Introduction to Semiconductor Devices
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Lecture - 11.2
Introduction to Solar Cells

Let us get started. So, in this video, we would like to talk about solar cells or photovoltaics. Solar cells are very important in our life today because they are putting they are replacing the fossil fuels for an energy needs. Fossil fuels like petrol and diesel are very polluting to the environment. And, we would like to go to renewable energy resources. And, photovoltaics or PV is a very important component of the renewable energy.

So, photo solar cells are not very new. They have been there for a long time almost 40 to 40 years or so.

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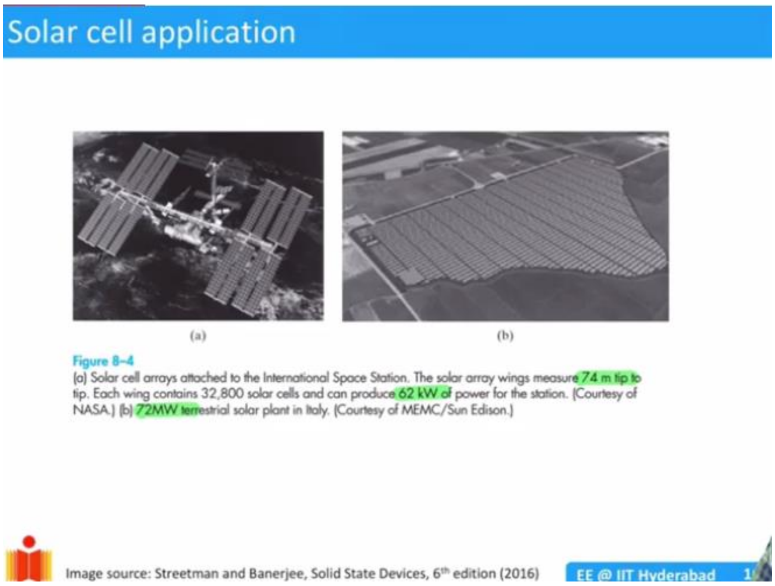

Solar cell application

Figure 8–4
(a) Solar cell arrays attached to the International Space Station. The solar array wings measure 74 m tip to tip. Each wing contains 32,800 solar cells and can produce 62 kW of power for the station. (Courtesy of NASA.) (b) 72MW terrestrial solar plant in Italy. (Courtesy of MEMC/Sun Edison.)

Image source: Streetman and Banerjee, Solid State Devices, 6th edition (2016)

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They were used in the satellites or you know space applications in the 70s and 80s. The reason is you know in those applications we do not really care about the cost. Initially, the cost of the solar cell was very large. But, slowly with the progress of silicon technology, the cost of the solar cells has come down. And now, we can afford them to you know afford them so that we can even easily install them on the rooftops and things like that.

So, this is there are couple of images. So, the first one is of the international space station the arrays that you see here. These are panels of solar cells. So, their large arrays about 74 meters as mentioned in this caption. And, they generate about 62 kilowatts of power which is a very large amount of power. You know a typical home might have about 5 kilowatt of power. So, about 12 times larger. So, it is a large amount of power that we are generating.

And, because you need to run the space station and you need this much of power. There is no other source there in the space. So, this is in the space application and even on the land you have now big solar farms coming up all across India actually nowadays already. So, we have you know this is a picture of a solar farm which you know which is generating about 72 megawatts of power.

So, these solar cells are now you know very important. And, we would like to understand them. The fundamentals of it we will understand in this lecture.

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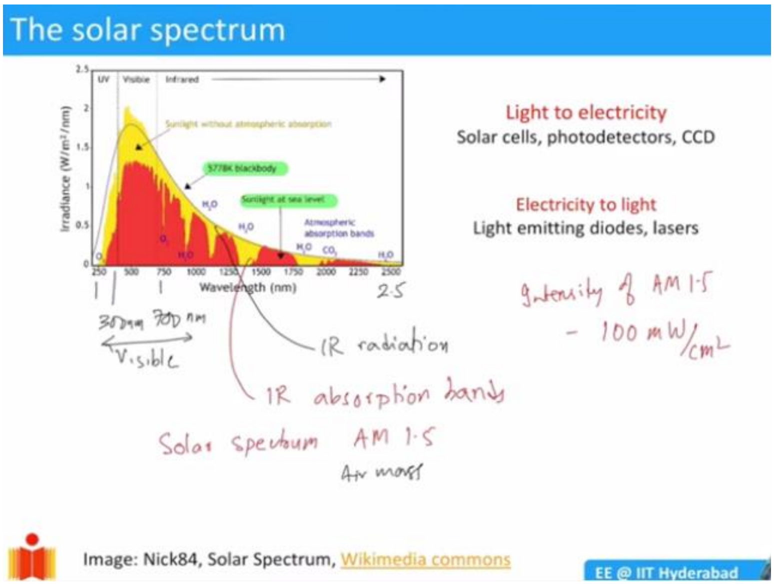

The solar spectrum

Light to electricity
Solar cells, photodetectors, CCD

Electricity to light
Light emitting diodes, lasers

Intensity of AM 1.5 - 100 mW/cm²

Solar spectrum AM 1.5
Air mass

Image: Nick84, Solar Spectrum, Wikimedia commons

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So, when we think about solar cells, the first important feature that we need to understand is the solar spectrum. So, Sun is generating a lot of energy . You have see you see that. So, it generates heat and light. So, if you look at the spectrum of the solar radiation it looks like this. So, that the picture in yellow is a spectrum of the solar radiation. You see that the radiation is in from 250 nanometers to about in this case I am only showing 2.5 microns.

But, typically, it can even go up to longer you know the intensity falls. You can even have up to 4 microns or so. But, the intensity falls rapidly. So, this is a solar radiation. And, we say that Sun behaves like a black body. You know you might wonder you know why blackbody. So, in scientific terms, but blackbody is a perfect absorber of radiation. It absorbs all wavelengths with equal intensity.

And, if you heat up a black body, it will emit all wavelengths with equal intensity. Or, rather you know very large efficiency basically. So, here you see that if you have a black body the, I mean there is theoretical analysis for that and essentially the solar spectrum is you know behaving as if it is basically a black body heated up to 5800 Kelvin. So, that is why you know we say that the solar temperature is about 6000 Kelvin typically.

So, because of that you have this peak energy in the visible part. So, you see this radiation you know between 300 to 700 we call it visible range 300 nanometers to 700 nanometers. Only this is what you are seeing. And, because it has all of these wavelengths in almost equal intensity you see that Sun is you know whitish in color. And, you but you still have IR radiation which is extending up into longer wavelengths.

So, this is basically the IR radiation, infrared. Infrared means beyond red. So, in the 600 to 700 nanometers is a red part of the spectrum. So, beyond red is infrared. And, in the lower wavelength part, below 300 is called ultraviolet because below violet. So, that is the terminology we use. And, if you are not familiar, you should just refresh this part. So, now, when this solar radiation is incident on earth, the yellow spectrum is what is measured outside you know in the space.

But, the red part is what you get on the ground. The red I know this is spectrum on the ground or in that is why it is same sunlight at sea level. So, what you see is there are certain you know of course there is some absorption in the atmosphere absorption of all the wavelengths. But, mainly in the visible and blue part of the spectrum, there is more absorption. And, then in the IR also, you see some bands.

These are IR absorption bands corresponding to various molecules. For example, if you have water in the atmosphere which is there. I mean the water vapor is there in the atmosphere that will lead to some absorption. The specific characteristic absorption features at around you know this part. You know this part and harmonics. And then, there is nitrogen related absorption and other things.

There are a lot of molecules or gases which will absorb. So, because of that you see at certain windows you have complete absorption. And, other wavelengths, it is transmitting. And, you see nearly almost all the solar radiation is reaching the Earth. So, this is about the solar radiation. And, because you know at each location, the solar radiation is different. And, depending on the latitude longitude, it will vary.

The amount of intensity that reaches Earth will vary. So, scientists adopt a very standard spectrum. And usually, we refer to it as you know solar spectrum AM1.5. What this means is air AM stands for air mass. It is just a notation saying that it is the amount of radiation that is absorbed when Sun is at roughly 45 degrees of angle. So, that is the standard spectrum we refer to so that you know people can compare with solar cells performances in different locations.

And, it turns out that if you have AM1.5 spectrum if you sum up all the intensity that is available in the at all wavelengths, the total will turn out to be about 100 milliwatts per centimeter square. This is the intensity of AM1.5 spectrum. So, this is the total amount of power that is incident on the earth at a typical you know let us say at 45 degrees angle on the surface of earth. So, this is what we have.

And now, how much of it can we harvest? That is what is important for us. Now, when we build a solar cell, we would like to harvest as much energy as possible from here. To understand that, of course, we need to calculate what is known as you know we have intensities.

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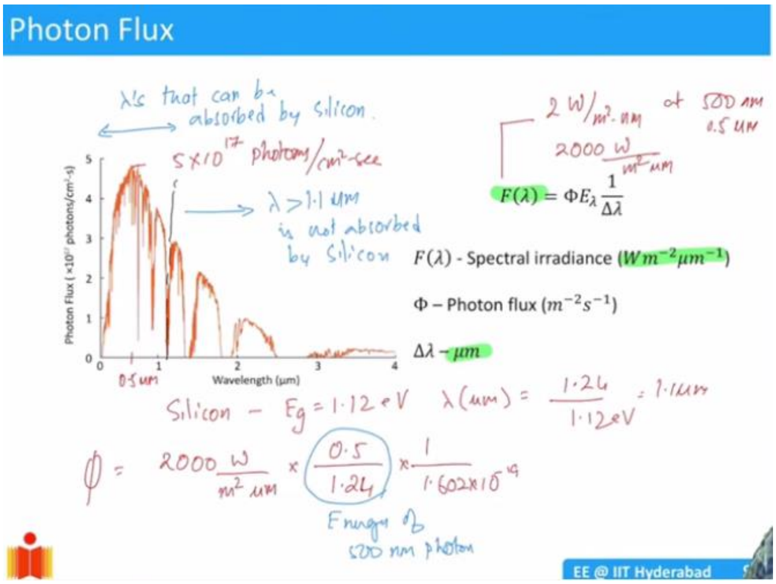

Photon Flux

λ's that can be absorbed by silicon.

5×10^{17} photons/cm²-sec

$\lambda > 1.1$ um is not absorbed by Silicon

2 W/m².nm at 500 nm 0.5 um

$2000 \frac{W}{m^2 \, um}$

$F(\lambda) = \Phi E_\lambda \frac{1}{\Delta\lambda}$

$F(\lambda)$ - Spectral irradiance ($Wm^{-2}\mu m^{-1}$)

Φ – Photon flux ($m^{-2}s^{-1}$)

$\Delta\lambda$ – μm

Silicon – $E_g = 1.12\,eV$ $\lambda(um) = \frac{1.24}{1.12\,eV} = 1.1um$

$\phi = 2000 \frac{W}{m^2 \, um} \times \underbrace{\boxed{\frac{0.5}{1.24}}}_{\text{Energy of 500 nm photon}} \times \frac{1}{1.602 \times 10^{-19}}$

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That is given to us. But, we would like to calculate the number of photons that are incident. And, that is going to depend on each wavelength because you see we have already seen that the photon intensity is dependent on the energy times the number of photons. So, if you have a higher energy, then you will have a lower number of photons. And also, there is this feature that we call as spectral irradiance which is the amount of intensity at each wavelength per centimeter square.

$$F(\lambda) = \phi E_\lambda \frac{1}{\Delta\lambda}$$

$F(\lambda) - Spectral\ irradiance\ (Wm^{-2}\mu m^{-1})$

$\phi - Photon\ flux(\ m^{-2}s^{-1})$

$\Delta\lambda - \mu m$

So, the expression that we used to calculate that is given here. So, F lambda which is the total irradiance is equal to the flux. So, this is phi is the photon flux. And, E is the E lambda is the energy of the photon. And, 1 over delta lambda is just the window. In that particular window, how many photons are incident? And, for making these calculations, typically, we use them in micrometers. So, F lambda, we take it in micrometers.

And, delta lambda, we take it to micrometers. To make sure that, there is no error. So, if you look at this the number of photon turns out to be about 10 power 17 photons. Typically, if you take let us say this is I would say around 0.5 micrometers you take 0.5 micrometers roughly about $5 \times 10^{17} \frac{photons}{cm^2-sec}$. So, this is a peak. So, which of these photons will be absorbed?

And, which will not be absorbed? So, we know that let us say if you take silicon, silicon has a Eg of 1.12 eV. So, let me put the Eg of silicon here. So, let us say somewhere here approximating it. So, if your photons are having you know wavelength higher than this number 1.12 oh sorry this is 1.12 eV. Well, I should actually do a calculation. So, lambda in micrometers is going to be 1.24 divided by 1.12 eV.

That will be roughly about 1 micrometer roughly 1.1 micrometer maybe. So, I mean I am nearly there. So, in lambda scale also, it is 1.1 micrometer. So, if the wavelength is larger than 1.1 micrometer. So, if the wavelength is larger here, this is not absorbed. Lambda greater than 1.1 micrometer is not absorbed by silicon. So, all of this intensity that is there, the photons that are there at those wavelengths are not really useful to us. What is useful for us?

If you are building a solar cell out of silicon, we can only absorb this range of wavelengths, lambdas that can be absorbed by silicon. So, I will come back to this thatswhy I am spending some time on this. I will come back to it and then explain how you know how to choose materials. You know when we talk about the efficiency of solar cells we will come back to the spectrum and understand this in greater detail.

So, I will give you a problem and assignment on this. Essentially, you could take you know if you take the spectral irradiance and I will give you some numbers this would be something like you know we saw this in the first graph. This is, well, this is at AM1.5. If you take AM0 or you know if you take the irradiance outside you know in the space, it is roughly about 200 2 watts per meter square per second at let us say you know typically let us say it is 500 nanometers or 0.5 microns at 0.5 micrometers.

It is just take it this way and then try to compute, what is the number of photons? And essentially, what you will have to do is use it in this is also if you go back and look at this, this units is watts per meter square per nanometer. So, what we will have to do is I am sorry since I said watt, they should not be a second that is a mistake on my part. This should be nanometer per nanometer. So, we would like to use it in the units of micrometers.

So, I will write this as 2000 watts per meter square micrometer. So, the flux you know photon flux phi is going to be this number, 2000 watts per meter square micrometer divided by the energy of the photon I said it is 500 nanometers. So, if you take 500 nanometers, this is going to be 1.24 which is a denominator divided by 0.5 micrometers. This is the energy of the photon.

Energy of 500 nanometer photon times delta lambda which is going to be 1 micron here and divided by, so, I do not have in micrometers I have to mention this. So, I do not I just put 1 there, delta lambda and then divided by into 1 by 1.602 into 10 power minus 19. So, with this you should be able to compute the number of photons. And, I will leave it to you. But, you know in the assignment, you can verify it that you know it will be typically in the range of 10 power 17 or so.

I will leave that to you. Please do that as part of the homework. So, this many photons are incident on the semiconductor. So, how do we convert into electricity? So, that, we can do by using a pn junction.

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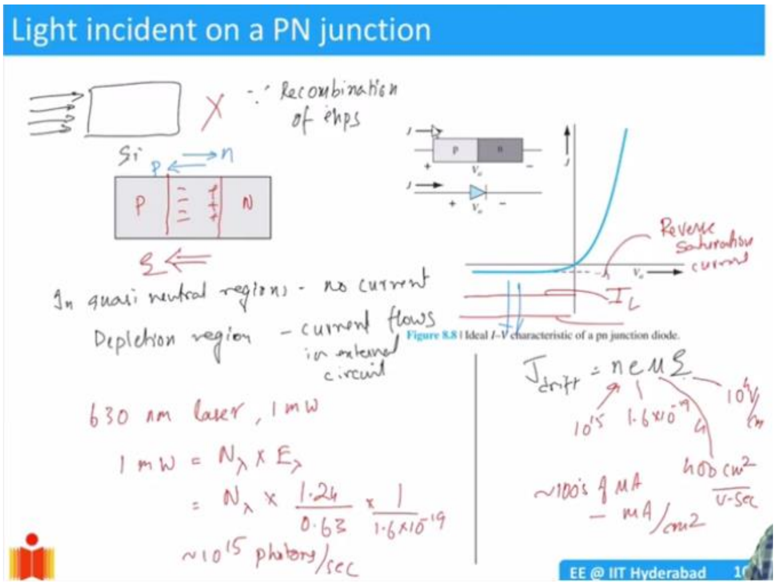

Light incident on a PN junction

∵ Recombination of ehps

In quasi neutral regions - no current

Depletion region - current flows in external circuit

630 nm laser, 1 mW

$1\ mW = N_\lambda \times E_\lambda$

$= N_\lambda \times \frac{1.24}{0.63} \times \frac{1}{1.6\times10^{-19}}$

$\sim 10^{15}$ photons/sec

Figure 8.8 | Ideal I–V characteristic of a pn junction diode.

$J_{drift} = n e \mu ℰ$

10^{15} 1.6×10^{-19} $400\ cm^2/V\text{-}Sec$ $10^4\ V/cm$

~100's of mA

– mA/cm2

We have already studied pn junction in great detail. So, let us say you have this you know p and n regions. And then, there is this IV characteristic that you get for a pn junction. But, if you know you shine light on this, what will be the number of what is the amount of current that is generated? Is there any current? Let us start with a simple piece of silicon. I shine light on it. Will it generate current?

Well, it does not generate current. The reason is if you shine photons, you are going to generate electron hole pairs. But, they will recombine. You are only going to create a certain excess of minority carriers. But, you are never going to cause them to move on an average because if you let us say assume uniform illumination, you are going to generate uniform excess minority carriers.

But, you are not going to generate current. So, this is not suitable because recombination, you generate electron hole pairs of ehps. You are essentially shining this with photons. If you assume uniform illumination, then you will essentially just generate and then they will recombine and they will be at steady state some excess minority carriers. So, if you want to really extract that current, you need a device which has certain field.

So, you can generate electron hole pairs and then they should be swept away. And, that is what is you know that is what happens in a pn junction. That is why we use pn junctions for solar cells. Let us say I have my pn junction this way. And there is a depletion region here. There is a minus and there is a plus. This is p type. This is n type. So, we know that the electric field in this pn junction is in this fashion, in this direction.

So, now, if you shine photons, what happens? If you have quasi-neutral regions, in quasi-neutral regions, no current. Why? Because, there is no field, there is a very tiny field. It does not really result in current. But, in depletion region, if you shine light, whatever light is incident on that, it will generate electron hole pairs. So, let us say it generated electron hole pair. Immediately, the hole will move towards this direction.

Hole will move in this direction. Electron will move in this direction. And so, they will separate out in terms of in term they form current. So, this generates current flows in external circuit if it is there. So, that is what happens. So, how much is this current? Let us try to estimate that. Let us say I take instead of directly using the solar spectrum, let us assume that you are shining a 1 milliwatt laser.

Let us say we use a 600 nanometer laser or you know 630 probably is better. Let us say 630 nanometers laser with 1 milliwatt of power. I am saying laser because laser has 1 single wavelength. We do not have to worry about various wavelengths. So, if you have this laser, how many photons are there? Well, you can compute, how many photons are there? Because, the, this is power 1 milliwatt is going to be number of photons N lambda times energy of the photons.

So, this is going to be number we can compute. How many photons are there? This will be 1.24 divided by 0.63 in micrometer. So, that will be the they should also be 1.6 into 10 power minus 19. So, with this, you can compute. You will see that if you do this calculation, you will end up getting something like 10 power 15 photons per second. If you have a laser which is having 1 milliwatt of power roughly I mean it will be 2 or something.

I do not have we do not really need to care about, the order of magnitude will be 10 power 15 photons. So, if you have 10 power 15 photons and they are swept across the device. What is the amount of current that we generate? Just a moment, So, when you shine this 1 milliwatt of laser, you will get about 10 power 15 photons per second. So, how much current is generated?

Well, to calculate the current, you know we know that you know essentially there is an electric field and that is going to cause drift of these carriers. Electron hole pairs are generated and they will drift across the depletion region. So, the current is going to be J drift, is going to be n times e. e is a charge. μ times into electric field. So, we do not really you know I mean if you know the electric field and the mobility of the carriers, you can compute.

$$J_{drift} = ne\mu E$$

But, this number n is going to be 10 power 15 photons per centimeter cube. And, this is going to be charge. This is going to be mobility. You can compute, 1.6×10^{-19}. And, typical depletion voltages would be you know 10 power 4 $V/_{Cm}$ and mobility, let us take it to be 400 $cm^2/_{V-Sec}$. Let us try to, you can compute it.

You can see how much is the current that flows in a pn junction? You will see that it is you know 10 power 15 and 10 power 19, so, 10 power 4. So, roughly, it will be you know few milliamps per centimeter square kind of current. So, what happens is just by shining light, you are getting current you know in the range of maybe milliamps or 100s of microamps. You know that sort of a scale you should get currents.

So, you know 100s maybe 100s of microamps to milliamps you know of current per centimeter square. So, if you have that you see what is happening. So, when you shine light, you are essentially increasing the current in the reverse bias. When it is in the forward bias, it is anyway going to be dominated by the regular current. But, you are essentially causing in the reverse bias, there was this saturation current before.

This is reverse saturation current. But, when you shine a light on a pn junction, the reverse saturation current increases. So, this is basically light I you know I_L I call it. You know current due to light. And, if your intensity of light increases, you get greater amount of current. So, as you increase light intensity, the current increases in this direction. So, you have more and more current that flows in the because of light.

So, this is very useful for us because we will try to calculate the characteristics of a pn junction based on this.

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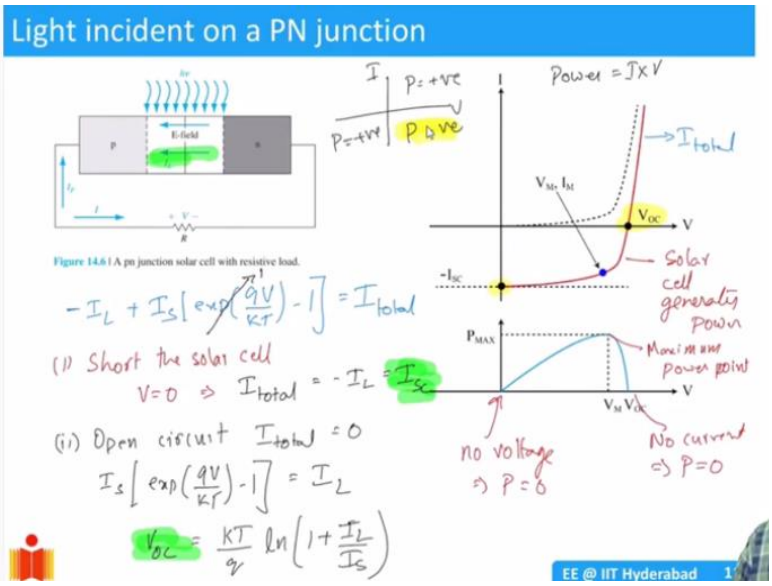

Light incident on a PN junction

Figure 14.6 | A pn junction solar cell with resistive load.

$$-I_L + I_s\left[\exp\left(\frac{qV}{KT}\right) - 1\right] = I_{total}$$

(i) Short the solar cell

$V = 0 \Rightarrow I_{total} = -I_L = I_{sc}$

(ii) Open circuit $I_{total} = 0$

$$I_s\left[\exp\left(\frac{qV}{KT}\right) - 1\right] = I_L$$

$$V_{oc} = \frac{KT}{q} \ln\left(1 + \frac{I_L}{I_s}\right)$$

Power = $I \times V$

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So, now, the same scenario, let us say you have a pn junction, a simple pn junction. And, you shine light. And, there is a resistor across the pn junction you connect it across the resistor. So, when you shine light, there is a current that flows in. So, the direction is I_L here you know in the opposite direction to the regular current. It flows across the resistor. When it flows across the resistor, it creates a voltage drop across the resistor.

And then, the, you know you can apply the KVL. And then, you can write the expression for current in this structure. What happens is first of all you know there is a current which is flowing in the negative direction. You know I will call it $-I_L$. That is flowing. And then, that leads to a bias across the voltage. I will call it V. And, that is applying across the voltage. So, there should be some its forward biasing the pn junction.

So, this gives you a current which is basically going to be I will call it I_s reverse saturation current

$$-I_L + I_s\left(exp\left(\frac{qV}{KT}\right) - 1\right) = I_{Total}$$

This entire thing is essentially going to be a total current, I total. So, basically, you have the diode current plus the reverse saturation light generated current. And, that is your total current, just taken into account the direction of the current. So, there is a minus I L for this.

So, in terms of IV characteristic, how does it look like? Well, if you have a regular pn junction, you have this forward bias current like this which is you know above a threshold voltage it is increasing. And, if you shine light you are going to cause a reverse current which is kind of fixed. And now, the total amount of current is going to be the red curve which is given here. This is the, I total.

So, there are a few features that you know we have to notice here. That is what happens when you apply you know there is no voltage. Let us say we open circuit we do not have any current let us say. If you do not have any current in the external circuit, we short it basically. So, short the cell. Let us do this. I am sorry. That is first case I will take it to be short the solar cell. What happens if you short a solar cell?

V is going to be 0. V is equal to 0. That implies your, this term this is going to go to 0. No, this is going to go to 1. Sorry, it is going to go to 1. So, this term is going to go to 0, second term. So, $I_{Total} = - I_L$. And, this is very I mean this is a very commonly found scenario. We call it short circuit current. You know we call this as I_{SC}. This is the term we use in the solar cell community.

So, I_{SC} basically means short circuit current. So, you take a solar cell short it and then shine light and see how much current you are generating in that. That is short circuit current. The second scenario is you take open circuit. Open circuit which is I total is 0. There is no flow of current in the external circuit. So, what happens? Well, you can simply you know rearrange this equation. So, this is going to be

$$I_s\left(exp\left(\frac{qV}{KT}\right)-1\right)=I_L$$

So, rearranging this, we can write. We will call it open circuit voltage, V_{OC} is going to be equal to KT by q ln of 1 will go that side. So, 1 plus I L divided by I S.

$$V_{OC}=\frac{KT}{q}ln\left(1+\frac{I_L}{I_s}\right)$$

This is called as open circuit voltage. This is another important parameter for a solar cell. So, if you do not just connect the solar cell to anything and you just shine light, you are going to generate electron hole pairs. And, they will be swept across.

And, they will essentially give you a potential that you can measure at the edges of the solar cell. And, this is called as open circuit voltage. And, these 2 things are very easy for us to measure. And, that is why we there is so much of significance for this. And, if you want if you show these 2 parameters on a IV graph, so, what happens is the open circuit voltage where the short where the current is not flowing, this is going to be this point.

And, the short circuit current, when there is no voltage across the diode is going to be this point. And, between them, the IV changes the current changes in this fashion from short circuit current to the open circuit voltage. So, there is one thing that we need to note here. So, if you take a regular IV characteristic say here let us say IV characteristic this fashion. In the first quadrant, let us say, this is voltage and this is current.

So, here I into V, power is going to be given by power equal to I into V, current into voltage. So, if you have here IV power is positive. Here also, power is positive. That means, essentially, you are supplying power into the diode. So, whether it is in forward bias or reverse bias that happens. But, when you shine light, you are not supplying power from any external battery. But, power is getting generated from the solar cell.

And, that is why you see that. Here, the current is negative and voltage is positive. So, power is negative here. Power negative means essentially it is supplying the solar cell is supplying to the external circuit to the external node. That is why this is in the fourth quadrant. So, basically here, so, solar cell generates power. It is delivering to an external circuit. So, what is the range of power that you can generate from a solar cell?

Well, it goes between 2 extremes. Power is basically the voltage into current. So, when you are in the short circuit condition, you have current there. But, there is no voltage. So, power is 0. So, here, at this point, no voltage implies P is 0. At the open circuit condition, you have no current implies P is 0. So, between these 2 extrema, you can have non-zero power. And, there will be some sort of a voltage wherein the power is going to be maximum.

And, that is we call it as maximum power point. At this point, maximum power point. So, the solar cell generates power I mean you can measure that. And, we would like to operate the solar cell at that maximum power point so that you draw as much power as possible from the solar cell. So, what is this maximum power point?

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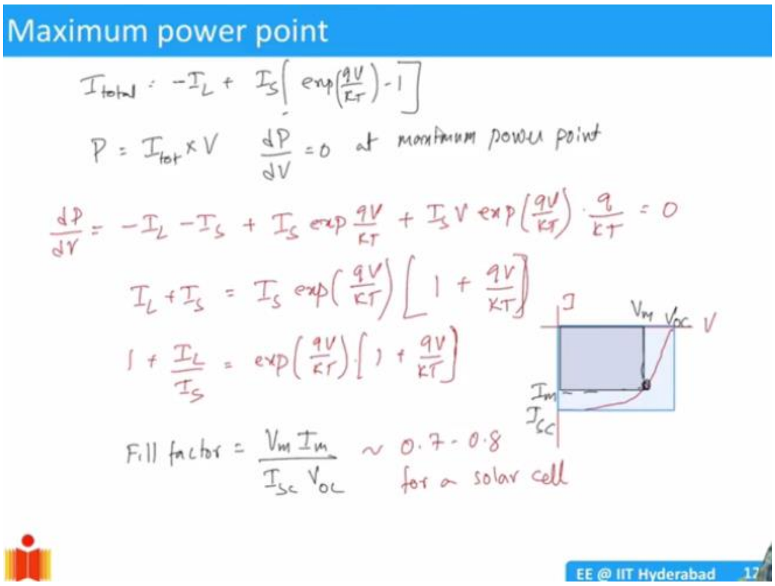

Maximum power point

$$I_{total} = -I_L + I_s\left[\exp\left(\frac{qV}{KT}\right) - 1\right]$$

$P = I_{tot} \times V$ $\quad \frac{dP}{dV} = 0$ at maximum power point

$$\frac{dP}{dV} = -I_L - I_s + I_s \exp\frac{qV}{KT} + I_s V \exp\left(\frac{qV}{KT}\right)\cdot\frac{q}{KT} = 0$$

$$I_L + I_s = I_s \exp\left(\frac{qV}{KT}\right)\left[1 + \frac{qV}{KT}\right]$$

$$1 + \frac{I_L}{I_s} = \exp\left(\frac{qV}{KT}\right)\left[1 + \frac{qV}{KT}\right]$$

Fill factor $= \frac{V_m I_m}{I_{sc} V_{oc}} \sim 0.7 - 0.8$ for a solar cell

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So, to, it is very easy to analyze. So, we have already seen the total current, I total is going to be minus I L plus I S times exponential qV by KT minus 1.

$$-I_L + I_s\left(exp\left(\frac{qV}{KT}\right) - 1\right) = I_{Total}$$

This is the total current. And, power is basically going to be power P equal to I total times the voltage.

$$P = I_{tot} \times V \qquad \frac{dP}{dV} = 0 \ \ at\ maxium\ power\ point$$

So, I can write that. And then, I can take a derivative of it with respect to voltage to find out where is the maximum power point. dP by dV is going to be 0 at maximum power point.

So, how much is this? Well, if you differentiate it, power into voltage, so, current into voltage, sorry. This is going to be dP by dV is going to be equal to minus I_L and I_S into that minus Is, I will take out. So, minus I_S plus exponential qV by KT times voltage.
So, this is going to be that voltage I will take a derivative. So, exponential qV by KT plus now I have to differentiate with respect to the, differentiate the exponential.

So, this is going to be plus I S into voltage times exponential qV by KT. And then, I have to take q by KT. So, there will be a, into q by KT. So, this has to be equal to 0. That is the condition at that is the voltage at which you get the maximum power.

$$\frac{dP}{dV} = -I_L - I_s + I_s\left(exp\left(\frac{qV}{KT}\right)\right) + I_sVexp\left(\frac{qV}{KT}\right) * \frac{q}{KT} = 0$$

So, if you rearrange this equation, if you have, this will be I L plus I S is going to be equal to I will take I S common here, exponential qV by KT and then I will write a bracket so, 1 plus qV by KT, I think.

$$I_L + I_s = I_s exp\left(\frac{qV}{KT}\right)\left(1 + \frac{qV}{KT}\right)$$

So, what this gives you is basically an expression to calculate you know it is a kind of a transcendental equation. I can take out I_S here. So, I will put, so, 1 plus I_L by I_S is going to be equal to, well, it did not really help much. But, exponential qV by KT times 1 plus qV by KT.

$$1 + \frac{I_L}{I_s} = exp\left(\frac{qV}{KT}\right)\left(1 + \frac{qV}{KT}\right)$$

So, this is a transcendental equation that we are getting. So, you have to substitute. Let us say you are given some reverse saturation current.

And, you know the saturation sorry the light generated you know current. Then, you can try to compute, what is the maximum power point maximum voltage at which the maximum power occurs? So, if you look at the IV characteristic again one more time of the solar cell, what you saw was, this is voltage, this is current. So, you have a graph which looks like this. So, you have the V_{OC} and I_{SC} which kind of represent the limits.

And, the maximum power point is going to occur somewhere in between. This is somewhere here. This is going to be V maximum. And, this is going to be I maximum at which you get the maximum power. So, in the solar cell community, we define one parameter which we call as a field factor. The way we define field factor is equal to Vm times I m divided by I_{SC} V_{OC}.

$$Fill\ Factor = \frac{V_m I_m}{I_{sc} V_{oc}}$$

So, I will take the extreme. So, I can imagine this thing to be a rectangle.

So, if I draw it in blue, this entire thing I will draw a rectangle. My approximation of a rectangle is in that how much fraction of that is occupied. That is the field factor. So, you imagine the maximum power point as one rectangle. So, there are 2 rectangles here. One is the bluish rectangle. The other rectangle is going to be my blackish rectangle. So, how much of the area of the black rectangle compared to the blue rectangle is my field factor?

This is kind of you know it tells you how good your technology is. And, if you fabricate a very good device, you can get high field fractions. Typically, this number is going to be somewhere between 0.7 to 0.8 for the solar cell. So, this gives us a very easy way of comparing. Because, in the end, in the next video, I will show you a few solar cells. And, we will also talk about the efficiency of solar cell.

And, when we analyze the efficiency of solar cell, it turns out that this field factor is going to be a very important parameter. So, what did we do in this video? We first introduced a solar cell. We said, if you shine light, it is going to generate electron hole pairs. And, they will get separated out and that will result in some voltage across the external circuit. So, it is going to deliver power to an external circuit.

And, that delivery happens you know at a particular point which we call as maximum path point is where the maximum power is transferred. And, we derived an expression. So, I will give you some problems in the exam in the assignment. Just try to compute. You know using these formulas you should be able to compute. And then, you will get a feel of you know what is the kind of currents involved. So, I will stop this video at this point.

I will go back and you know I will in the next video, I will talk about the efficiency of a solar cell and with that I will stop the discussion about the solar cell. Thank you very much. Have a great day, bye.