Solar Energy Engineering and Technology
Dr. Pankaj Kalita
Centre for Energy
Indian Institute of Technology, Guwahati
Lecture No. 11
Performance Characterization of PV Cells

Dear students, today, we learn Performance Analysis of Solar Cell. So, before we start our today's discussion, let us summarize what we have discussed in the last class.

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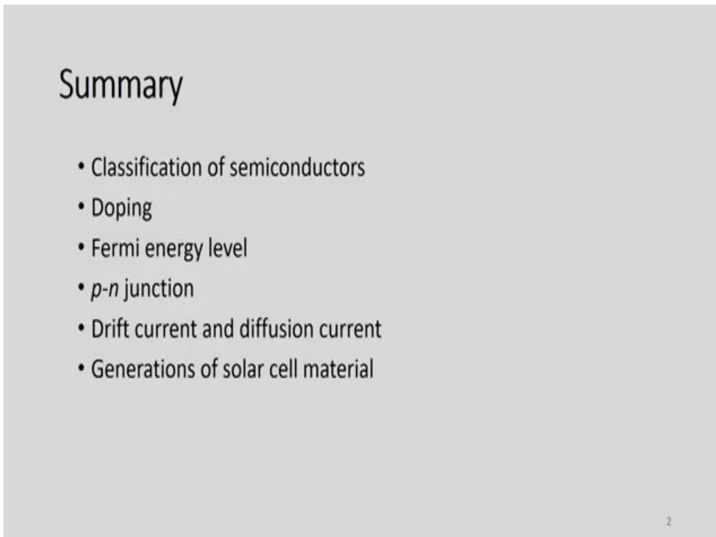

So, we have discussed classification of semiconductors, doping, Fermi energy level, p-n junction, drift current and diffusion current, and generations of solar PV materials. Of course, we have studied the working principle of a solar cell.

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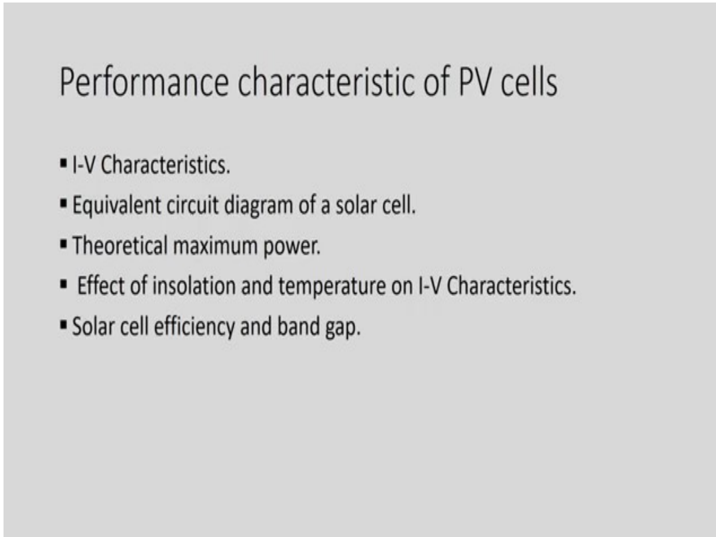

So with this background, we will now move to today's discussion on performance characteristics of PV cells, which includes I-V characteristics, equivalent circuit diagram of a solar cell both in actuarial and theoretical as well as our conventional equivalent circuit diagram, then theoretical maximum power, how to calculate theoretical maximum power, then effect of insolation and temperature on I-V characteristics, and finally, cell efficiency and band gap will be discussed.

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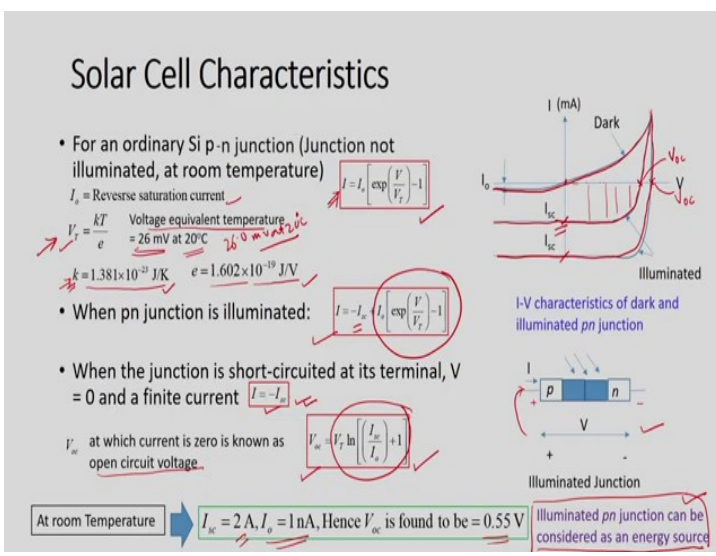

So, solar cell characteristics at room temperature when a junction not illuminated, so how it will look like? It will be something like this. And mathematically it can be represented by

$I = I_o\left[\exp\left(\frac{V}{V_T}\right) - 1\right]$. This is the expression we can use for dark current. So, this I_o is nothing but reverse saturation current which is dependent on temperature. Of course, it tells about the diffusion of minority charge carrier from neutral section to the diffusion layer. And this V_T is something called voltage equivalent temperature, and mathematically it can be represented by k×T/e, what is k, is a Boltzmann constant. Already we have discussed this Boltzmann constant in the last class. Its value is about 1.381×10^{-23} J/K. And charge of an electron is about 1.602×10^{-19} J/V. So this V_T value is about 26.0 mV at 20 °C. So, its value is 26.0 mV at 20 °C at room temperature.

Now, we will discuss what happens when p-n junction is illuminated, or light source is applied. So, what will happen, the shape of this I-V characteristics will change. So, it will go downward and then you can see how this shape has been changed. So these two figure is for two different light level. So, this is Isc for one light level; this is I_{sc} for one light level. This I_{sc} is short circuit drift current. So, we will define how this can be investigated.

So, mathematically when the p-n junction is illuminated, we can express something like this, $I = -I_{sc} + I_o\left[\exp\left(\frac{V}{V_T}\right) - 1\right]$. So, this I_{sc} what we have got after exposing to the light, so that has to be added. Since it is the 4th quadrant, so this will be $-I_{sc}$. So, when the junction is short-circuited at its terminal, this V is zero, this voltage is zero, and the finite current will be $I = I_{sc}$ which will flow through this junction, from positive terminal to the negative terminal. So, this current is known as short-circuited current or short circuit current.

Now, if we provide some kind of voltage source to this p-n junction and positive side is connected to p-side and negative, will be negative n-type, then what will happen? This voltage will start rising from zero, and then it will increase, so this will also change. And finally what happens, at certain voltage, this current will be zero ok this current will be zero. So, these voltages are known as V_{oc} for light source one and V_{oc} for light source two. So, this V_{oc} at which current is zero is known as the open-circuit voltage. So, if we substitute I = 0 in this equation, and then we simplify then what we will get? An expression for calculation of V_{oc}. So, $V_{oc} = V_T \times \ln\left(\frac{I_{sc}}{I_o} + 1\right)$. So, we can calculate the value of V_{oc} by knowing these parameters.

So, at room temperature, normally if we consider a silicon solar cell, then I_{sc} is about 2 A and I_o is about 1 nA. Hence, if we substitute this value here and we use Boltzmann constant and charge of an electron, then V_{oc} is found to be about 0.55 V for a single crystal silicon solar cells. So, what we have understood from here is that when light source is provided to a p-n junction that can be considered as an energy source. So, now we can understand we can generate energy out of this junction.

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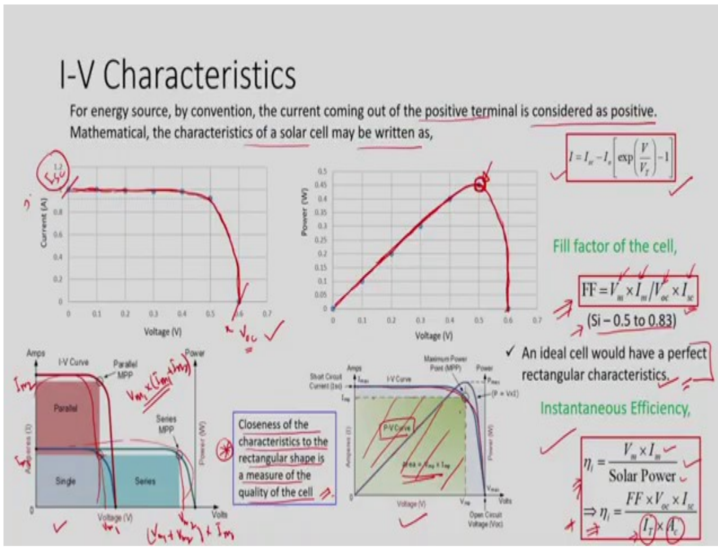

Now, let us learn the I-V characteristics, and in the convention what we normally use. So, for energy source, by convention, the current coming out of positive terminal is considered as positive. Mathematically, the characteristics of solar cell may be written as $I = I_{sc} - I_o\left[\exp\left(\frac{V}{V_T}\right) - 1\right]$. This is the expression normally we use. So, if I have to draw I-V characteristics, then we need to follow some kind of instrument, I-V tracer or maybe we can make our own arrangement to know how this voltage and current is related.

So, if I am interested to generate this I-V characteristic curve, then what we will use I-V tracer we can use, and we can get different values of current at different voltage. So, these are the points. So, if we join this point, so this will be something like this, and finally it will be joining at 0.6, if we say open circuit voltage is 0.6.

So, how it varies? Initially, this current will will be almost constant, and then sharply it is decreasing to zero. So, if we consider this is x-axis, this is y-axis, so intersection of x-axis will give V_{oc} and intersection of y-axis will give I_{sc}. So, this I_{sc} is very sensitive to solar insolation, but not V_{oc} much. Also, if we can generate this I-V, we can also generate PV curve, power versus voltage curve. So, if we vary power with respect to voltage, then what will happen? We can join those points, ok and we will get a maximum point and then it will decrease to this zero power. So, in every cases, what we will have? We will have this kind of plot, and it will pass through a maximum and then it will reduce to zero. So, this maximum point is very, very important.

So, if we can operate our system at this maximum point, then we are expected to have higher power conversion, and of course, we will get higher solar energy conversion efficiency. Now, combining these two, we can generate this kind of plot. This is the I-V part, and variation of power with respect to voltage is given here. And if we identify this is the maximum voltage, and this is the maximum current, so we can form this kind of rectangle. So, this is the area under the curve. So, area will be I_m into V_m.

So, this closeness of the characteristics to the rectangular shape is a measure of the quality of the cell, which is very, very important. So, this will give rise to a parameter called fill factor, which is nothing but mathematically $FF = (V_m \times I_m)/(V_{oc} \times I_{sc})$. So, this V_m is the maximum voltage, I_m is the maximum current and V_{oc} is the open-circuit voltage, I_{sc} is the short-circuit current. So, value of this I_{sc} varies from 0.5 to 0.83 for crystalline silicon solar cells. So, an ideal cell would have a perfect rectangular characteristics that we should remember.

Now, come back to this figure here what is shown, two cells are connected in series for this case, and two cells are connected in parallel. So, if we are connecting two cells in series then what will happen? Of course, voltage will rise, and if we are interested about this maximum voltage, so this may be we can put V_{m1}, and this may be we can put V_{m2}. So and this may be I_{m1}, and this may be I_{m2}. So, here voltage will be at this point $V_{m1} + V_{m2}$, and if we are interested in power that has to be multiplied by I_{m1}. And in this case, what will happen, we will have V_{m1} multiplied by $I_{m1} + I_{m2}$. So, that way, we can calculate for different cells.

Also, what we can define the instantaneous efficiency, if I am interested to know the maximum instantaneous efficiency of a solar cell that can also be calculated by using this simple expression. This I_m multiplied by V_m to the solar power means the amount of solar radiation received by the solar cell. Since, we already know the expression for FF, we can relate instantaneous efficiency with respect to fill factor.

So, if we relate this, then our final expression will be something like $\eta_i = FF \times \left(V_{oc} \times I_{sc}\right) / \left(I_T \times A_c\right)$. So, this A_c is the cell area, and I_T is the amount of solar radiation falling on the particular cell. So once we know these parameters, we can calculate η_i or instantaneous efficiency. So, here point is, if any system operates less than this power point or maximum power point, then we are losing the efficiency. So, our attempt is to operate the system at maximum power point.

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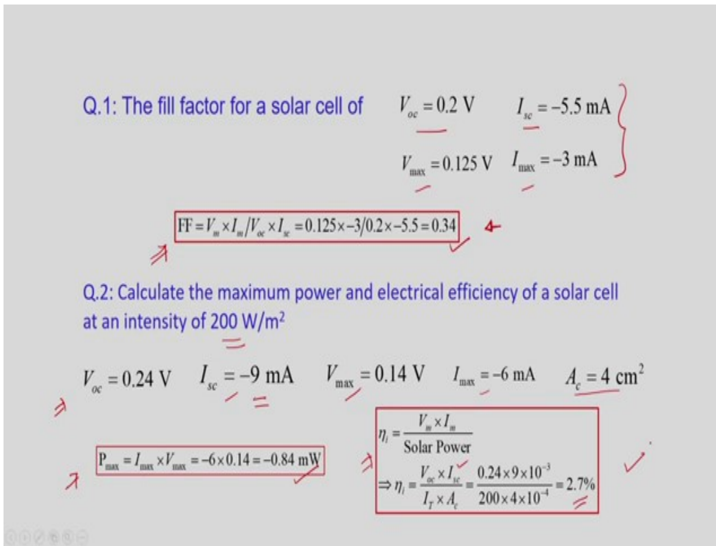

Now, let us do some kind of calculations to know fill factor of a solar cell. So, if these informations are given to us like V_{oc}, I_{sc}, V_m, I_m, then straightway we can calculate what will be the fill factor of a solar cell. So, here based on our calculation it is found to be 0.34, which is not so good, but still, what we have shown, this is the way how to calculate fill factor.

Now, if I am interested to calculate the maximum power and electrical efficiency of a solar cell at an intensity of 200 W/m^2, how to do that if these values are given. V_{oc} is given, I_{sc} is given, V_m or V maximum is given, I maximum is given and area of the solar cell is given as 4 cm^2. So, straightway you can calculate P_{max} is I_{max} into V_{max}. So, this will be 0.84 mW and instantaneous efficiency by using the expression what is discussed in the last slides, so we can get an efficiency of 2.7%, which is very, very less. Here, of course, we have used positive sign because conceptually we need to use a positive sign. So, we can we can have this instantaneous efficiency as 2.7%, which is very, very less. So, this is a demonstration how this can be calculated.

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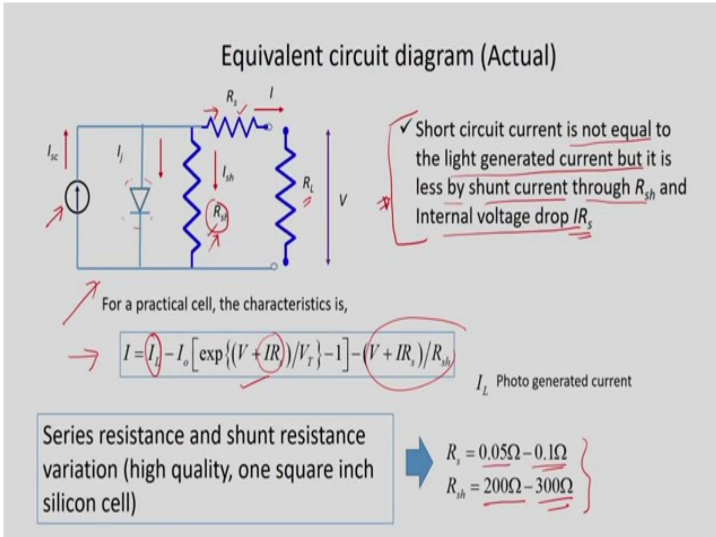

Now, let us learn the equivalent diagram. So, in order to understand the characteristics of a solar cell, we need to plot this equivalent circuit diagram. Of course, this is an actual equivalent circuit diagram. So, what are the components involved in this diagram? We will have a current source, and we will have junction, p-n junction or say diode and we will have shunt resistance, then series resistance and this is the load resistance. So, current source supplies current which is equal to I_{sc} and I_j is the amount of current which flows through this p-n junction and I_{sh} is the amount of current which flows through this shunt resistance, and I is flowing through this R_s. R_s is a series of resistance. So, this is an actual equivalent circuit diagram.

This short-circuited current is not equal to the light generated current, but it is less by shunt resistance or shunts current through R_{sh} and internal voltage drop R_s. So, normally in practical situation when we do the calculations, so these are neglected. It is assumed that this is R_{sh} is very, very high and R_s is very, very low. So, dissipation of power is very, very less when current flows through this series resistance. So, in this situations, the mathematically these characteristics can be written something like this, $I = I_L - I_o\left[\exp\{(V+IR_s)/V_T\}-1\right]+(V+IR_s)/R_{sh}$. So, these are the components which are added, R_s is also here.

So, values of this R_{sh} for a high quality 1 in^2 solar silicon cells is about 200 Ω to 300 Ω, and R_s is about 0.05 Ω to 0.1 Ω. From here, you can say the how these resistances varies in case of shunt resistance and series resistance. So, here point is this is I_L so cannot be directly equal to I_{sc}. So, it involves lot of losses if we connect this R_{sh} and R_s. So, normally resistance is very, very high in case of shunt resistance and here series resistance, no resistance is not much, thats why energy distribution is not much.

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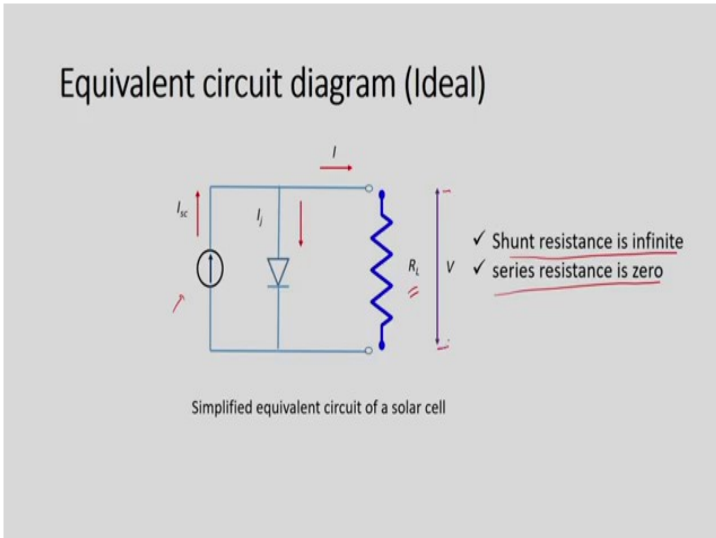

So, let us see what happens in case of ideal equivalent circuit diagram. So, we can omit these two components; shunt resistance and series resistance. So, our considerations are shunt resistance is infinite, and series resistance is zero. So, here only current source we have, then we have I_j the junction current, and I is the current flowing through this load resistance having voltage drop of V. So, now our intention is to calculate this P_{max}. So, in order to calculate P_{max} that is the maximum power which can be provided by a cell, we need to calculate what is I_m and what is V_m. Let us see how this can be calculated.

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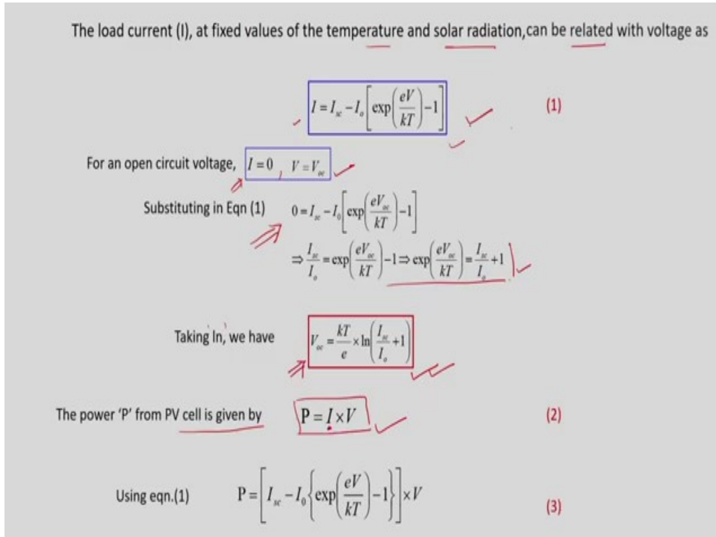

So, this load current at fixed values of temperature and solar radiation can be related with voltage. So, this I is related with voltage with this expression which is already defined. So, I is equal to $I = I_{sc} - I_o\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$. So, as we know, for an open circuit voltage I is zero, so V is equal to V_{oc}. So, if we substitute this in equation one, then our equation will be something like this. So, if we simplify it, then we will have this expression. And once we have this expression if we take ln in both the sides, then what we will have, we can calculate what is V_{oc}; which is nothing but $V_{oc} = \frac{kT}{e} \times \ln\left(\frac{I_{sc}}{I_o} + 1\right)$. So, by using this expression, we can calculate what the open circuit voltage. The power P from a PV cell can be calculated by using P = I × V, which is known to us. So, if we substitute this I from equation one, then our equation will look like this, so this equation may be equation three.

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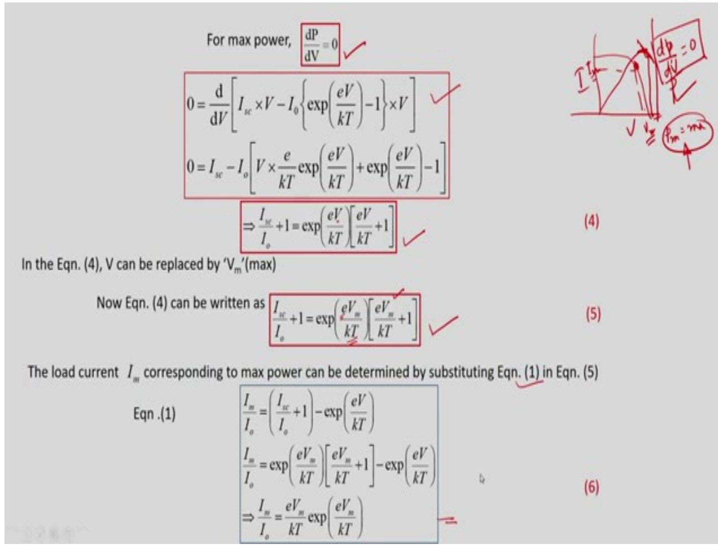

So, as you can understand when we have discussed in I-V and PV characteristics curves, so combined we can have this kind of plots. Not exactly, so, we will have maximum points somewhere here. So, this is the maximum point. So, at this point, what happens, dV by dP, sorry dP by dV is equal to zero, its gradient will be zero. If P is here and then V is here, of course, dP by dV will be zero at this point. So, this is the point.

So, under that conditions what we will get that we will call P_{max} if we know these values, then we can calculate P_{max}. So, if we use the expression what is developed in the last slides and if we differentiate with respect to voltage, so our equation will be something like this and if we multiply with voltage and then differentiate with respect to voltage and then finally expression will be something like this.

So, here what we can do? This V can be replaced by Vm because at this point or here for I-V, so if you sorry, actually here this will be I, and P may be in the secondary line, P. So, this maybe I_m, this may be V_m, this may be I_m. So, once we know V_m and I_m, so of course, we can calculate what is P_m. So, at these conditions here where dP by dV is zero, then what we will have, we can have this expression for V_m. So, by using this expression, we can calculate what will be the value of V_m once we know I_{sc} and I_o. Since, these values are known these values are known and we can we can have V_m. And this load current Im corresponding to maximum power can be determined by substituting this equation one in equation five. So, by using these and simplifying these, so we can have this expression. Let us continue with the next slides.

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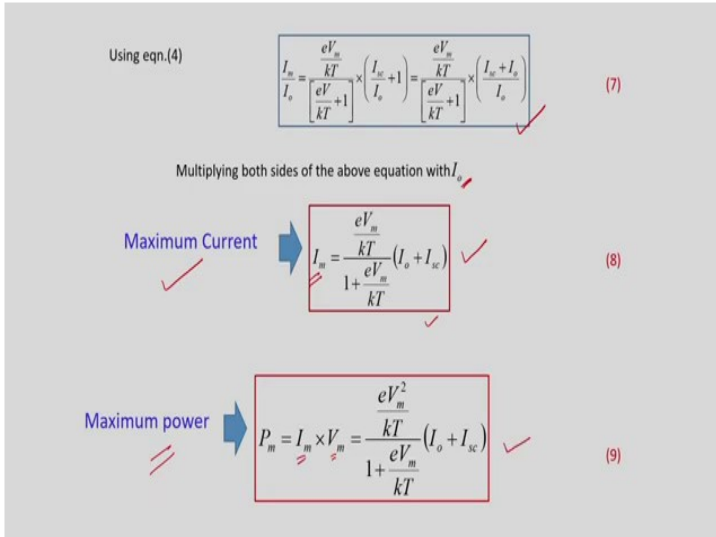

And by using equation four, then we will have this kind of expressions and if we multiply this equation, both side of this equation with I_o, then what will have is a maximum current. So, expression for maximum current is something like this. And once we know this I_m, then finally we can calculate what will be the maximum power. So, maximum power is nothing but multiplication of I_m into V_m. So, I_m is known here and V_m already we know the expression. So by using this expression, we can we can calculate what is P_m. Of course, while calculating P_m we need to do trial and error. So, that way, we can calculate the maximum power to be delivered by a solar cell.

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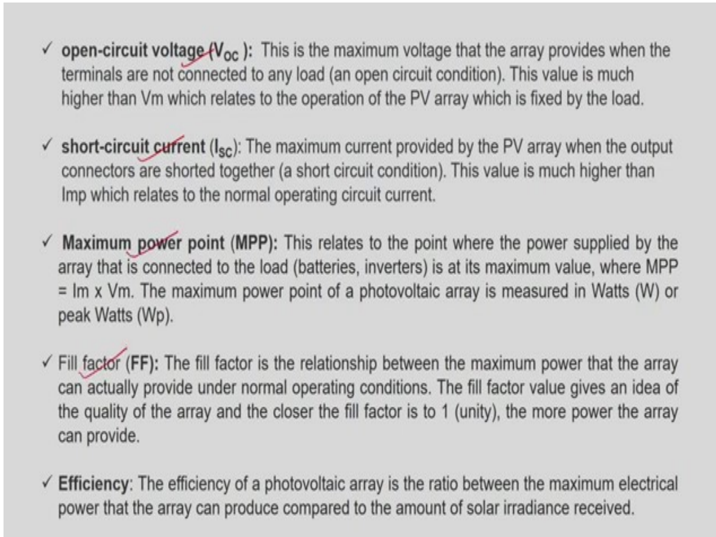

So, so far what we have learned is the open-circuit voltage, what is open-circuit voltage, what is short circuit current, what is the maximum power point, what is fill factor, what is efficiency? These five parameters we have studied, and we understand now what are those parameters and how these can be calculated.

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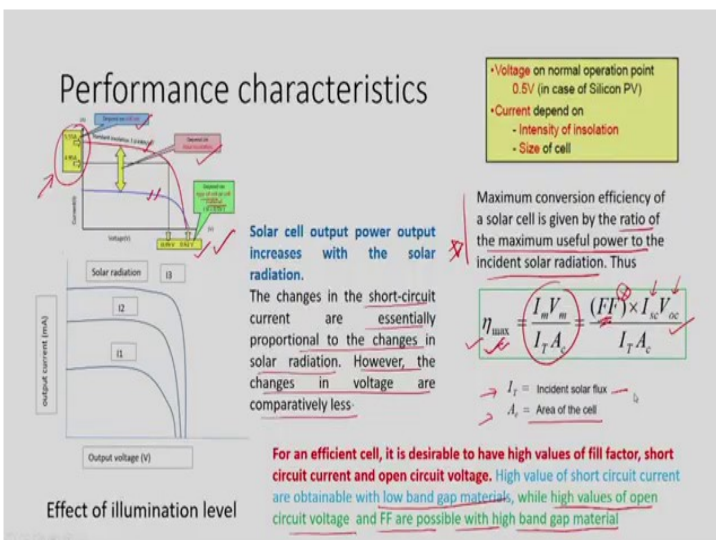

Now, again extension of these performance characteristics, as we can understand when solar radiation intensity increases, so I_{sc} value increases. So, as we can see here, so as I_{sc} increases again I_m and V_m also increases. So, here this is for one intensity, and this is for another intensity. So, of course, this will be at a higher intensity than this one. So, you can see this rise in I_{sc} when this solar radiation increases. But, variation of V_{oc} is not much even though solar intensity increases. And this I_{sc} is dependent on size of the solar cells and then solar insolation that we should keep in mind. If we increase the size of the solar cell, then it is expected to get higher I_{sc} values and also if we increase the solar irradiation, then I_{sc} value can be increased.

But this V_{oc}, the open-circuit voltage depends on the type of cell and, type of cell or cell material. So, this is fixed for a particular solar cells. This solar cell output power increases with solar radiation. The change in short circuit current are essentially proportional to the change in solar radiation. However, the change in voltage is comparatively less what we have shown in the figure.

Also, in the very beginning of this class, we have demonstrated how this eta max can be calculated. So, this expression already familiar to you, so this, with respect to FF, how it will look like and if we do not have FF only I_m and V_m then also we can calculate η_{max}. So, already you know what is I_T, is the incident solar flux and A_c is the area of the solar cell. So, this maximum conversion efficiency of a solar cell is given by the ratio of maximum useful power to the incident solar radiation. So, this you should keep in mind.

So, for an efficient cell, it is desirable to have high values of fill factor as you can see here. So, if we can get high values of fill factor and then higher values of I_{sc} and higher values of V_{oc}, of course, we can maximize our efficiency. So, now interestingly you can notice that high values of short circuit current are obtained with low bandgap material, while these high values of open-circuit voltage and fill factors are possible with high bandgap material. So then, we have to make some kind of compromise. Otherwise, we can see how these efficiencies varies with bandgap; then we can pick the best bandgap for maximum energy conversion. That also we will discuss in the coming slides.

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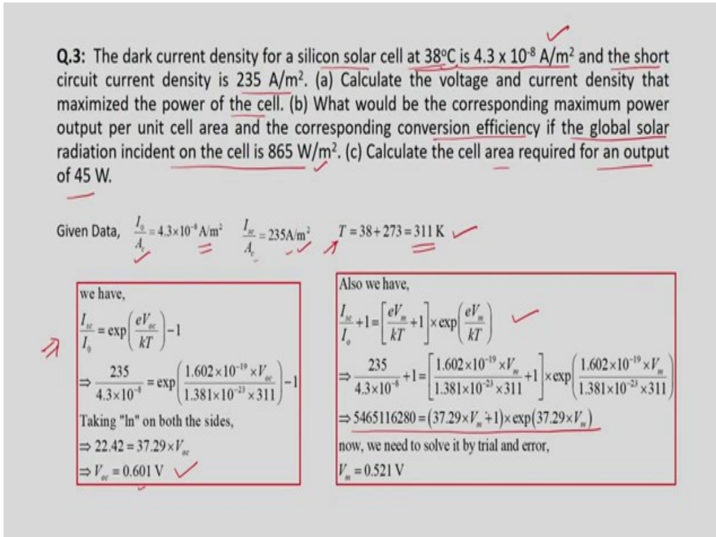

So, in order to understand the concept what we have discussed, so let us take an example of something like this. The dark current density of a solar cell at 38 °C, as I said this dark current density is always dependent on temperature. So, it is very, very sensitive to the temperature. And the short circuit current density is 235 A/m^2. Now, we need to calculate the voltage and current density that maximize the power of the cell. That means, we need to calculate I_m and V_m. Then second case, what do we need to calculate, what would be the corresponding maximum power output per unit cell area? That means power density you need to calculate and then corresponding conversion efficiency, if the global radiation incident on the cell is given as 865 W/m^2. Also, in the third case, we need to calculate the cell area if the output power is given as 45 W.

What is given here is I_o by A_c is given as 4.3×10^{-8} A/m^2. And I_{sc} by A_c is given as 235 A/m^2, and temperature since we need to convert this centigrade to Kelvin, then we have to add 273, so it will be 311 K. So, this, our relationships are varied only when we take T is in K or temperature is in K. So, already we have those expressions already derived. $\frac{I_{sc}}{I_o} = \left[\exp\left(\frac{eV_{oc}}{kT}\right) - 1\right]$. By using this expression, what we can calculate is the V_{oc}. So, open circuit voltage we can calculate. So, we substitute these values and taking ln on both sides and then finally, what we can have is V_{oc} is 0.601 V.

Also, we know this expression, in order to calculate the V_m, we need to use this expression. Then on substitution of those given data, then we can develop this expression. So, we cannot solve these expressions straightaway. So, we need to solve it by trial and error. So, we need some kind of prior knowledge about V_m, because already you know V_{oc} is 0.601, so V_m has to be less than 0.601. That way, we can decide what will be the probable values of V_m. Maybe we can start with 0.5, then maybe 0.55; then we can see which one is closer to these values, then finally, we can decide what will be the exact values of V_m which satisfies this equation. So, once this equation is satisfied with this assumed V_m, then we can calculate what is V_m. So, this V_m will be 0.521 V for this case.

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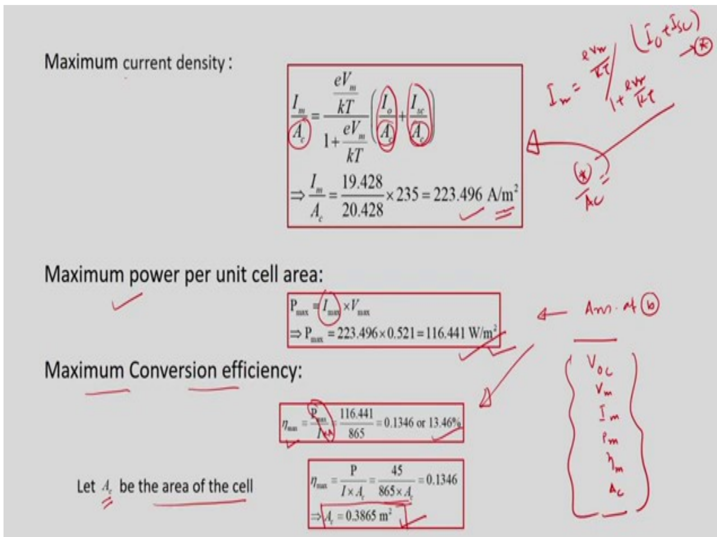

Now, once we know this, then we can calculate maximum current density. So, this expression we can use. So, the kind of expression what we have used during derivations, there A_c was not there. So, what we can do? We can take that expression so that expression was Im is equal to $I_m = \frac{\frac{eV_m}{kT}}{1+\frac{eV_m}{kT}}(I_o + I_{sc})$. And if we divide this expression, this maybe star expression. This star if we divide by A_c then what will be the expression is something like this. So, why we have done it, because these values are given in terms of densities, so that is why we have done it. So, I_m by A_c on substitution of these values, then what we will get is about 223.496 A/m^2.

So, now what we can calculate is the maximum power. So, P_m is equal to I_m into V_m. So, this will be the P_m. Since, we know this I_m and this will be W/m^2; since this I_m is in W/m^2. So, this is for maximum current density. So, $P_m = I_m \times V_m$. So, finally, what we will have, this is a maximum power per unit cell area. So, this is the answer of answer of question b. And and this is also part of answer b. So, finally this maximum conversion efficiency, we know the equation P_m/I because this P_m here is density. So, $I \times A$ is taken care of this P_m. So, that is how, we can calculate I_{max}, so this will be about 13.46%.

So, if we need to find out A_c or say cell area, how to do that? Let A_c be the area of the cell, and we know this η_{max} and P is given as 45, then we use this equation, and from that, we can calculate what A_c or area of the solar cell. So, this area of the solar cell, we can calculate by using this procedure. For this case, it is about 0.3865 m^2.

So, in this problem, we have first calculated V_{oc}, then we have calculated V_m, then we have calculated I_m, then we have calculated P_m, then we have calculated η_{max}, and finally, we have calculated η_c. So, we have shown how these parameters can be calculated from given data. So, this kind of exercise is very, very important to understand how these equations can be used for calculation of all those performance parameters.

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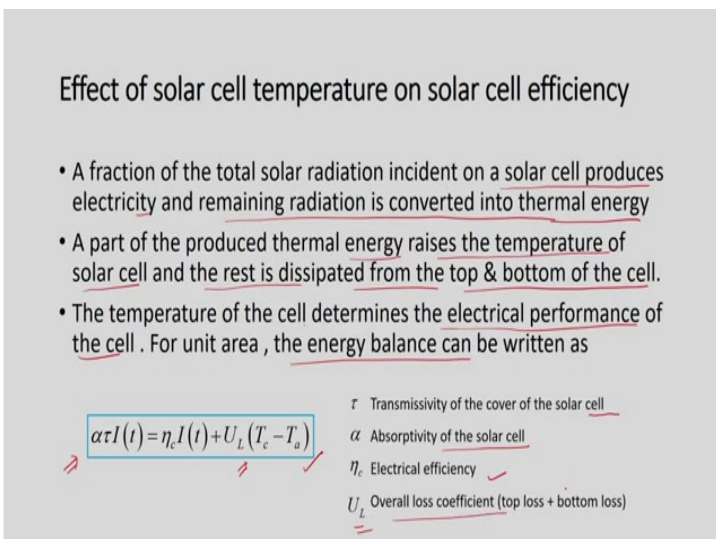

Now, let us learn the effect of solar cell temperature on solar cell efficiency, which is very, very important. A fraction of total solar radiation incident on a solar cell produces electricity, and remaining radiation is converted into thermal energy. A part of the produced thermal energy raises the temperature of the solar cell, and the rest is dissipated from the top and bottom of the cell. The temperature of the cell determines the electrical performance of the cell. So, if we do the energy balance per unit area, so we can have this kind of equations. Losses will be there, and then we have efficiency and then amount of energy received by the system. So, what is τ, the transmissivity of the cover of the solar cell, then α is the absorptivity of the solar cell, then η_c is the electrical efficiency, and of course, U_L is the overall loss coefficient which includes top loss and bottom loss.

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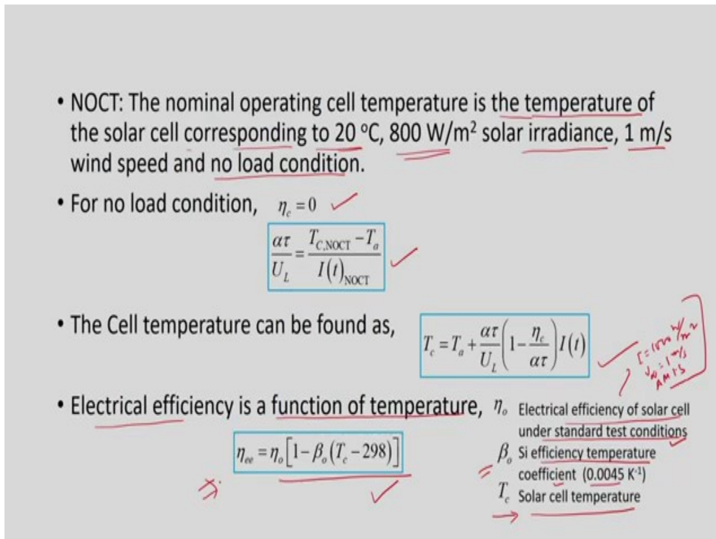

Also, we will introduce one term called NOCT. So, in the backside of the PV model, normally you can see this NOCT is written. That is, normal operating cell temperature which is nothing but the temperature of the solar cell corresponding to 20 °C and 800 W/m^2 solar irradiance and wind speed is 1 m/s under no-load condition.

So, for no-load condition η_c will be zero, no electrical conversion will be there. So, this expression what we have discussed in the last slides, it reduces to something like this and from here you can calculate what will be the cell temperature. So, expression of cell temperature will be something like this. The electrical efficiency is a function of temperature. So, this electrical efficiency again related with this expression. So, what η_o, is the electrical efficiency of the solar cell under standard test condition.

So, what is under standard test condition? This solar radiation has to be at 1000 W/m^2; then wind speed is 1 m/s and AM1.5, these are the minimum requirement for this standard test condition. And β_o for silicon solar cell is about 0.0045 K^{-1}, which is known as efficiency temperature coefficient. And already we have defined what T_c, which is nothing but solar cell temperature. So, by using this, we can calculate what will be the electrical efficiency of a solar cell.

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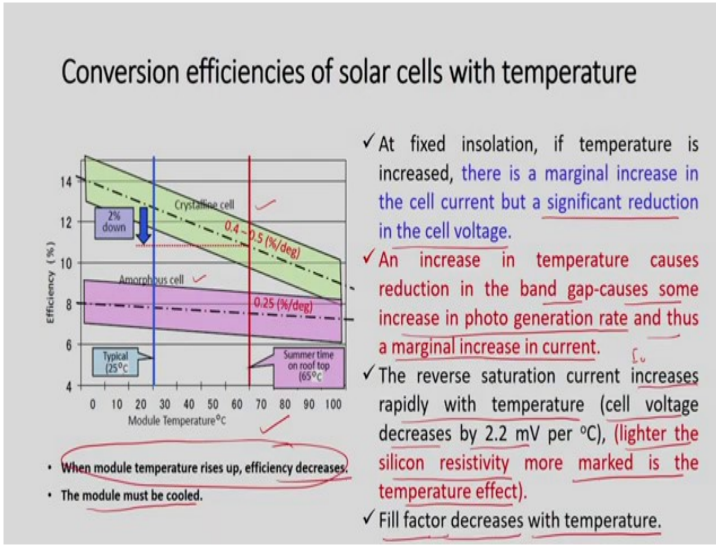

Now, let us learn how this efficiency of a solar module related with temperature. As temperature increases, what happens in both the cases, for amorphous cells and crystalline cells, efficiency decreases. This decrease is more significant in case of crystalline solar cells. So, as you can see this decrease is about 0.4 to 0.5 % per degree rise in temperature, and for amorphous cell, its about 0.25 % per degree rise in temperature. So, when the module temperature rises up, the efficiency decreases. So, we need to have some kind of cooling for improving the efficiency. So, normally natural coolings are preferred.

But why this is happening? So, let us learn at fixed insolation, if temperature is increased, there is a marginal increase in the cell current; but a significant reduction in the cell voltage. And the second cause is, an increase in temperature causes a reduction in the bandgap, which causes some increase in photogeneration rate and thus a marginal increase in the current. The reverse saturation current, which was represented by I_o, increases rapidly with temperature. So, it was reported that the cell voltage decreases by 2.2 mV per degree increase in temperature. And also, it is observed that lighter the silicon resistivity, more marked is the temperature effect. And last cause is, fill factor also decreases with temperature. So, these are the causes why actually know this, with rise in temperature, conversion efficiency decreases significantly.

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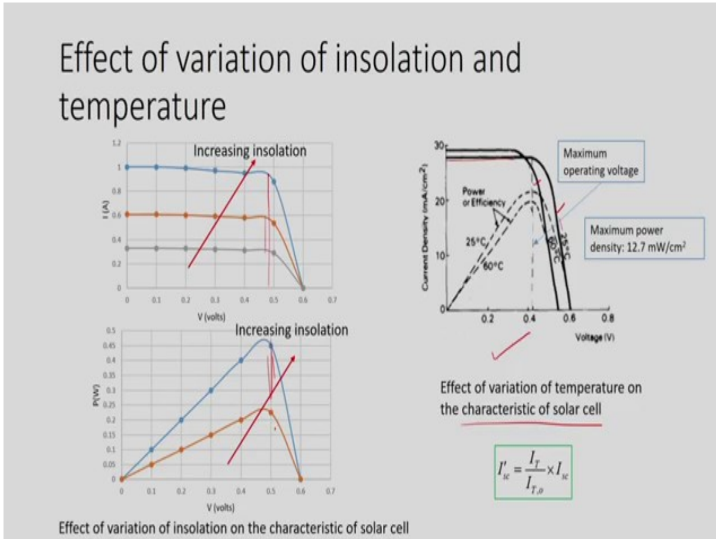

Now, here it shows the variation of insolation, as insolation increases, how this characteristics curve changes. Also, this P Vs V curve changes. We can see the shift of maximum power point if we trace it from here ok. And this plot shows the effect of variation of temperature on the characteristics of the solar cell. So, as temperature increases, this I_m, V_m also decreases. So, these are, this is very, very clear. So, this may be for one one case, and this may be for another second case ok, and this is for at 25 ºC, and this is for at 60 ºC. See how these changes are taking place.

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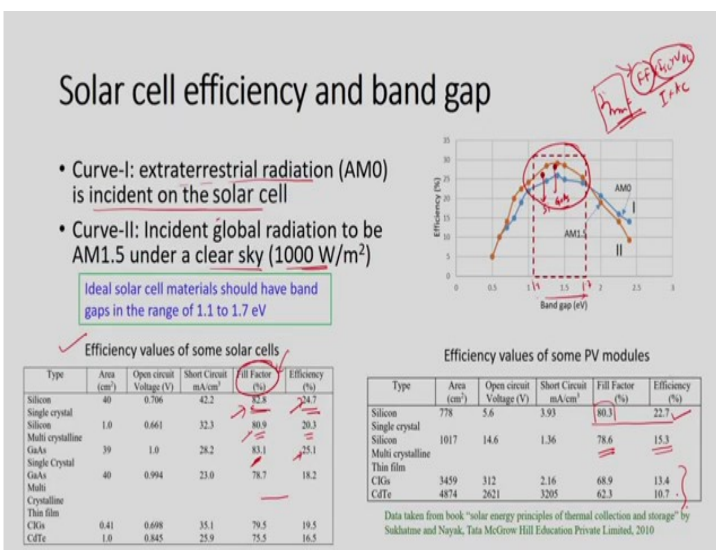

Now, let us see how this solar cell efficiency and band gap are related. So, here in this figure, two curves are considered. So, one curve is generated under a spectrum of AM1.5, and another curve is generated under the spectrum of AM0, which is extraterrestrial region. So, this curve one, is extraterrestrial radiation is incident on the solar cell and curve two, incident global radiation to the AM1.5 under a clear sky. And it is assumed that intensity of solar radiation is 1000 W/m^2. So, if we plot it then what we can get, so this is for silicon, and this is for gallium arsenide. So, if we see as we understand, this η_{max} is related to fill factor ok, then I_{sc}, then V_{oc}, then we have here is the $I_T \times A_c$. So, this is, this will be more, this will be good for high values of bandgap, and this will be for low values of bandgap.

So, what we can say, in this range, solar cell efficiency is found to be high. And if we see this, this is about 1.1, and this is about 1.7, close to 1.7. So, if we consider a bandgap in between this range 1.1 to 1.7, it is expected that we will get higher conversion efficiencies. Of course, we can do a lot of iterations by varying this bandgap, and we can optimize, or we can maximize what will be the maximum efficiency of conversion.

So, this table shows the variation of efficiency with different solar cell material. As you can see very precisely, this fill factor and efficiency, there is a relationship, see. When fill factor is more, efficiency is very high. So, fill factor is more, efficiency is high. So, this fill factor plays a very important role in enhancing the efficiency of a solar cell. And this table shows the efficiency values of some PV modules. So, this also quite clear. So, for silicon single crystal module, so we will have higher efficiency of about 22.7 and the same time, we will have higher fill factor. So, comparison can be seen. For multi-crystalline, it is about 15.3 % efficiency and fill factor is about 78.6, and the other two cells are also given here.

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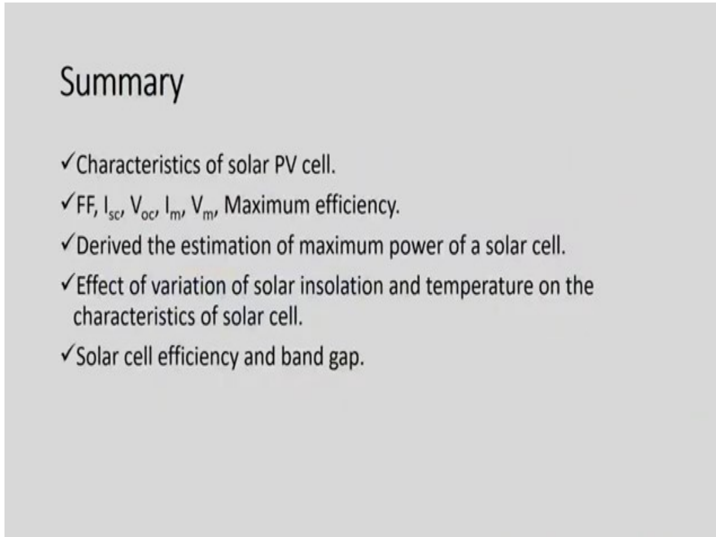

So, what we can summarize in this talk, we have understood the performance characteristics of a solar cell. And also, we have studied how this fill factor can be calculated, I_{sc} can be calculated, V_{oc} can be calculated, I_m, V_m and maximum efficiency can be calculated. And what is I_{sc}, what is V_{oc}, how this I_{sc} and V_{oc} are sensitive to solar insolation and size of the cells; that also we have discussed. And also, we have derived to estimate the maximum power of a solar cell. Also, we have studied the effect of variation of solar insolation and temperature on the characteristics of solar cell. Finally, we have studied solar cell efficiency and bandgap. Hope you have enjoyed this lecture. Thank you very much for watching.