventually it will decrease the efficiency of the solar cell. So that is why we have to intelligently design the materials whenever we are designing a solar cells. Now there can be loss due to the excess energy of the photon just like other extreme, 1 extreme is the low energy of the photon other extreme is the excess energy of the photon when the photon energy e is higher than the band gap energy Eg.

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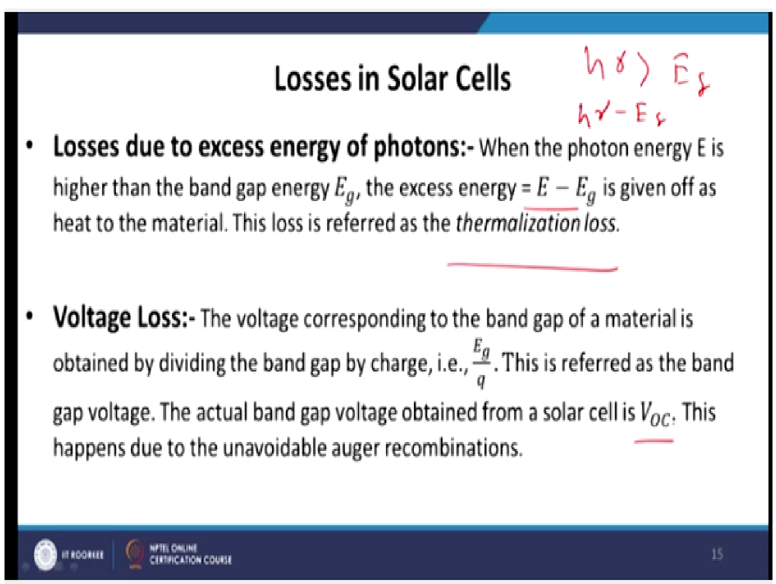

So here the h nu is greater than Eg, so what will happen to the fate of the electron. So Eg is enough to take them from the ground state to the first excited state but now we have enough energy to take them from the ground state to the excited state, what will happen to the excess energy, what is the amount of excess energy. That is h nu -Eg or E - Eg, that is given as a non radiative emission or that is given as a heat to the material.

So as you know that if we give the heat to the solar cell then the efficiency will decrease, so this loss is refer to as the thermalization loss. So there can be 2 different loss, one is due to the low energy of the photons that is the transmission and then there can be excess energy of the photon loss, that is called the thermalization loss. Now there can be also be voltage loss, the voltage corresponds to the band gap of a material is obtained by dividing the band gap/charge right.

So if we divide Eg/q, so we will get the voltage because Eg is q times V and if I divide by q qq cancels giving you the voltage. So this refer to as the band gap voltage, now the actual band gap voltage obtained from a solar cell is Voc open circuit voltage. This happens due to the unavoidable auger recombination.

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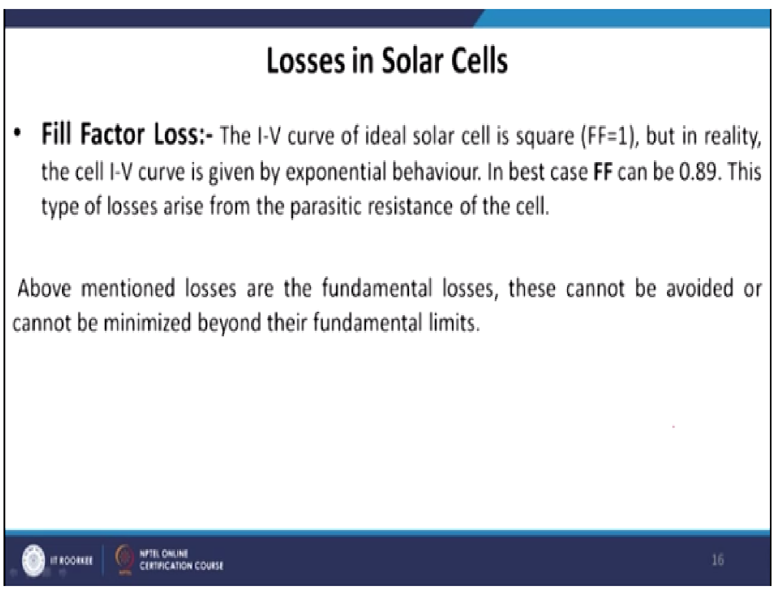

Fill factor loss, the IV curve of the ideal solar cell is square fill factor is 1 but in reality the cell IV curve is given by an exponential behavior. In best case FF can be 0.89 this type of loss arises from the parasitic resistance of the cell. As I said that if I have a higher values of the series resistance and a lower values of the shunt resistance then fill factor changes. And looking at the fill factor we can say how good is this devices.

Because if the fill factor is very high close to 1 then we have a higher efficiency. So above mention lost at the fundamental loss, this cannot be avoided or cannot be minimized beyond their fundamental limits. So from the thermodynamics (() (29:43) limit we have learn that there is a limit of the maximum efficiency for a single junction solar cells and that limit comes from the thermodynamics limit.

But even for considering that thermodynamics limits these are the sources of the loss which contributes to the lower efficiency in a solar cell.

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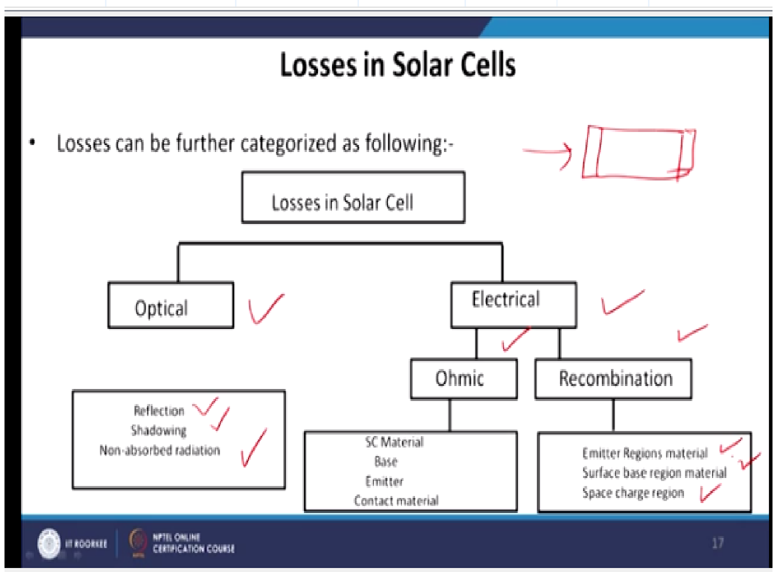

So this losses in a solar cell can be broadly categorized into 2 different factor one is the optical loss another is the electrical loss. Now what are the optical loss when we make a solar cell there can be reflection, there can be shadowing, there can be non absorb radiation. Let us say I have a solar cell like this but the front surface this is the front contact, this is the back contact. Now light is coming through here.

But if the front contact is too much reflective, so most of the light get reflected rather than being transmitted. But to generate the exciton we need the light to be transmitted through this material, so that kind of loss happens due to the reflections. Similarly the structure of device is such that there is a shadow effect, so we do not get the amount of the solar radiation which we intended to get, that is called shadowing.

Similarly there can be significant amount of radiation which goes for non absorbing, that is non absorb radiation. Now also there can be electrical loss there can be ohmic loss or that can be recombination, now recombination is a fundamental problem. That happens due to the electron hole recombination, we cannot avoid it. We can try our best to minimize it but there are some recombination loss that will always happen.

Now what about the ohmic loss, ohmic loss that happens due to the semiconductor material if the material is not very (()) (31:15) if there are lot of defects in the material then there can be loss. It can comes from the base, it can come from the emitter, it can come from the contact material these all contribute to the series resistance. Then there can be parasitic resistance also, now the another source is the recombination where can be the recombination happens one is the emitter regions material, one is the surface base region material another is a space charge region materials.

All of these regions contribute to the recombiantions, so today we will learn that you know I mean the difference source of the recombinations which contribute to the lower efficiency of the solar cells. Once we know like the difference source of the recombinations then we can optimize those parameters, so that we can get a high efficiency solar cell that we will learn in the next chapter.

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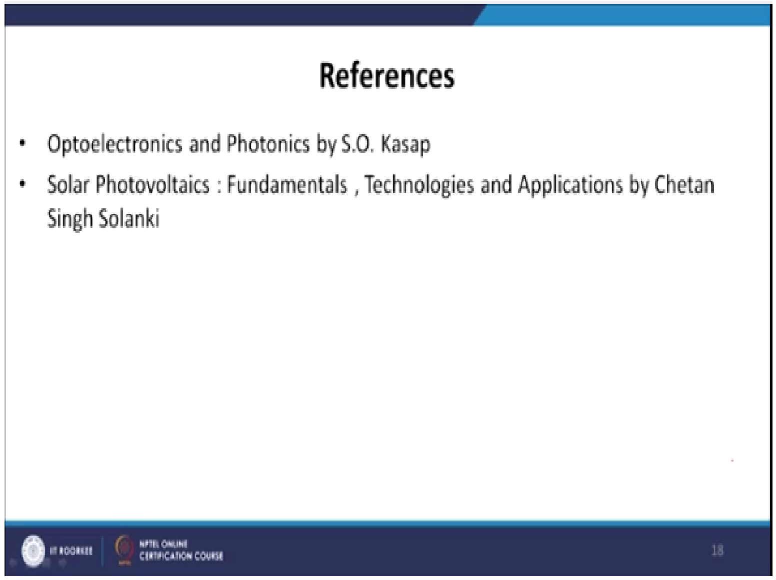

For this part we can refer to the optoelectronics and photonics book by S.O. Kasap and the solar photovoltaics book by the Chetan Solanki, thank you.