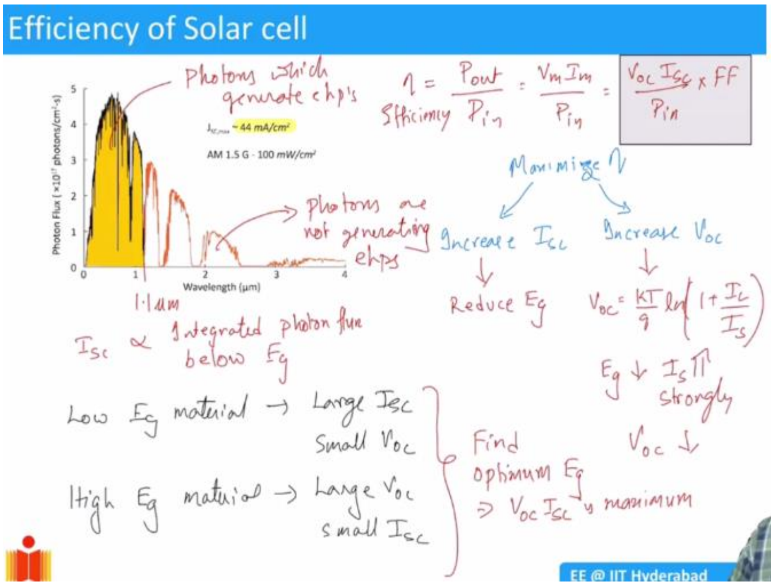
Introduction to Semiconductor Devices
Dr Naresh Kumar Emani
Department of Electrical Engineering
Indian Institute of Technology – Hyderabad

Lecture - 11.3
Efficiency of a Solar Cell

This document is intended to accompany the lecture videos of the course "Introduction to Semiconductor Devices" offered by Dr. Naresh Emani on the NPTEL platform. It has been our effort to remove ambiguities and make the document readable. However, there may be some inadvertent errors. The reader is advised to refer to the original lecture video if he/she needs any clarification.

Hello. So, in the last video, we talked about the basic working of a solar cell, how it generates a current. And, we introduce some metrics for you know open circuit voltage and then short circuit current which are very important parameters in a solar cell. So, today, in this video, we will talk about the efficiency of a solar cell.

(Refer Slide Time: 00:34)



The way we define efficiency of a solar cell is like this. So, η is the efficiency. I can basically say that what is the maximum power output of a solar cell divided by power input. What is the power output that I am getting at the maximum? We are getting basically the $V_m \times I_m$, the maximum current and the maximum voltage at the maximum power point. We defined that in the last video.

So, if you are not familiar just go back and review that. So, divided by Pin, how much ever that is. So, maximum power points are not easy to measure. So, it is very convenient for us to rewrite this in a slightly different form. So, I will make this as $\frac{Voc}{Isc} \times FF$. So, we have already defined field factor. That is quite easy to analyze for a particular technology. Once we know that it is typically 0.7 to 0.8.

So, if you would measure the V_{OC} and I_{SC}, then we can easily calculate the efficiency of a solar cell. So, this expression is quite convenient to actually use it. So, now, the question is if you want to maximize the efficiency, this is my efficiency. So, my goal is to maximize η . How can I do that? While looking at the expression, I have 2 approaches available to me. The first approach would be to increase I_{SC}, short circuit current.

If I increase I_{SC}, I will improve my efficiency. The other option available to me would be to increase V_{OC}, open circuit voltage. If I improve that then again my efficiency will improve. So, how do I improve I_{SC}? So, I_{SC} is a short circuit current. So, essentially, it is let us say you have certain amount of solar radiation that is incident on the solar cell. How many photons are getting converted into electron hole pairs?

That is going to dictate my I_{SC}. So, to calculate that we can look at the graph for a photon flux which I have already shown, but, this time, I have added I have shaded certain part of the spectrum. So, let us say if you have silicon we said that all the photons that are in the higher energy or the lower this lambda is going to be 1.1 micrometers. If the lambda is less than 1.1 micrometers, the energy of the photon is higher than Eg and they will get absorbed.

So, these are photons absorbed, photons which will generate electron hole pairs. So, how much is short circuit current? Well, your short circuit current I_{SC} is going to be proportional to integration of, you know all the current you know all the photons that are available in this spectrum. Integrated photon flux below Eg, so, whatever wavelengths are below Eg you integrate.

Then, you get the total amount of photons that are absorbed by the silicon. And we can compute this number actually. For silicon, it turns out to be about 44 $mA/_{cm^2}$. Now, if you want to increase the short circuit current, what do we have to do? Well, I have to integrate more photons. So, right now, what is happening is the photons here, photons are not generating ehps.

That means they are not resulting in current in external circuit. So, one way to improve efficiency you might think would be to reduce the bandgap so that more and more photons are you know above the bandgap and then you can absorb them. So, one way to solve this problem would be so reduce Eg. If you reduce that you know because let us say I make Eg to be about 0.2 or something. You know very small number among Eg I will make it.

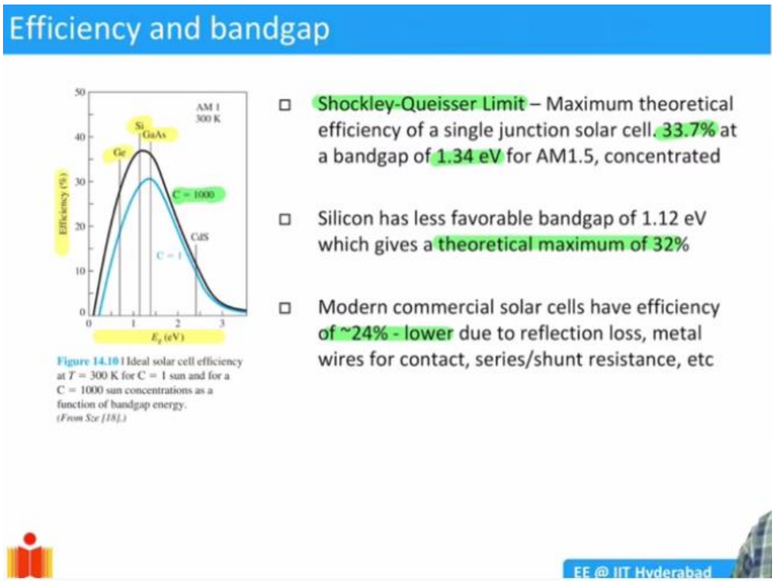
Then, 0.2 if I make it even 6 micron I think will become, so, all of this wavelengths. If I make Eg equal to 0.2, all of this spectrum will be absorbed. So, you get more short circuit current. So, what is the trade-off? What happens? So, well, it turns out that this is not quite good. The reason for that is we also have to think about what happens to the open circuit voltage. And we have already seen open circuit voltage expression.

$Voc = \frac{KT}{q} \ln\left(1 + \frac{I_C}{I_S}\right)$. So, what happens if you reduce bandgap? Eg reduces implies you know we have already seen in the pn junction analysis that I_S increases dramatically. Is increases strongly. When I_S increases strongly, V_{OC} reduces. In an extreme situation, let us say if you choose a low bandgap material. So, let me see I will choose low Eg material. In this case, I will see that I will get I will large I_{SC}.

Short circuit current will be large because all the photons are going to result in electron hole pairs. But, then, V_{OC} will be less. V_{OC} is less or I_{SC}, I will say small V_{OC} if you choose a low bandgap material. On the other hand, if I choose a high Eg material, what will happen? Well, if I choose high Eg, my I_S will be less. That is reverse saturation current will be less. Because of that, I get a large V_{OC} and small I_{SC}.

So, either extreme are not good for us. What we want is to maximize the product of short circuit current and the open circuit voltage. So, what I need to do is find optimum Eg such that V_{OC} into I_{SC} is maximum. That is where I get the best output power. So, what is that? Well, I will not really go into the analysis of it. But, I will just show you the efficiency curves that we get for various materials.

(Refer Slide Time: 08:09)



Here, there are 3 material 2 materials. Well, no, actually, so, there is gallium arsenide which is in blue here. Gallium arsenide, silicon, so, actually, these lines represent the bandgaps of various materials. So, here, this is gallium arsenide. Bandgap is 1.42, silicon 1.12. And, this is germanium which is 0.8 eV. So, correspondingly, the lines are representing. And then, there are 2 curves here.

The first one is the efficieny, theoretical efficiency as a function of bandgap. So, this is efficiency as a function of bandgap. Eg is the x axis. Efficiency is the y axis. And, there are 2 curves here. One is what is you know typically you would just if you have just pure sunlight without any concentration you do not use any lenses or anything you just have pure sunlight the efficiency turns out to be about a maximum of 33.7

Maximum theoretical efficiency that you can get from a solar cell is 33.7. And this is very famous. And it has a separate name. We call it Shockley-Queisser limit, after the guys who did the analysis. So, it tells you the maximum efficiency of a solar cell single junction solar cell only that you know what is single junction I will talk about later. So, the maximum efficiency turns out to be 33.7 roughly 34% at a bandgap of 1.34 eV for AM1.5 spectrum.

So, this is the maximum efficiency that you can get. And, if you have silicon which is basically not really at the perfect bandgap because silicon bandgap is only 1.12 eV, so, it is off the peak. If you have silicon, it turns out that the maximum theoretical efficiency is only about 32%. And if you use concentrated light you put some optics and big lenses so that you focus your light onto the solar cell, then you can improve the efficiency.

The black curve is with concentrated so light. This is AM concentrated. Sorry, concentration factor is 1000. So, you concentrate the light then you can improve the efficiency. But you see that it is not really going to improve that much. It is going to become from 30 to 38 or so efficiency. So, this is how the efficiency looks like. You know for a theoretically efficiency, this is what it is going to be.

But, if you go to the practical field scenarios, nowadays, the efficiencies are lower. It is in the, you know 20's range. So, because the commercial efficiency is going to be you know dependent on so many other factors, we cannot use a single solar cell. We have to put lot of arrays because if you I will give a homework problem wherein you will calculate the open circuit voltage for a solar cell.

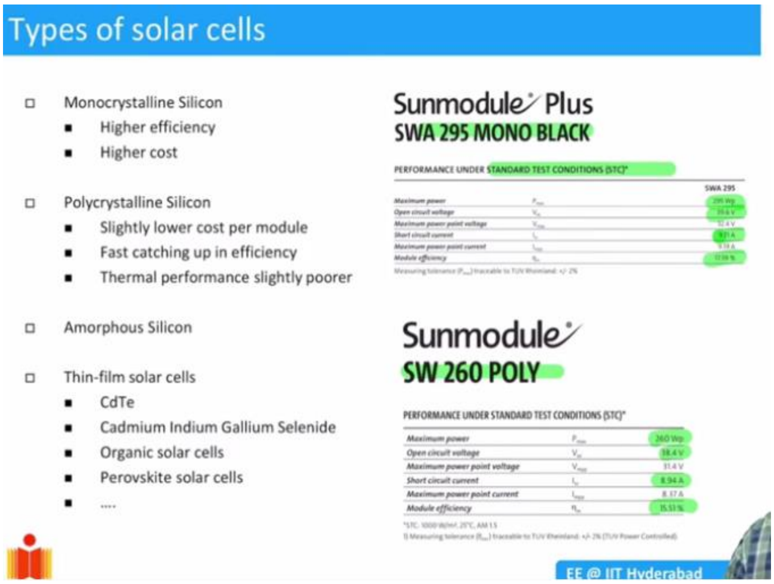
If you do that you will see that it will be 1 volt or something and a few milliamps of current. That is not really going to be enough for you to generate you know large power. So, we put lots of arrays of the solar cells in the form of an array and then we try to get maximum efficiency maximum power rather. And if you do that we have to introduce additional you know wires and we have to make contacts from the solar cell.

All of those you know non-idealities will come into picture. You know that their various resistances that come into picture also. And because of that, the efficiency will be reduced. So, the commercial solar cells it turns out have an efficiency of about 24%. That is reasonably high actually. So, this is the picture. And, right now, there is a huge race to improve the efficiency of solar cells.

Because if you are able to extract essentially this is translating to how much power you are extracting from the sun. And, we would like it to be nearly 100%. If you make it nearly 100%, we are very efficiently using the solar energy instead of you know throwing away it as heat or something. There are various techniques that people are you know researching. If you are interested in that you could work on some of this later on.

But, right now, this is a basic overview of solar cells. So, efficiency is good. And then, if I just wanted to you know lastly introduce couple of types of solar cells and then stop there.

(Refer Slide Time: 12:20)



So, so far, what we talked about is you know we did not really talk about the material part of it. But, it turns out that if you use a perfectly crystalline silicon wafer which we use for electronic devices, it has high efficiency. But it is very expensive. So, we have to trade-off the economics versus the efficiency. So, if you are able to make a large enough array then maybe you know with a slightly bad solar cell we might get enough power.

So, monocrystalline efficient silicon is very efficient. And it is used for applications where you do not care about the cost. For example, on a satellite or you know space station, you would not care about the cost. We want to use the maximum efficiency. So, we will use that there. But, let us say you want to deploy it in the field you know solar farm maybe we do not want to pay that much of cost. So, we can use polycrystalline silicon.

We already talked about what is polycrystalline silicon. So, when you have this you know domains and all that, so, that will degrade the electrical efficiency of a solar cell. But, the cost of solar cell also comes down. So, scientists have been working on and you see that this polycrystalline solar cells are also reasonably efficient nowadays. But, you know they are not very good at dissipating heat. So, there are some trade-offs.

And also, there are something called as amorphous silicon based solar cells. And nowadays, there is a lot of research in what is called as thin-film solar cells. You know use different materials, organic materials or different perovskite materials, all of these are being researched to improve the efficiency of solar cell. So, with the background that we have in this course, you will be able to understand what they are trying to do.

If you read any of these current papers, you just glance at it and you will see all these graphs that are appearing the maximum power point the current transfer characteristics all of this will appear in the literature. So, before I close, I just quickly wanted to show you the data sheets for a couple of solar cells. Just to say that you know now you have the necessary tools to analyze. You know this is for a monocrystalline solar cell. This is a, you know Sunmodule.

This is a brand. You can look up this. So, this is solar cell panel. And, under standard test conditions, they are saying that their maximum power is 295 watts. They have put an array of solar cells and they are getting open circuit voltage of 39.6 and short circuit current of 9.71. And then, module efficiency is going to be about 18%. This is what they claiming. So, if you look at if you let us say you are designing a solar cell for your home.

You want to buy some solar cells. And, you want to do a more intelligent analysis and design this. Then, you can use some of these things this, the parameters that we studied in this small video, just open circuit voltage, maximum power point and efficiency, we can easily calculate all of these. Similarly, if you choose a polycrystalline solar cell, so, this is SW 260 POLY which is another module. You will see that it has a similar you know slightly lower power.

This is the peak power. And, maximum power point short circuit current of you know 8.9 amps and then open circuit voltage of 38. So, the maximum efficiency is about 15%. You see the efficiency is lower for a polycrystalline solar cell. But, it might be cheaper. So, you have to do the analysis and find the trade-off. So, you are looking for let us say you want a solar cell that will drive your, you know some application. Let us say your monitor.

You want to drive it on a solar cell. So, monitor is about 100 watts. So, it might work. But, then, we should always remember solar cells are dependent on the solar and the sunlight. If you have it is a cloudy day then you might actually get less than the peak. So, you might want to have more redundancy. So, you have a larger solar cell so that even on a cloudy day you might be able to run your monitor. Or, you want to have a solar heater.

Whatever you know, we can think of lot of applications. So, this is what is a quick overview of a solar cell. So, I hope with this, you will, you got some insight into the working. And, in the next video, we will talk about photo detectors based on silicon. Until then, thank you so much. Have a great time, bye.