Solar Photovoltaics: Principles, Technologies and Materials
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Lecture - 25
Solar Cell Device Parameters

So, welcome again to a new lecture of Solar Photovoltaic Course, Principles, Technologies and Materials. So, we will wind up today our discussion on P-N junction in light with a emphasis on solar cell. So, what have what we have been doing is, we have done P-N junction analysis. And we have been talking of P-N junction in the context of solar cell now, which is P-N junction in light. So, basically we have been looking at the device characteristics of P-N junction in light that is a solar cell. So, essentially in this lecture we will also look at solar cell device parameters also ok.

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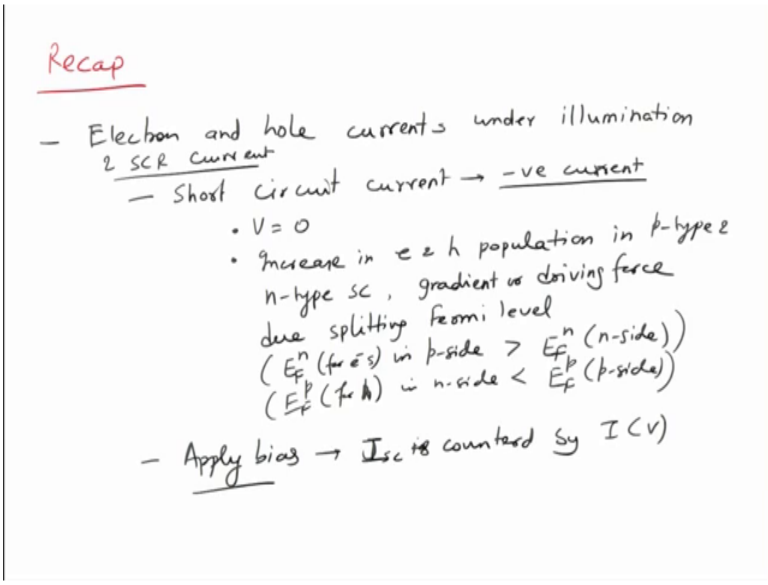

So, let me just to give you a brief recap, what we did in the last lecture was we looked at the so in the last lecture we looked at we looked at the electron and hole currents under illumination. So, the first is short circuit current and of course the SCR current all right, there are three components of the current.

So, first we looked at a short circuit current, which is on which is basically a negative current. And what it meant was that in the under short circuit your V was equal to 0. So, this was short circuit condition, when the current you get is negative and that is mainly because of increase in electron and hole population in you can say p-type and n-type semiconductors right.

So, as a result you get the current which is which you do not get in forward current when you have when you apply a bias. So, essentially you get negative current, what mean what it means is that holes travels from electron n-side to p-side, and electrons travel from p-side to n-side, because and this happens because of because you have a you can say gradient in the or driving force due to splitting of Fermi levels the electron Fermi level rises above the electron Fermi level in the n-side.

So, basically you can say E F, E F n for electrons in p-side is greater than E F n in n-side. Similarly, E F p for holes in n-side is lower than E F p in p-side. So, we can say electron like to sink and hole like to float. So, as a result when there is a downhill gradient for a Fermi level for electrons, electrons will go from p to n-side and holes will go from n to p-side. And this happens, because illumination causes massive increase in the carrier density especially for minority carriers within p and n-side ok. And this leads to the current in opposite direction, which is what. And this current as you apply bias then J SC oh sorry, I SC is counted by counted by I V ok. So, now when you plot this, you start getting a curve like this.

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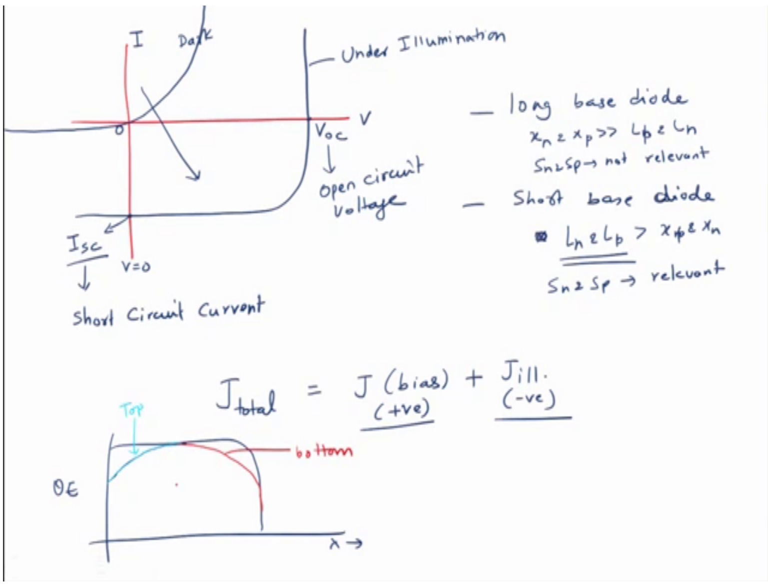

So, when you plot this, I goes like this, so this is I, this is V. So, this is at this 0 potential, this is V is equal to 0. So, you are going from 0 to a parameter called as V OC. So, at 0 bias, the current that we get is equal to I SC which is called as short circuit current.

And up to some point the bias induced current is not large enough as a result I SC is stays nearly constant, now this depends upon the type of solar cell that you have material quality that you have what kind of recombination you have. So, for a for a perfect solar cell which does not have high level of a recombination, which does not have high level of SCR current or other or other kind of currents.

The J S, I SC stays flat up to quite a bit of voltage and before it suddenly starts increasing. So, within dark for a dark solar cell you should obtain characteristics like these and this shifts to fourth quadrant when you apply a when the solar cell is under illumination. So, this would be under dark and this is under illumination.

And we also look that the operation under two assumptions, one was long base diode and another was short base diode. So, which basically modifies the equations, because in the long base diode when the diode is very long, then you can say that x n and x p are much larger than L n and L p and L n right. As a result surface recombination basically happens, and so everything will get recombined. So, as a result you do not consider x n and x p, because they would have anyway happen.

In case of short base diode, you say that your L n and L p are larger than x n and x p x p and x n. So, this region this is when the diffusion lengths are longer than x n and x p are relevant, because you will have surface recombination. And here S n and S p are not relevant. So, we made these two approximations and when you make these two approximations, your diode equations change in a little bit.

However, when you whatever the case is and if you plot the I V characteristics of solar cell, I V characteristics look like this. So, I V characteristics show a diode like behavior in the dark, and this curve shifts to fourth quadrant and giving you negative current at 0 bias, which is called as short circuit current. And this short circuit current starts reducing slowly and gradually, and it becomes 0 until you reach a voltage called as V OC, which is called as open circuit voltage.

Essentially, what happens is at this point is if you now look at the total current, J total was equal to J bias which is positive and you can say if I and this was J illumination right. J illumination is negative, this is positive at this point these two components outweigh each other completely right. And we also looked at the effect of various parameters on the quantum efficiency; we looked at the quantum efficiency shows the behaviour like this.

So, perfect quantum efficiency would be something like that ok. So, this is quantum efficiency as a function of wavelength. So, whenever the quantum efficiency reduces on lower wavelength side, which means you are top of the solar cell is playing an important role or if you have so this would be the top part contribution. And if your quantum efficiency is decreasing on the on the higher wavelength side, then you know that you have decrease this is mainly from the bottom part of the solar cell.

And if you have a decrease in the middle, it comes on the somewhere in the middle you have recombination taking place or some other effects taking place. So, this will be helpful for you to look at your data yourself, when you work on if you work on solar cells and analyze this in this context that which of the layers may be playing important role in specially from the important from the context of bi layer junctions like P-N junction wherever you have silicon kind of solar cells. So, now what we will do is that we will now move on to.

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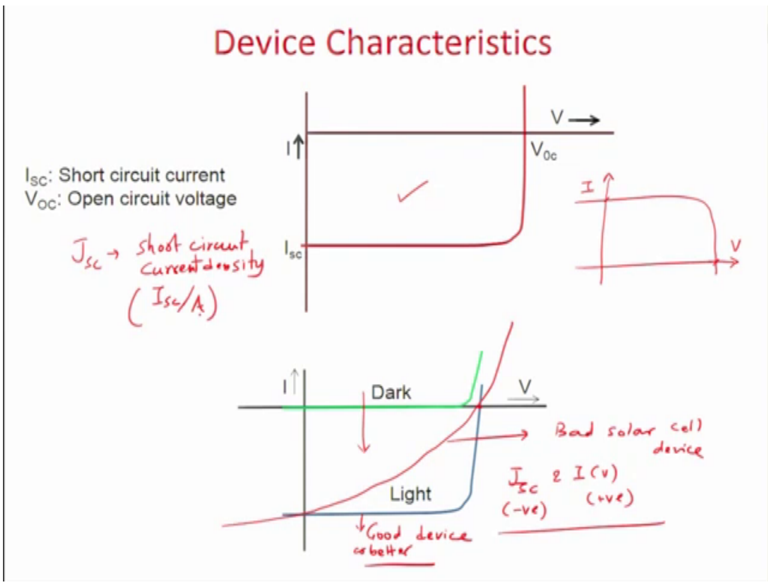

So, these are the device characteristics that you get for solar cell under illumination. As I said, the current at 0 bias is called as the short circuit current and the current and the voltage at which the current becomes equal to 0 is the open circuit voltage. And this is in remember, this is in fourth quadrant. So, even though in literature there are some papers which there are some literature, which plots this in the first quadrant. Some you will see that there are enough books and literature, which plot I V of solar cell like this.

Technically speaking this is not correct, but it is it is a it is plotted for the sake of convenience just to show that how much current you get from the solar cell and this is open circuit voltage. Technically speaking this is a correct plot; this is not from the sign perspective.

So, in the dark solar cell is going to behave in this fashion, you will have 0 dark current and then you will have increase in the current at higher biases, and this curve shifts to fourth quadrant as you apply light as you as you put it in light. So, under illumination you generate current from the solar cell which is negative current and this current gets outweighed curve. So, as I said earlier your the competition is between I SC and I V; one is negative and another is positive. And these two outweigh each other at this point.

So, if you have more recombination mechanisms, if you have more recombination mechanisms, this curve will start looking like this. So, in fact, I V will start dominating right the early stages. So, for a perfect solar cell the plot is like a rectangle, whereas for a imperfect solar cell with lot of recombination mechanism defects traps, etcetera. You will have you will see, this I starts rising as increase the voltage in the early stages of the plot itself. So, this is you can say a bad solar cell device, and this is a good device or better device.

The idea is to get as rectangular curve as possible. So, these are the two important parameters I SC short circuit current, V OC the open circuit voltage, you a lot of times we write this in J SC which is short circuit, current density and this is nothing but I SC divided by area of the device ok.

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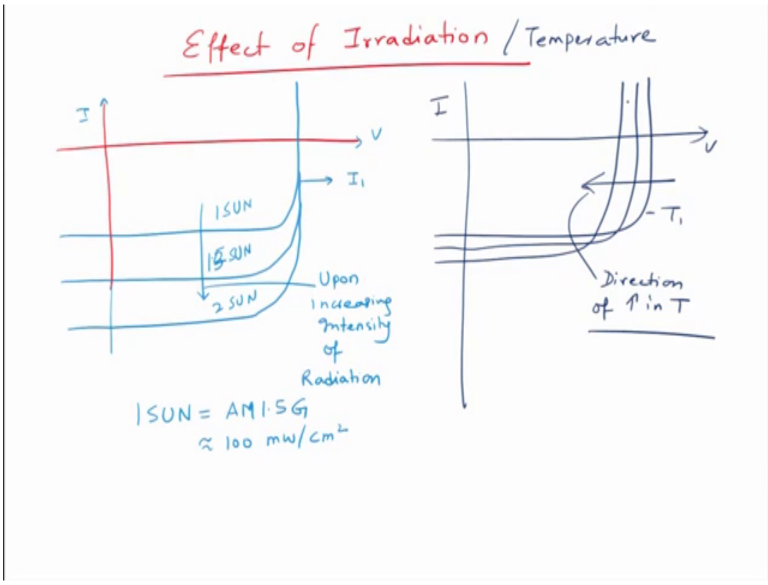

So, now we look at the effect of irradiation on this I V curve. So, effect of irradiation. So, this I V curve, which is so if it is let us say for a solar intensity I 1 if this is I V curve you obtain. If you look at the equations, since I since the since the current is directly proportional to I the intensity; if you increase the intensity, the curve should shift down.

So, and you can keep going in this direction, ideally speaking this is how it should behave. So, this will be upon increasing intensity of radiation. So, as we said earlier we defined this in 1 sun. Write 1 sun is equal to AM basically 1.5 G ok, which is equivalent to 100 milliwatt per centimetre square. So, if let us say this was at 1 sun, then 2 sun should lead to so this would be 1.5 sun nearly one and half times increase, and this would be nearly 2 sun. Theoretically speaking provide if there is no change in the V OC and the other things, which are not changing.

So, generally it should show ideally speaking, it should show double the increase in the current. V OC will not change, because V OC the voltage that you obtain is it well. There will be some change, because V OC is a function of current, but there is not a huge change that is seen in V OC. Similarly, if you and as you as you change the temperature the temperature change also. So, this is let us say and temperature. So, as you change the temperature the temperature change leads to so this is increasing intensity, if I make a plot for this. For example, this is for the first temperature T 1 and if you if you if you go it for high temperature, the high temperature leads to more emission, but also it reduces a V OC.

So, as a result high temperature will result in reduction the V OC generally like this. So, this would be you can say direction of increase in temperature. So, this is how I V will change as a function of temperature for a given, because you will be able to thermally excite little bit more career has increased the temperatures. So, some current will we will see some increase in the current, but it also leads to change in the voltage as we will see later on in the in the expression, this is what we discussed.

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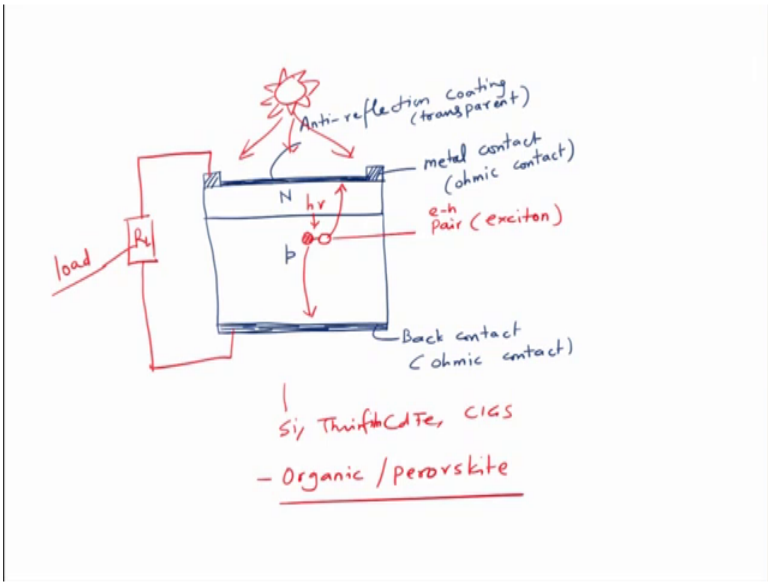

So, a typical P-N junction devices you have let us say in this case the emitter, then you have all let us not talking terms of emitter and base that we will talk when we learn about the silicon solar cell. So, we just restrict our self to. So, let us say this is a N junction, this is a p-type junction, then you will have a front contact here and on top you will have a anti-reflection coating. So, this would be anti-reflection coating which will so it looks dark, but it should be transparent all right.

So, it should be transparent, anti-reflection coating, on top you have metal contacts, metal contact should be conducting enough and they should be have ohmic contact to the semiconductor, so you should have ohmic contact. And then on the back also you have a contact, this is the back contact which again should make a ohmic contact, so that charge carriers are extracted efficiently and then as you as light shines on it.

So, as you have sun shines on it, the radiation falls over it, you create electron hole pairs in the semiconductor. So, the photon h nu will give rise to a electron and a hole pair right, which is called as exciton. This exciton dissociates and so this guy will travel to this side, this guy will travel to this side and you will have and this is connected to a let say external load, some R L.

This is what the typical solar cell geometry is of course, in case of so this is followed pretty much in case of silicon, in case of thin film semiconductor devices such as cadmium telluride, CIGS, etcetera, but the geometry is different in case of solar cell which are for example, organic or perorskites. In this case the although you have bi layer solar cells also, but the typical architecture is where P-N junction p and N devices are mixed together with each other at an at an microscopic scale.

And in between the contacts, there are also carrier selective coatings which preferentially allows certain type of careers to go to. So, holes will go preferentially to anode and electrons will go preferentially to cathode. So, this is the typical device architecture that we see for a solar cell.

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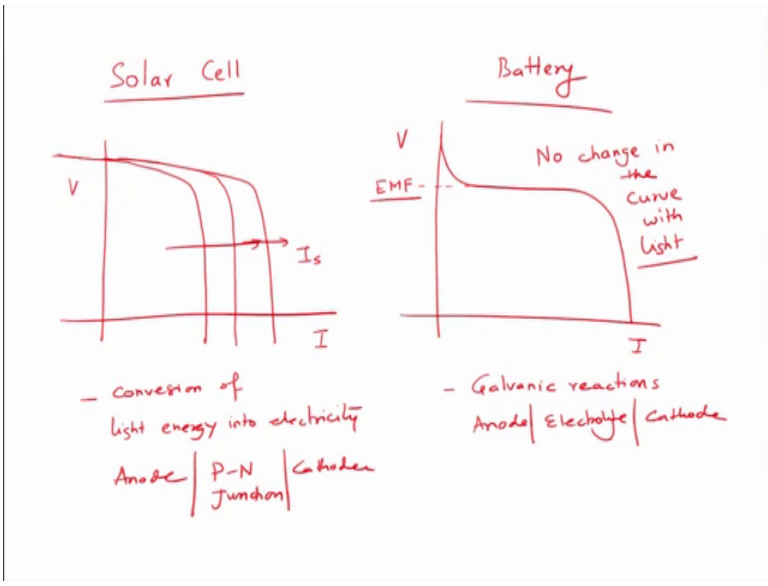

So, there is a now solar cell may appear to you something like you know what is the solar? You have a solar cell, on the other hand you may have battery. Solar cell is generally it gives you characteristics, which are like this. So, in case of solar cell if you plot current as a function of voltage, so without bothering too much about the sign, you have something like this kind of behavior all right.

In case of battery and this will change as you increase the intensity of light. So, intensity of light will move this to shift to right, your current will keep increasing right. So, if we increase I S, your current will increase for a solar cell whereas, for a battery gives you a EMF; if you plot V versus I for a battery, the battery I V curve is something like this. And there is no of course, change with light of course, it may change with the temperature. So, it will give you a EMF, which is corresponding to certain voltage.

And then of course, it gives you certain current at voltage and there is no change in the curve with light ok. So, in because we use both batteries and solar cells; batteries also a power generator, solar cell is also power generator with a fundamental differences between the way to operate. Battery is based on basically you can say is based on galvanic reactions; whereas, this is conversion of light energy into electricity ok. So, this uses a things like electrolyte.

So, you of course you have anode and cathode, but anode you have electrolyte and then you have a cathode. In this case of course, you have anode you have cathode, but in between we have a P-N junction these are the differences between the battery and a solar cell.

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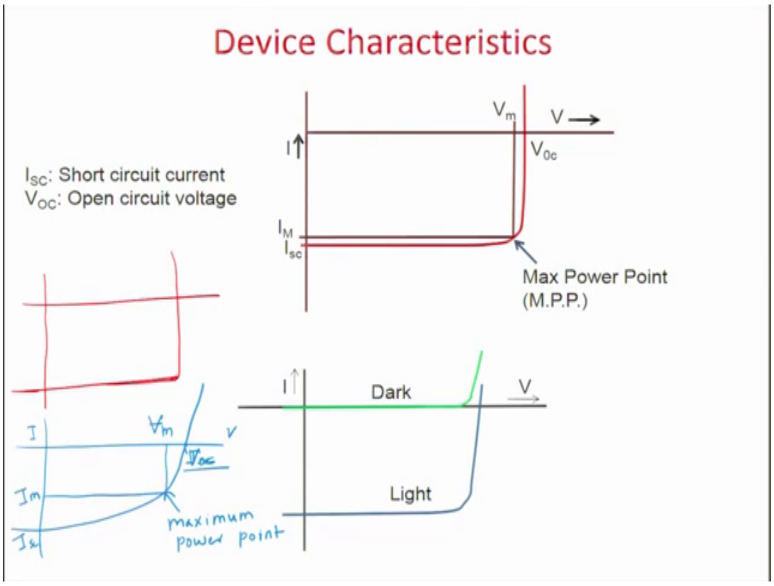

In the context of solar cell, there is something you need to remember that the device characteristics if we look we looked at this plot earlier, a point in the I V curve, there is a point in the I V curve at which you get maximum power point and this corresponds to the rectangle of maximum area that could be drawn within this I V curve. So, rectangle that can be drawn is drawn by this blue line, sorry the brown lines. So, the current and voltage corresponding to those is called as V m and I m. And this point in this case is called as maximum power point.

So, you can now this of course, can be determined mathematically wherever so you basically you want to maximize the power. So, of course, if your I V curve is like this, the rectangle is also same as the I V curve. However, if you are I V curve appears to be let us say like this, let me make another plot. So, if you are I V curve is like this ok, then the maximum power that you can extract will be somewhere here. So, this point is maximum power point and the voltage and current corresponded to this point are called as V m and I m, they are lower than I SC and J SC.

So, basically you can see that if a just, sorry v o V OC and I SC. So, if you if you multiply I SC and V OC, this is a theoretical amount of power that you should be able to generate from a solar cell, but this is limited by the fact that you have device recombination mechanism and so on and so forth, which we will see later on because of the decrease in the current as a function of voltage because of recombination and other issues.

The maximum power that can be extracted from a solar cell is much smaller than what you can. So, this is where the shape of I V curve is extremely important, we should try to our aim as a materials and devices engineer is to maximize this power that can be extracted which means to have a I V curve which is as rectangular as possible.

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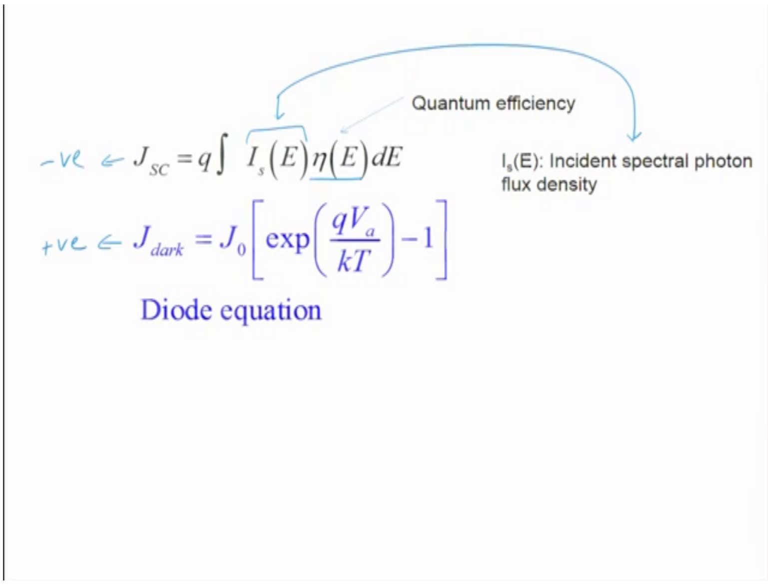

So, this the current that we that we extract from a solar cell is depicted as J SC is equal to basically q integral over all the energies I S E which is the incident spectral photon flux density, eta E is the quantum efficiency, quantum efficiency will come from your current expressions basically. So, if your quantum efficiency is 1, then basically all the photons that you are able to capture will be converted to the current.

However, quantum efficiency is not equal to 1 in most cases, it is always lower than 1 because of losses inside the semiconductor. As a result if you if you capture 100 photons, if 90 are converted, then you get 90 percent quantum efficiency. So, this is basically the short circuit current essentially theoretically speaking.

And the dark current as we have seen earlier, dark current J dark is equal to J naught into exponential of q V a by k T minus 1 and these two so this current which is the which is the dark current is basically is a is a positive in nature. So, this current is negative in nature and this current is positive in nature at positive biases. And these two basically compete against each other to give you a I V curve that we obtain for a solar cell.

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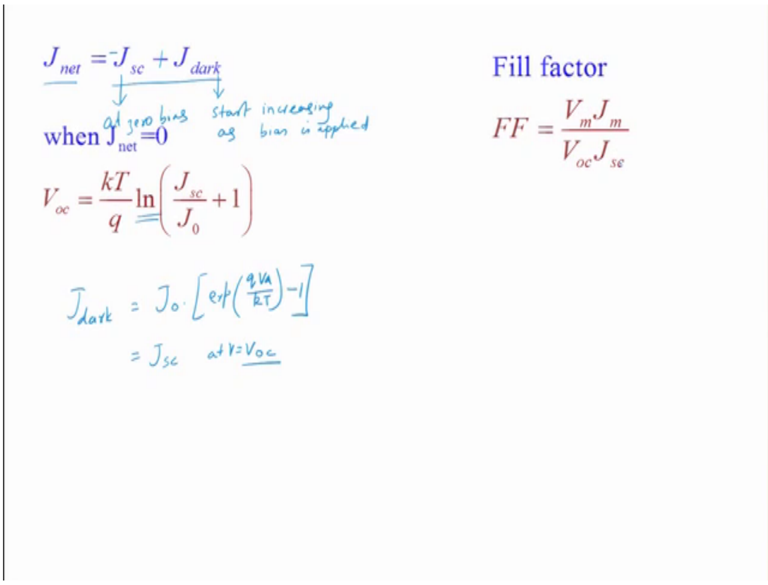

So, for a solar cell J net basically is equal to J SC minus J dark ok. So, it is a balance between these two is what you get in a solar cell, so J SC is at 0 bias right. And as you apply the bias, this component starts increasing as bias is applied. Of course, you have to take care of signs. So, this is you can say this would be minus and this would be plus in the in the in the in the real contexts. So, this is the negative current and this is the positive current. So, these two outweigh each other, but if you just take the mod of 2, there is the current that you will obtain ok.

So, when J net is equal to 0, I can balance out; when J net is equal to 0, then I can write V OC is equal to. So, if you if it see the expression for J dark, J dark was equal to J naught into exponential of q V a by k T minus 1. So, I am saying that J net is equal to J SC minus J dark, assuming so I am just taking the mod of both of them. Just I am also taking J SC as a positive current. So, when J net is equal to 0, then in that case J SC is equal to J dark, and that is when V is equal to V OC right. So, V OC can be obtained as so if you now make it equal to J SC at V OC ok, at V V is equal to V OC, then I can obtain I can replace V V a with V OC ok.

So, V OC will become k T by q into l n of J SC by J naught plus 1. So, we can see from this factor as the temperature increases. So, as the temperature increases you will have some increase in V OC, but V OC is quite critically dependent upon the dark current and the short circuit current. It is a function of both dark current as well as short circuit currents. So, if you have defects in the semiconductor, if you have recombination in the semiconductor, if you have anything which leads to higher recombination current or dark current, in that case V OC V OC will go down. And if you are able to increase the short circuit current, your V OC will slightly go up.

Of course it s a log it varies a logarithmic function. So, the increase is not as much as you would see in case of current, but a still there is a impact in certain terms on the open circuit voltage. So, based on the shape of this curve, we get another factor which is called as fill factor.

Fill factor is the maximum power that can be drawn maximum energy the maximum energy that can be extracted out of a solar cell practically speaking with respect to the maximum possible that you can extract. This is V m into J m divided by V OC divided by J SC ok; this is called as fill factor. It is a very important parameter in the context of solar cells. And a last, but not the least we will just we will look at the power conversion efficiency.

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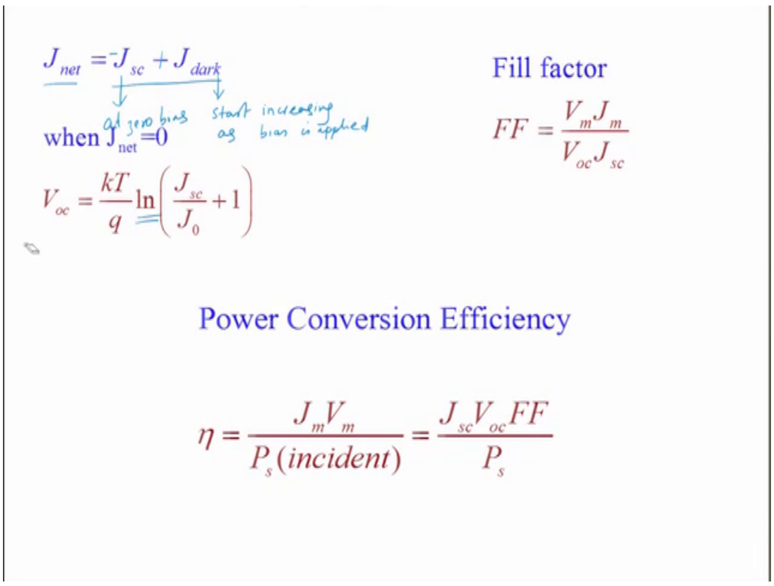

So, this power conversion efficiency is eta which is J m V m divided by P incident. So, amount of maximum power that you can. So, maximum power that you can extract or maximum energy that you can extract from a solar cell divided by what is the incident energy or incident power. Power extracted divided by power incident will give you the power conversion efficiency, which is nothing but J SC into V OC into fill factor divided by P S, which is the incident power.

So, these are the solar cell device parameters that we have learned in this class. And we will further discuss them in the next class, before we go on to discuss in the technologies ok. So, we will stop here today.