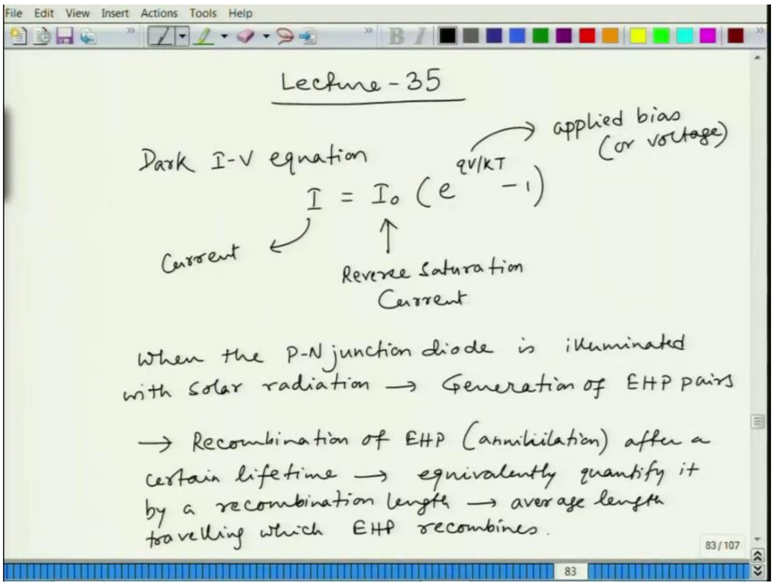
Elements of Solar Energy Conversion
Prof. Jishnu Bhattacharya
Department of Mechanical Engineering
Indian Institute of Technology, Kanpur

Lecture - 35

Hello everybody, welcome back to the series of lecture on Solar Energy Conversion. And today here we are at the last lecture, which is lecture number 35, ok.

(Refer Slide Time: 00:29)



So today we are going to talk about the real interesting thing which is when light falls on the photovoltaic material or the P-N junction diode, what happens, ok. What magic happens that it gives you electric current, ok. So, up to the last class, we have looked at the dark I-V equation, which is given by,

$$I = I_o\left(e^{\frac{qV}{kT}} - 1\right)$$

here I_o is the reverse saturation current, right. This V is the applied bias or voltage and I is the current.

So, you can see this equation is valid when there is no generation. That means, no illumination by light is happening and that means, there is no generation of electron hole-pair. Now when diode is illuminated with solar radiation, it can be other radiation as well, but to create the radiation you will require energy. So, that does not make sense; the radiation which is already available through sun that is what we are going to use for conversion into electricity, ok.

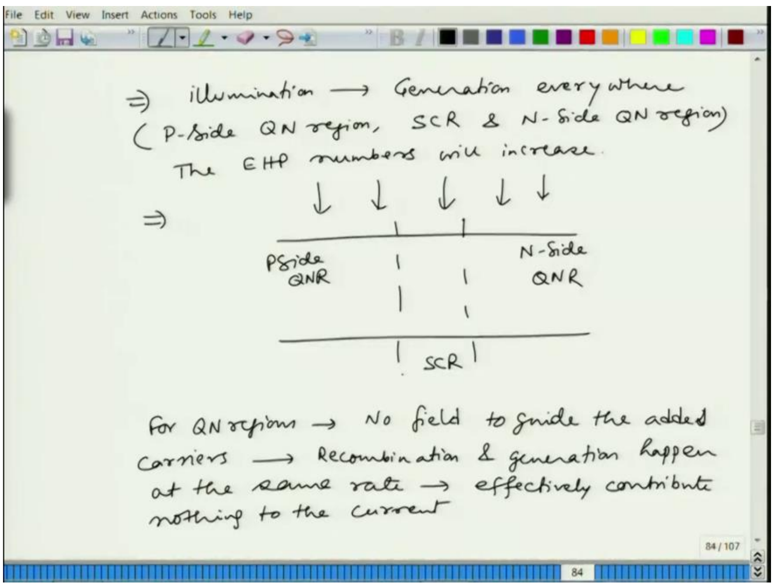
So, when that happens, we have generation of electron-hole pairs. So, this generation term we have introduced it in the continuity equation, but every time before using that continuity equation we set it to 0 because there was no generation happening. So of course, whenever there is generation there will be some recombination as well— recombination of a fraction of that, ok.

Or I should not say fraction of that, it is basically recombination of all of that if you take out the generation and after a certain time everything will recombine, because there is no extra energy to sustain that generation, ok. Recombination of EHP which is also called annihilation because recombination means the electron and hole both the carriers are now gone annihilated.

So, recombination of EHP after a certain lifetime or you can equivalently call it, quantify it by a recombination length. What does recombination length mean? After travelling this much distance the average electron hole pair will recombine, that is what the recombination length means. We have introduced this earlier.

The L_n and L_p those are the recombination length of electron and hole you have seen. So, average length traveling which EHP recombines that is the meaning of recombination length.

(Refer Slide Time: 05:31)



Now whenever we have illumination, so this generation will happen everywhere equally, right. Generation everywhere; everywhere what do we mean by that? We mean that the P side quasi neutral region, space charge region and N side quasi neutral region. Everywhere this thing will happen, ok. Everywhere the EHP numbers will increase by equal amount, because we are assuming the illumination is same everywhere. So, the generation will happen in equal amount.

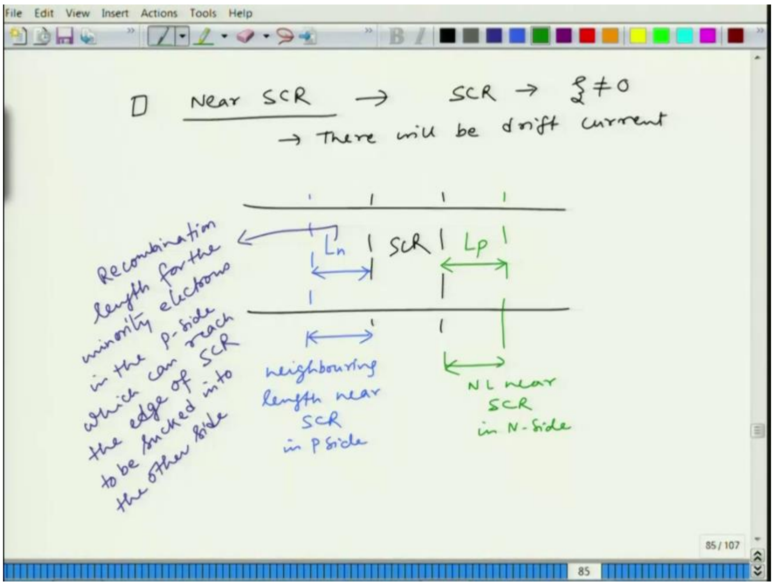
Let me draw it with figure. So, that you can visualize it easily. So this is our standard figure we have used multiple times this is our SCR (space charge region) and this is our P side quasi neutral region (QNR) and this is N side QNR, right. So, when light falls everywhere the generation is happening, but for the quasi-neutral region, there is no field to guide those added carrier's, right.

So for quasi neutral regions, no field right to guide the added carriers through generation, right. So, what will happen? You think of it physically; you close your eyes and think of it that these things will generate and then each of them will get recombined after travelling a certain distance or after a certain time period (τ_n and τ_p) ok.

And the generation will happen at the same rate, recombination will happen at the same rate. So, effectively you will have an extra concentration of electrons and holes, but they are ineffective; they are not contributing to the overall current. Because if you do not have a concentration gradient there will be no diffusion current, just adding the concentration will not give you any current, right.

So, if that is the case then recombination and generation happen at the same rate and they effectively contribute nothing to the current, right.

(Refer Slide Time: 09:20)



So, what where the interesting thing happens? It is in the near the space charge region. I am not saying only in the space charge region, but near the space charge region. What do you mean by that? So, SCR is where you have $\xi \neq 0$. So, you have a guiding force or a field to guide these extra electrons and holes in proper direction and what is that called? That is called drift current.

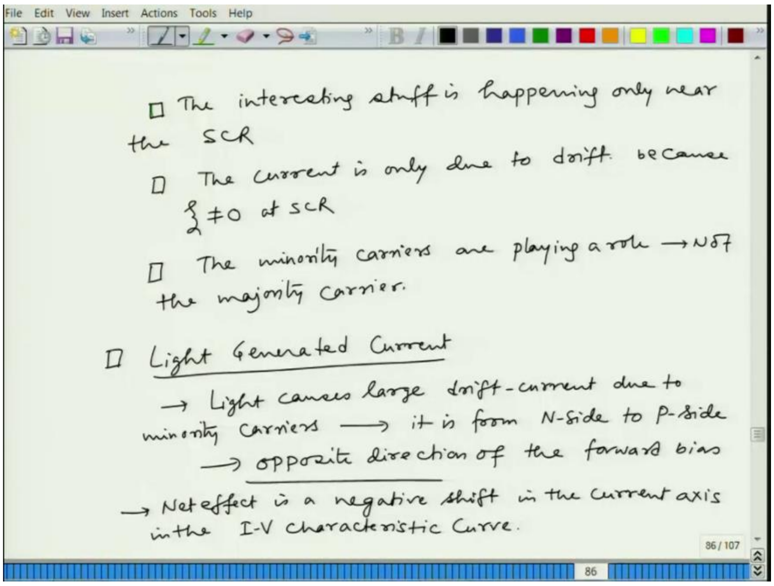
A current that is generated by the guidance of a field. So, there will be drift current and not only in the space charge region the carriers will be guided, but also near the space charge region or some region in the quasi-neutral region. Let me just draw it again. If this is your space charge region and let us say in each side, there will be a certain neighboring area in the quasi-neutral region.

So, this part is neighboring length near the space charge region in P side. Here this is the same thing (neighboring length) near SCR in N side, ok. Now you think of this close areas nearby the space charge region. Here the generated electrons and holes they will move around randomly, right. And the length after which they recombine is known that is called recombination length L_n and L_p, right.

Now, if you have some particular electron which is up to that length from the space charge region, it has a probability of drifting near the space charge region or at the edge of the space charge region. If it reaches that edge then it will be sucked into the other side, is not it? So, in that case we can say that this length is the recombination length for minority carrier in the P side, which is recombination length for the electrons, ok.

So, this is recombination length for the minority electrons in the P side which can reach the edge of the space charge region to be sucked into the other side, right. And similarly, you can say this is the L_p which is the recombination length for the holes in the N side. And you see that only the minority carriers which are playing a role here. Because this is all drift, there is no diffusion current. It is all drift due to the field and it is only near the space charge region.

(Refer Slide Time: 13:33)



So, let me just summarize these observations. So, the interesting stuff is happening only near the space charge region and the current is only due to drift because $\xi \neq 0$ here or at SCR. But the effect is failed nearby region as well because the added electrons or holes they can come drift near the space charge region edge. Just by thermal agitation or thermal movement and they can be sucked into the other side.

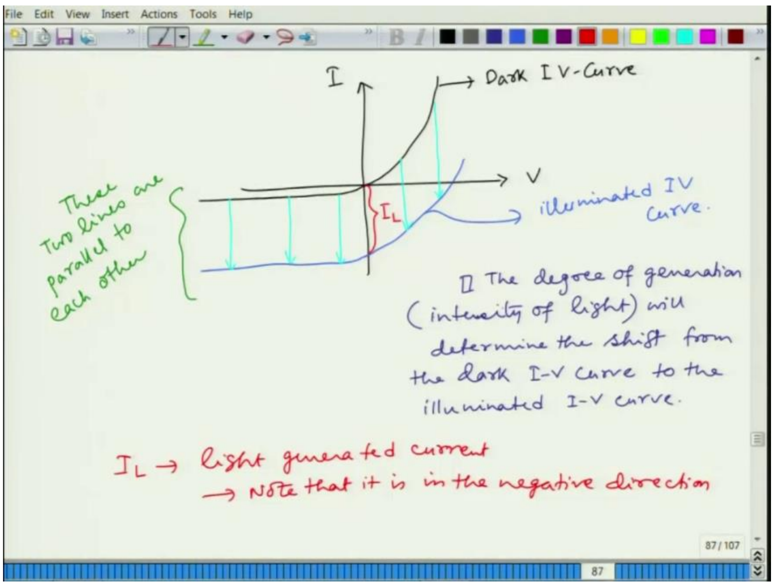
Here the major observation is the minority carriers are playing a role, not the majority carrier. So, you see that majority carriers they are giving you the background diffusion current and all, ok. And they are of course, important without getting the majority carrier there is no point having minority carrier. They are inter-linked, ok. But in the photovoltaic effect whatever you are getting, the interesting stuff is all contributed by the minority carriers.

So, it is very important point which you should keep in mind. So, the net effect what you will find. So, if we try to find what would be the light generated current; that means, when you illuminate what would be the effect in terms of current. So, this light causes large drift current just as we have seen, right now. And very-very important, drift current is always in the opposite direction of the bias, right.

So, it is from N side to P side right, so opposite direction of the forward bias. So, forward bias direction is what? It is from P side to N side. P side is positive, N side is negative ok. But for the drift current, the current is in the opposite direction right. You have seen it couple of classes ago that why drift current is in the other direction because the drifting happens only downhill of energy for the carriers.

So, this opposite direction you have this drift current. So, the net effect is a negative shift in the current axis in the I-V characteristic curve, ok. So, for any value of bias, any value of V you will have that offset (a constant shift) in the negative direction of current that is the physical reason why we are getting it. So, earlier what did we have.

(Refer Slide Time: 18:29)



We have this particular V- I characteristic curve, right. So, this is the +V and this is the +I direction, ok. Now due to light, what will happen? This whole thing will be shifted downwards for any bias, ok? So, you see that everywhere it is shifted downward, and they will be parallel to each other, ok.

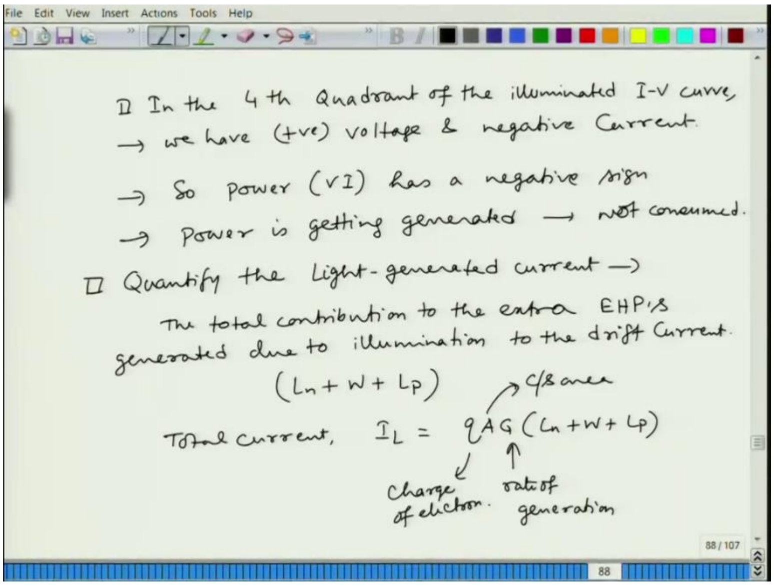
So, what should I say that these two lines are parallel to each other. And how much shifted that will depend on the degree of generation. If the intensity of light is higher you have more energy to make more electron hole pairs, right.

So, the shifting will be larger and for less intensity will have less shift. So, these are very important points. So, the degree of generation, which will of course depend on the intensity of light will determine the shift from the dark I-V curve to the illuminated I-V curve, ok.

So, this one is our dark I-V curve and this one is the illuminated I-V curve, isn't it? Are you are you getting the concept? It is important you think through this again, I mean the concept is not clear, but from the start of this class up to now about twenty minutes you please go through again and try to visualize why this parallel shifting towards the negative current detection will happen, ok.

And this particular shift which you can call, let us say here only, let us show because that is on the current axis, we call it I_L, ok. So, this I_L is called light generated current and note that it is in the negative direction. So, current is positive when it is flowing according to the forward bias direction. Here it is happening in the opposite direction that is why we are calling negative direction.

(Refer Slide Time: 22:50)



Now, if you look at this curve little more closely then you can see that in the 4th quadrant of the illuminated I-V curve. We have positive voltage and negative current, right. So, V- I, if you multiply what will happen? You have a negative value for power; that means, power is getting generated not consumed. If the power was positive, I mean the $V \times I$ is positive; that means, power is getting utilized in the process, right.

But here with the negative sign, $V \times I$ gives you power that is generated. So, power which is $V \times I$ has a negative sign. What does that mean? That power is getting generated and not consumed and that is what we want. We do not want our PV cell to consume power when you apply some voltage and then illuminate light on it you will have some current output in the circuit; that means, power is getting generated.

So, now if we want to quantify this light generated current, so, we have to take into account what is the contribution of the space charge region and the nearby regions, L_n and L_p in the P and N side, respectively, ok. So, the total contribution to the extra electron hole pair's generated due to illumination to the drift current.

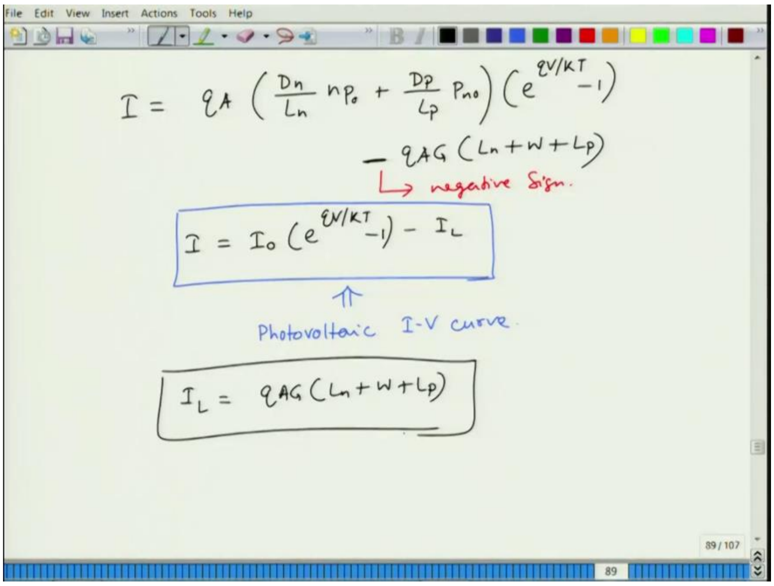
So, the hole generation happening in the area $L_n + \mathrm{W} + L_p$. This is the hole area that is getting used for generation of drift current, ok. So this is the area. So, total current would be,

$$I_L = qA\left(L_n + \mathrm{W} + L_p\right)$$

A is the area of cross section we are saying. And then rate of generation multiplied by this length or this effective length for which the P-N junction diode is contributing to the drift current.

So, you can see that this is the rate of generation, and this area is our cross-sectional area in the opposite direction, and this is the charge, right. So, this will be the total amount of drift current that you get.

(Refer Slide Time: 27:30)



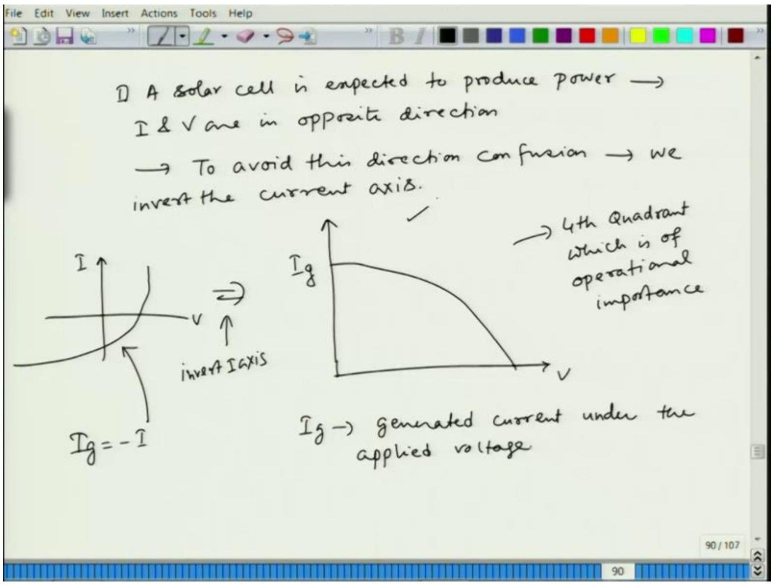
So, ultimately what you have, I, which is the total current it will have the earlier we have the dark I-V equation. So, from there, we will have right this we have seen in the case of the I-V curve for the dark situation, and then we have this minus shift which is is not it. So, I again draw your attention to this negative sign. So, in concise form, what we can write $I = I_o\left(e^{\frac{qV}{kT}} - 1\right) - I_L$.

So, this is what we get after all these different kinds of, I mean going through the band structure how the Fermi level is changed how doping contributes now under equilibrium how the currents are distributed, ok.

And then, we introduced a bias to break that equilibrium and see under the dark situation. What would be the current and for and after that we introduce the light the effect of light on it, and we have gotten this final equation which is called the photovoltaic I-V curve. Now we have light also.

So, it is different from the dark I-V curve and here. So, this I_L, I_o, is we have already mentioned I_L is the added part which is causing everything interesting.

(Refer Slide Time: 30:11)

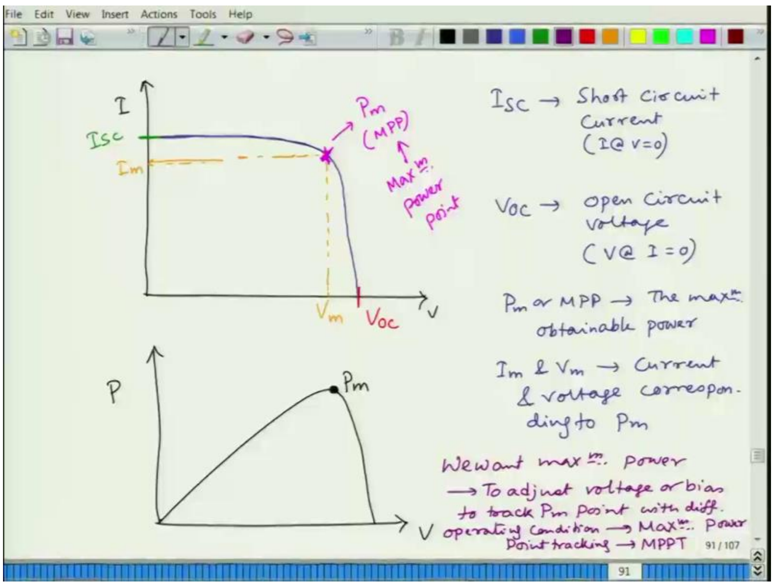


So, now, if we look at a solar cell, so a solar cell is expected to produce power right, and that means I and V are in the opposite direction as we have seen earlier that in the 4th quadrant, which is actually giving us meaningful operation. But that often confuses us. So, what we do to avoid this directional confusion we invert the current axis. So, what do we do? We draw *I* to be positive and V to be negative, and in the 4th quadrant earlier, what was this? Let me draw it like this.

So, earlier we have seen it will be somewhat like this V and *I*. Now, if we invert *I* axis, this 4th quadrant will look like this right. So, this is the 4th quadrant which is of operational importance others are good to know, but you are not going to get anything out of it ok that is why this 4th quadrant and we have inverted it. So, basically, this is we can say I_g ok. So, I_g is the generated current under the applied voltage.

So, I_g is basically minus of , ok. So, ultimately this particular plot we are boiling down to for photovoltaic effect.

(Refer Slide Time: 33:14)



Now, let us look at this curve a little more closely because that is what is important ok. So, let me try to draw this curve more clearly, so usually, the curve takes shape it is more or less flat, and then comes down and then drops sharply. So, this is typically the shape of the I-V curve, ok. So, earlier, we were doing just a schematic diagram; now, we are trying to make a little more realistic what we get ok.

Now, the point where it cuts the I axis we call it I_{SC} or short circuit current SC stands for short circuit current. Because short circuit means the voltage is 0, and that gives you the maximum current ok. And on the other hand, where you cut the voltage axis, that is we called V_{OC}, which is the voltage at open circuit ok.

Open circuit means the current is 0 and what voltage you get. Now you can think of this point where. So, what we are interested in $V I$ right $V I$ the operational like voltage and current product will give us the power. So, where it gets maximized, it gets maximized here, right at the edge of the curve.

So, this is called P_m or we often call it MPP, which is maximum power point ok maximum power point and corresponding to that you can draw or you can find what the corresponding voltage and current are.

So, this is called V_m, and this is called I_m ok. So, let me quickly write them so that it is clear. So, I_{SC} is your short circuit current; that means, I at V equal to 0 cases and then V_{OC} is your open-circuit voltage which is V at I equal to 0 cases ok and this P_m or MPP that is the maximum obtainable power, right and I_m and V_m are current and the voltage corresponding to this P_m point ok.

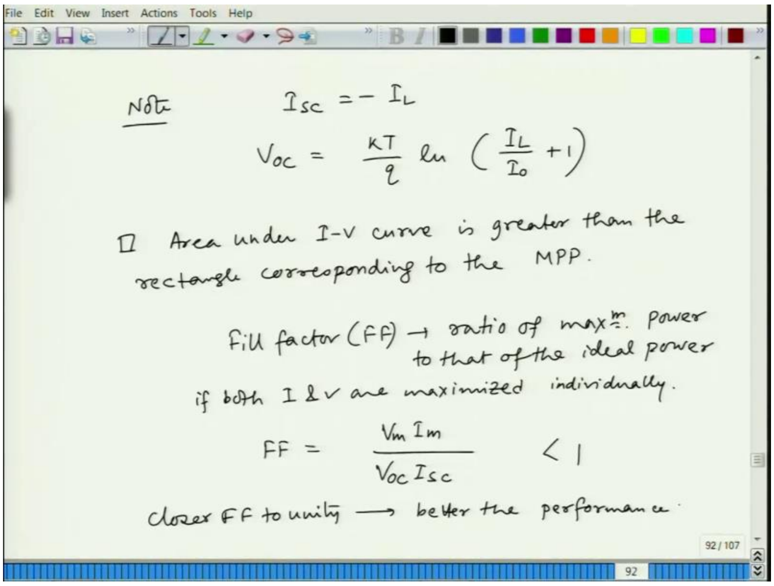
So, you can see that I_{SC} is the maximum current you can obtain, but for maximizing the power, you can go only up to I_m similarly V_{OC} is the maximum voltage you can go up, but that is useless because current will be 0. So, for maximizing the power, what you require to restrict yourself to V_m.

So, if you operate it at V_m, then you will get the maximum power with the current I_m that is the and the same plot or same idea you can plot it in this P V curve; P means power V means voltage. So, if we see that, it will be somewhat like. So, this will be the maximum power-point. So, when the voltage starts from 0 at 0, you have power also will be 0 and it increases as you go up and then it decreases sharply near the V_{OC} ok.

So, we want what we want maximum power, and for that, you have to adjust this voltage continuously to do the maximum to maximize the power. So, that is called to adjust voltage or bias to track P m point with the different operating conditions is called maximum power point tracking ok or MPPT ok.

So, you will hear this term if you go into the photovoltaic's like jargon, you will find this term very often MPPT; MPPT is maximum power point tracking which is a must for getting the maximum obtainable power from a photovoltaic panel ok.

(Refer Slide Time: 40:04)



So, some quick notes; note that this I_{SC} is nothing but $-I_L$. If you look back a couple of yeah here, yeah, I_L is the current value when V equal to 0. Now we have inverted it in the positive direction. So, I_{SC}, the short circuit current is nothing but the minus of light generated current ok and V_{OC} is

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

This you can just get by using that I-V characteristic curve ok and then converting it to natural log from exponential ok.

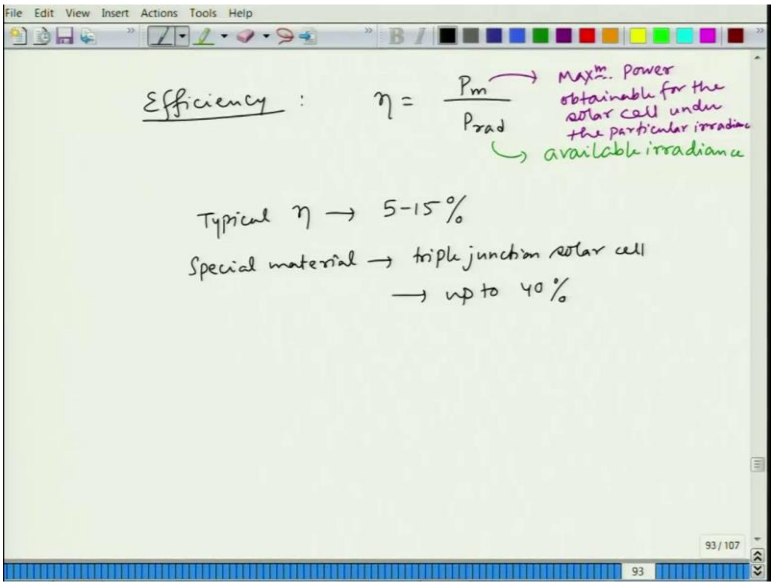
So, these two terms I_{SC} and V_{OC}, are very much properties of that particular panel; ok, the material properties are inside all these I_L and I_o ok. Now you can see if you look at this particular diagram, you can see that the area under the curve of the IV curve is greater than what you get under the Pm point, ok. So, this is another note that the area under the IV curve is greater than the rectangle corresponding to the MPP point or maximum power point ok.

So, this difference in area is obtained through fill factor ok basically the P_m rectangle how much of that is filling the I-V curve. So, this fill factor which is called FF, is the ratio of maximum power to that of the ideal power if both I and V are maximized individually right, and that means.

Your fill factor is V_m I_m, which is the area under that rectangle and divided by V_{OC} into I_{SC}, and you can see it is often less than one; the closer it is to the one the value of unity, the better performance we would say ok.

So, closer FF to unity better the performance ok.

(Refer Slide Time: 43:51)

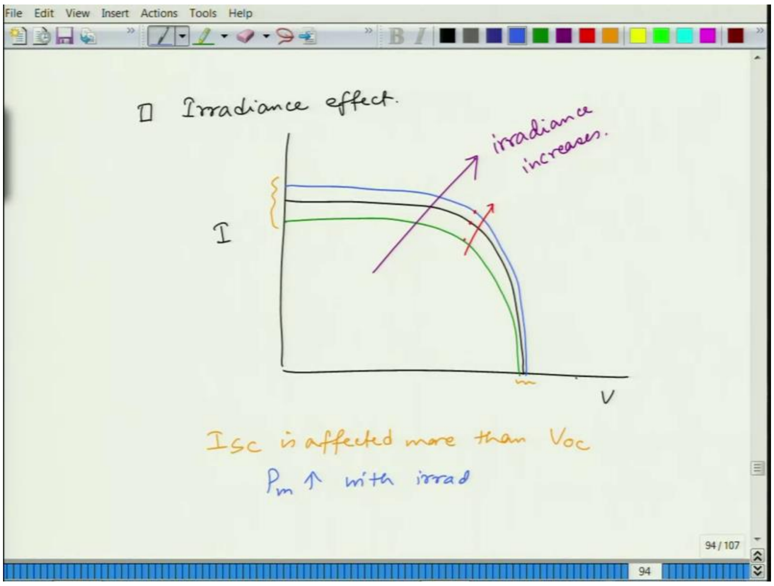


So, that is one quantity that talks about the performance metric you can say of the photovoltaic material or panel, and often you will hear this term efficiency; efficiency is very simple; it is what power you are getting. And by tracking the maximum power point and power that is put in the material, that means solar power that is coming on the panel ok.

So, this is available irradiance, and this is the maximum power obtainable for the solar cell under the particular irradiance ok. So, that is the, and typical efficiency values range from 5 to 15 percent. So, most of the panels that you will get can only convert about ten percent of the available solar radiation into electricity; it is pretty poor.

So, the current focus in research is how to increase this efficiency to a larger value, and of course, there are materials special material and we what we called triple-junction solar cells ok they can go up to 40 percent, which is a large number. But they are super costly. So, only when your efficiencies of prime concern would you use those kinds of materials.

(Refer Slide Time: 46:21)

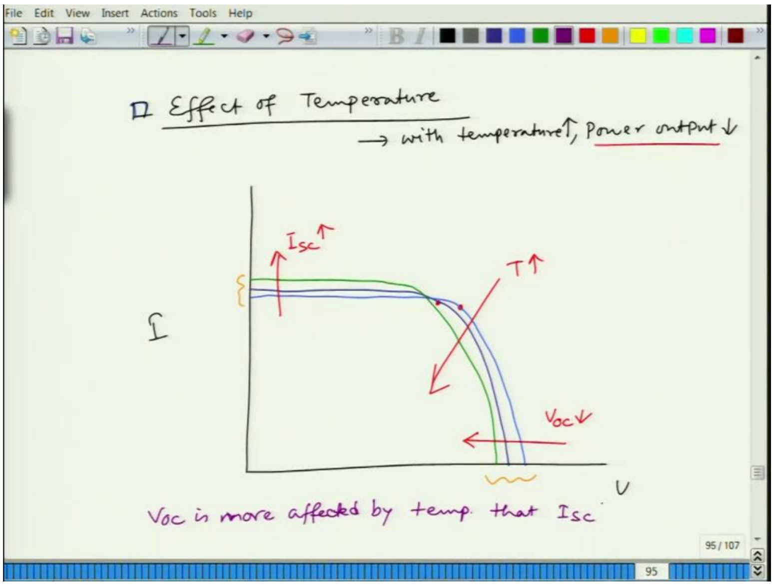


Now, we will quickly look at the effect on this I-V curve by the typical operating parameters. One operating parameter is irradiance. So, irradiance effect so, a cloudy day will have a less irradiance, and you would expect that it will generate less power right and a sunny bright day will produce large or more power right. So, how that effect is seen in the I-V curve ok. So, if this is a particular I-V curve and then if you go up in irradiance, the whole curve shifts, this is for a given irradiance.

Now, if you go up in irradiance, ok, and if you go down in irradiance, ok. So, basically, in this direction, we are going up. So, you can see that these maximum power points are going up as well with the irradiance ok and one more observation you can see the irradiance this current it is getting affected or the I_{SC} getting affected more strongly than the voltage ok.

So, I_{SC} is affected more than the V_{OC} ok by the irradiance change, but this P_m increases with irradiance ok; that is the intuitive thing you can say.

(Refer Slide Time: 48:40)



And another not-so-intuitive effect of temperature ok. Usually, at a lower temperature, the photovoltaic efficiency or photovoltaic generation is much more than for the higher temperature ok. So, with temperature, power output decreases ok with temperature increase, power output decreases.

So, how does it affect the I-V curve, ok? So, now when temperature increases, the current decrease, but voltage increases ok. So, you can see that here the maximum power point was here, but for increased temperature, the maximum power point drops slightly; similarly, with a drop in temperature, current will increase, and voltage will decrease ok.

So, that is how it's not overall shifting what is happening here the current is increasing ok with temperature increase is happening in this direction ok and voltage V_{OC} is decreasing. So, V_{OC} is decreasing with temperature increase, and here I_{SC} is increasing. And that is how the power is ultimately decreasing with an increase in temperature, and you note here unlike the effect of irradiation here, you have more.

So, let me write this is the effect on V_{OC}, and this is the effect on I_{SC}. So, observation is V_{OC} is more affected by temperature than I_{SC} ok. So, typically temperature close to the room temperature of 25 degrees centigrade or even less than that is always better. So, if we are increasing the irradiation by some concentrator or something, then the temperature also goes up, and that actually reduces the efficiency of the solar cell.

So, what we do we put some cooling arrangement as well to effectively take into account this temperature effect, ok? So, here I will stop and stop for this class and as well as for the course and here in this course. I have tried to give you the elements the title is elements of solar energy conversion. So, I have given you the elements; it's not like the complete description I have provided, and it is not possible to provide. If you look into a particular technology, it will take a complete course to go into details of that.

So, what I have done I have introduced to all the different technologies of solar energy conversion and the fundamentals that are behind those technologies ok. So, I hope that from here on, if you go into the solar energy conversion field, you will be able to take up from here. And utilize the background to build up your knowledge on each and every technology. Thank you very much for your attention and for participating in this course; good wishes.

Thank you, bye.