PROFESSOR: So we have an interesting class today. We're going to be taking this IV curve that we've so laboriously set up and understood-- sorry about that. And now we will subject it to illumination. So that's the essence of our lecture today, the diode under illumination.

And as part of today's lecture, we have some wonderful little kits over there in the corner where we'll actually be testing IV curves of solar cells. So I hope some of you brought the computers today, and if not, we have some extras up here as well we can use.

So again, just to situate ourselves. We're here in fundamentals. We're approaching the end of our fundamental section, but we still have a few really important lectures to get through. After we get through the fundamentals, we'll be in a good position to understand the different technologies and finally the cross-cutting themes.

And our goal is to, at least for the fundamentals, to understand solar cell conversion efficiency, which is the ratio of output to input energy. And for most solar cells, this breaks down to the following progression, from the solar spectrum to charge collection.

And we're going to be focusing on charge separation, incorporating elements of either side but mostly focused on charge separation today. reminding everybody, of course, that the total system efficiency is the product of each individual efficiency. And if any one of these is low, the efficiency for the entire system is low.

And since folks are tired of looking at this chart by now, every single lecture I intend to introduce something new that follows a similar pattern. Does anybody recognize what this is about? So you have over here some H_2O going into an oxygen-evolving complex, and light is coming in, essentially exciting up an electron, which is being stored in some form of chemical energy. What is that?

AUDIENCE: Photosynthesis.

PROFESSOR: Photosynthesis, right? And just like a solar cell, the photosynthesis conversion efficiency of the entire system is dictated by the efficiency of each individual part. Roughly it can be broken down to this little pie chart up here.

The total system efficiency in blue is somewhere, depending on the plant, somewhere around 1%, maybe as high as 7% or 8%, depending on very specialized plants that are experts at converting sunlight into usable chemical energy. And that, in part, is largely due to optical losses.

If you can see the absorption spectrum of chlorophyll, of the different types of chlorophyll here, you'll see large portions of the solar spectrum that go underutilized. So again, another system that's similar to a solar cell, that the total system efficiency is the product of each individual component going on here.

All right. So now what we're going to do is just quickly revisit the diode in the dark and construct the energy band diagram for pn-junction in the dark. Each of you should have on your desk these sheets. Oh, we don't have them on the desks. We need to pass those out. We need to pass those out.

So we should have sheets that describe essentially the equivalent circuit diagram, the IV characteristics, and the energy band diagram for our pn-junction in the dark. We laboriously filled this out last class. We're just going to refresh ourselves to make sure we're all on the same page and redo it this class right at the beginning because it's that important.

Thank you, thank you, thank you for those who came to our office hours and for those who came to the recitations, and we really tried to get this across. For those who are still struggling, let's make sure that you get this sometime between now and, say, the next two weeks because this will feature prominently on the exam, and it's pretty important for understanding how a solar cell works.

So if you would not mind working directly with your partner, the person who's sitting directly next to you. Let's walk through the diode in the dark and construct the energy band diagrams for the diode in the dark. I'll walk you through it as soon as you've done. Maybe I'll give you three minutes to complete that. And then we'll progress to the diode under illumination. Should be a lot of fun.

I see convergence among several of you, so let's move forward. Just to review quickly, the way I typically think about it, if we set up in the model circuit right here, we have our pn-junction. We have our space-charge region, also known as the quasi-neutral region, also known as the depletion zone. So we have this region right here that represents the space-charge region. So this is in the dark.

Now we have the energy band diagram shown right here, where this dashed blue line represents the chemical potential, also called the Fermi energy, throughout the entire device right here in cross-section. And just to be very, very clear, we've so far described the solar cell as like coming in through the top. And now we've rotated this structure by 90 degrees to represent the pn-junction. That's been a little confusing for some folks.

So just to be totally clear, in a device like this one, if it were subject to illumination you would have light coming in from the side, right, either from the p side or from the n side. So to transfer this into what we've seen so far with the solar cell devices facing up toward the sun, you'd have to rotate this by 90 degrees, right? Just to make sure we're all clear with orientations.

[? Because ?] we have the Fermi energy right here. The drift and diffusion currents for electrons-- electron diffusion, electron drift-- there is an abundance of electrons over here in the n-type side, and so they want to diffuse over to the p-type. That's why the diffusion current is pointing left.

Once they do to a certain degree, they set up a field, the electrons and holes, the mobile charges set up a field, and that creates a drift current that counteracts the diffusion. And once these two are in equilibrium, there's no current flowing through our device.

That's why current is equal to 0 right here. And there's also no potential difference because the Fermi energy, the chemical potential, is the same on either side of that device, and so the voltage output of that solar cell would also be 0.

When we forward bias our device, now we're forcing a separation, or we're forcing a separation of the chemical potential on either side of the device. If you connected this to an external circuit, the electrons would want to flow from this side to that side. But since we're forcing this condition here with a battery, we are reducing the barrier height here.

Electrons can now diffuse over from the n-type into the p-type side, and they do. And the diffusion current increases. And that's why we have current now a positive value. We've defined the electrons traveling to the left as being a positive current. We have now electrons traveling from the n-type to the p-type material.

When we reverse bias our device, notice the separation of the quasi-Fermi energies. Again, we have here one sign of voltage because the right side is higher than the left. And now the right side is lower than the left, so our voltage sign flips from right to left over here from positive to negative values. So notice the voltage.

And now the current as well. The drift current will outweigh the diffusion current in this particular case because now the barrier for electrons to diffuse from the n to the p-type is very large they'll have difficulty going from that side to that side. Whereas the drift current is larger because of the larger electric field.

And as a result, the drift current will dominate. And so now instead of electrons flowing from n-type to p-type, where we had defined as positive current, electrons are flowing from p-type to n-type in that, which we defined as negative current. And that's why our current has changed signs. Over here, notice that we're in positive current territory, and over here, notice we're in negative current territory.

Also, you'll notice the width of the space-charge region changing as we forward and reverse bias our device. As the barrier height decreases, we have a decrease of the built-in electric field. We have a decrease of the amount of charge on either side of the junction. That's why the depletion width decreases. And the opposite happens here under reverse bias.

So getting to the point where you can set up a pn-junction and understand how drift and diffusion currents come into being in the first place and then being able to bias your diode under different conditions is a really important fundamental skill for understanding how a solar cell works. Question.

AUDIENCE: On the forward and reverse bias, does the Fermi energy actually continuous, or does it actually [INAUDIBLE]?

PROFESSOR: So the Fermi energy, which we defined here as the chemical potential, notice we're avoiding talking about what's happening here in the middle until a couple of lectures from now. That gets into a gray zone where we talk about quasi-Fermi energies. We'll get to that in a minute or maybe a couple of lectures.

But yes, the Fermi energy in the extreme sides right here near the contacts, so your contact in your device over here and your contact in your device over here, those Fermi energies are different on an absolute energy scale. So there is an energy difference when you're driving the electrons from one side to the other.

Notice in this case right here, you would think that the electrons would want to travel through an external circuit to come back to this side because their energy's higher in this side and lower over here. But we're not illuminating the solar cell yet. We're biasing it using a battery. And this is why we have current flow coming from this side into that side.

We're essentially forcing the electrons from the n-type into the p-type material. We're pushing them up that hill with a battery. And that's why we have this diffusion current dominating in the dark, in the dark. So we have a current flowing from right to left.

In the illuminated case, we'll have all of our carriers traveling from left to right. And in the dark, this is the only case in which we have carriers traveling from right to left.

And it's happening because we're using that battery in the dark to change the chemical potential on either side, which, in effect, reduces this barrier height and allows carriers to diffuse from the n-type into p-type.

So you can think about it as forcing carriers up the junction. And this is a very useful technique because, in effect, what it's doing in a real device, when we you have a two-dimensional device within homogeneities, the current will travel through the weakest point of that pn-junction. Wherever the barrier height is lowest, current will begin crowding through that spot. And so it's a way of probing or testing the quality of your junction characteristic in the dark.

OK. So this is the basics of pn-junction in the dark. Let's flip our page over and now let's try to imagine what will happen under illuminated conditions, and let's start out in a very simple case.

We'll assume that the principle of superposition applies here, that the photo-excited carriers-- in other words, when light shines into our device-- I'm looking at this one right now or this one right here-- and light's coming in and generating electron-hole pairs, essentially exciting electrons across the band gap like we described in lecture 3, so we have carriers now being excited across the band gap, what will happen to those electrons now that they're in the conduction band? Where will they want to go?

AUDIENCE: To the right.

PROFESSOR: To the right, right? OK. So what you'll do is set up what's called an illumination current. Notice now at the bottom of the second row here, you have electron diffusion, electron drift, and IL current. IL stands for illumination current. So you have a third arrow here that will have to be implemented in some way. And that will-- by the principle of superposition you should think what happens to your IV curve as well.

So let's make an estimate of what we think should happen, and then I'll confer some notes, and then we'll measure what actually does happen under illumination. Why don't we give it a shot?

What does forward and reverse bias mean when there's no battery? This is a very interesting question. So once you start illuminating your solar cell device and you start injecting carriers into it, what will happen is, very naturally, this band alignment that you see right here, this band diagram, will begin to shift toward the forward bias condition.

Rationale? You'll be generating carriers. They'll be swept over into this region here. One way to think about is that you'll be increasing the number of electrons over here and the number of holes over here, which will naturally cause the energy of those electrons to increase on this side, the chemical potential on this side, to increase.

So one way to think about it is, as you're illuminating your solar cell more and more and more, you're forcing a forward bias condition on your device. To get the solar cell to go into reverse bias, you really do need to bias your device. You physically need to bias it.

Yeah. So when I mentioned illumination current here, we're really talking about the electron illumination current, right, what direction of travel the electrons are taking inside of our system. So yes, the electrons would be traveling from left to right. Very astute observation.

Current is generally described as a flow of positive charge. And in the absence of a definer or, say, electrons or holes, you rightly could assume that it would be the flow of positive charges. We're assuming electrons are flowing here in the illumination. current.

Good. All right. So This is very positive. I see everybody has settled on the notion that illumination will shift our IV curve down. Because of the way we've defined current, that if current flows from left to right that lands us in negative current territory. So that makes sense. If we shine light on our system, we have electrons flowing from left to right here. That'll put us into negative territory. So that shifts the entire thing down.

And we would add illumination current, an arrow pointing to the right right here, which would mean that we would have current flowing through our device, but there's still no difference in the chemical potential on either side. There's still a difference in Fermi energy in the p-type and the n-type, which means our voltage is equal to 0, which means we're intersecting the y-axis right here, and our little x should be marked right down here. So it's really just a superposition.

Great. OK. Now what happens if we forward bias our device either because we're adding a resistor in series to our solar cell? So instead of a battery there, you would replace that with a resistor. Or if we're applying a bias voltage as well, we could also do that under illumination. So we'd still have the illumination current, right? And we, through superposition, shift this entire curve down, we'd be operating somewhere in this quadrant right there, right?

So this we call IV quadrant, typically I, II, III, IV, IV quadrant. This is where power is coming out of the solar cell device. Because if we imagine instead of having a battery there, we have a resistor, the electrons will travel from the n-type material through that external load to get work the p-type material where the chemical potential is lower, right, because they'll desire to minimize their free energy.

And as a result, they'll deposit that power across that resistor, across that external load, in order to get back to this other side because that's the only path that they can travel easily, right? And so this entire curve shifts down. You have your red x somewhere in the quadrant over here. And power is flowing out of the solar cell across that external load.

So in the next slide, pretty much everything is right, except that, mea culpa, I forgot to replace the battery up there with a little resistor. So you'll want to correct that in your notes. Instead of having the little batteries up there, you can replace those with resistors or a resistor in series with a battery, if you prefer. Since depending on the illumination condition, the intensity we may have natural for a bias condition, we may need to apply a bias voltage.

OK. So we have our IV characteristic like this. We have our red x under forward bias conditions in the IV quadrant, denoting that power would be flowing out of this solar cell device under these conditions. And now the bias is inverted. We have reverse bias conditions.

And notice that the current still has the same sign. So the current is negative here, negative here, and negative here. So the net current is always flowing in the same direction in all cases because we have this illumination current, because we have this generation of carriers inside of the material.

That's pretty cool. That wasn't the case when we had the device in the dark. Here, in the forward bias conditions, we're actually forcing carriers from the n-type material into the p-type material. But under illumination, now we have all of our carriers traveling from the p-type into the n-type.

What's varying is the potential that the carriers have and, of course, the total amount of current. As you forward bias more and more and more, this downhill slope here decreases, right? So there's less of a driving force for the carriers to be going from the p-type to the n-type, and that's why the current approaches 0.

Eventually at some point, if you keep forward biasing here, the current will be 0. There will be no net current flow because there will be no driving force for the carriers to go from the p-type into the n-type. There will be no more built-in field. Kind of cool.

OK. So now we're beginning to wrap our heads around what's happening to the electrons and holes during solar cell operation. Let me put a little bit of mathematics to this. These are your IV curves. The blue is in the dark, and the red is under illumination. And we're focused on this IV quadrant right here because this is the quadrant in which power is coming out of our solar cell device, which usable power is coming out that we can power an external load.

Why? Well, first off, the voltage is such that we can power an external load. We have charge separation. The electrons are accumulated over here. And they have higher potential than they do on the other side, which means that there's an incentive for them to go through the external circuit, deposit the power across that external load to get back to this other side where their potential is lower, right?

So the voltage is favorable. And the current is also favorable because now we have light coming in. And this generation current is driving the carriers-- well, or is creating carriers here in the p-type that can then be driven toward the n-type because of the built-in field.

So the conditions are just right under illuminated forward bias conditions to drive power through our external load. Under all other conditions of operations of the solar cell, we're putting power into the device, not getting power out of it. This IV quadrant over here, this forward bias illuminated case is the only case in which power is coming, usable power is coming out of our solar cell that we can use.

So that's why we focus on this IV quadrant right here. The illuminated IV curve is, to the first order, is just your dark IV curve with a superposition, which we call the illumination current, I sub L. And that's what shifts our entire curve down by this I sub L right here, so this I sub L, that one right there or that right there. Kind of cool. All right.

What do we think will happen if our light intensity goes down by a factor of 2? So now if the amount of sunlight falling on our solar cell drops by 1/2, what will happen? What do we predict will happen based on this right here?

AUDIENCE: [INAUDIBLE].

PROFESSOR: The curve will shift, the red curve will shift up by about 1/2, right, because the illumination current is now cut in half. What will happen to the voltage intersect right here? What is the relation between voltage and current? It's the logarithmic relation, right? So it won't necessarily be cut in half, right? But it'll be cut by whatever this would be here, a log of 2.

So OK. So we're beginning to develop an intuitive understanding of where electrons are flowing inside of our solar cells in the dark and under illumination. In the dark is important because we can test our devices in the dark, and we can still learn a lot about our solar cell device characteristics in the dark.

As well, we can, under forward bias conditions in the dark, we can force carriers from one side of the junction to the other the wrong way and probe for weaknesses in the pn-junction regions. That's helpful.

And in the illumination condition, obviously we're testing the total amount of power that's coming out of our device. So again, this is very useful because It's off of this red curve here that we defined the efficiency or the performance of the solar cell.

So what I'll ask folks to do now is to-- we'll begin passing around these little tools. And I'll ask David Berney Needleman to come up to the front. David is our lab guru. He's the one who helped build these, really was the driving force behind getting them built.

These are IV testers that will allow you to measure the current voltage characteristics of solar cells right here in class. And he's going to-- well, we'll pass them out while maybe he comes to the front here and explains how they work.

So now that we have the basic IV curves rolling in, what I'd like you to do is modify the height or the intensity of the light. And the easiest way to modify the intensity of light is to move the light position up and down. So modify the intensity of the light and see how this IV curve changes.

Note the y-axis scale, which might change as well. It might rescale depending on the condition. But note the y-axis scale and see how the intercept of the y-axis is changing with illumination intensity. Give that a shot.

All right, folks. Why don't we circle back real quick. This has been a good experiment. I am very much in favor of multitasking and browsing. So if you want to keep your experiment running over the course of the remainder of the lecture, I will certainly have nothing opposed to testing a few different illumination conditions. And if there's anything really, really important I'm going to emphasize, this is a really important wake-up, folks.

The I sub L, just to really recap here, we have this ideal diode equation, the illumination current coming in from our light source. And in our little set-up, how many batteries did you see there?

AUDIENCE: One.

PROFESSOR: Look closer. How many batteries do you see total in our set-up? Look especially at that light source. Two of them, right? There's a 9-volt and a 1.5-volt. All right. So one of them is powering the light source. And we have, as well, bias to the solar cell device, right? So we have a bit of a combination of the last two slides, right?

In this case, in the dark, we were biasing our solar cell using the battery. And in the illumination conditions, the light itself was causing the solar cell to become forward biased. But we can add a battery to sweep the bias condition of the device, right? So even though we have a natural biasing of the solar cell by the light, we can force the solar cell under different operating conditions with the battery.

And so that's effectively what's happening right here is you have a combination of both simple scenarios that we just looked at, and we're building on those components to really understand the larger system.

Why might that be important, or why might that be realistic? Well, the light itself is biasing that particular solar cell device. But that solar cell might be connected in series with a bunch of other solar cells in a module, right? And those other solar cells might be biasing that one solar cell.

So that's why we have to think about the solar cell device both from the perspective of what bias condition is it under, what illumination is it under, and of course, what's happening around it. Is it just powering an external load? Is there a battery connected in series to it? Are there other solar cells connected in series with it? OK. Yes, Ashley?

AUDIENCE: So I don't understand still why having a load would bias the device.

PROFESSOR: So let's imagine under illumination conditions right here, what I'm going to do very, very quickly is replace this battery manually in my slides, if PowerPoint auto save will allow me, with a resistor. So if you'll excuse my quick introduction here of the resistor. Now, sorry about the little artistic license.

OK. So now I have my resistor here. And my illumination is coming into the device from-- say one of the sides is generating electron-hole pairs. I have a multiplicity of electrons that have now gone down the hill, right? It's more energetically favorable for these electrons to be on the other side.

And what has that done? It's raised the chemical potential of this side. It's difficult for them to get back the other way. It's not impossible, but it could be more easy for them to flow through an external circuit to get back to the other side. And as they flow through that external circuit, they're depositing their energy across that external circuit.

What energy? Well, it's the potential difference from this side to that side. So that's why the solar cell can be thought of, as in forward bias conditions, under illumination with an external load attached to it. Of course, the load has to be well-matched to the output of the solar cell device.

AUDIENCE: And is the biasing because there is a voltage drop across the resistor?

PROFESSOR: Yes. The biasing is because you have a shift in the chemical potential of this side up relative to-- you have a shift of the n-type side higher than the p-type side. That's a bias. Anytime you have a difference in the chemical potential in one terminal versus the other terminal of your solar cell, you have a bias.

Whether that's generated by light, whether it's generated by a battery, right, whether it's the energy input to create that bias is coming from the sun or if it's coming from an external battery, that's a matter of detail.

AUDIENCE: So is the sun forward biasing the cell?

PROFESSOR: Yes. One can think about this as--

AUDIENCE: I thought you were talking about the difference between light and the LE-- OK.

PROFESSOR: Oh. So the LED, in this case, could forward bias your device, too. I mean, it's just photons. Photons are forward biasing the device.

AUDIENCE: So then can some ever reverse bias?

PROFESSOR: No. That would be very difficult. What you could do, though, is have a bunch of solar cells connected in series with this one, right, that are producing forward power. You could shade this device, and then power could be flowing backward through it, right?

In other words, it could be in the dark right here, in a dark condition. And you could be in a reverse bias condition just because of the way the other solar cells around it are behaving, if you have a shaded solar cell, for example, in a module.

So imagine a seagull lands and kind of covers up one of the cells. That will be under reverse bias, and that could present problems if the solar cell can't withstand the reverse bias. No, this is a very ideal condition.

What happens in the real world is that at some reverse bias condition, you'll just have biased it so much that electrons will be able to tunnel through from the p-type into the n-type right here. The electrons in the valence band will be able to tunnel through into the conduction band.

And what happens to this IV curve is it goes zoom, begins dropping. So if the solar cell reverse bias-- let's see, the reverse bias current, or the current at reverse bias voltage, is not low enough, in other words, if the pn-junction is not strong enough, you could have a catastrophic failure of your module by just shading one of your cells. Thankfully, this is one of the testings that are done with the solar simulator to prevent that failure mode.

AUDIENCE: OK.

PROFESSOR: All right. I'll entertain deeper dives with questions. I'll try to keep the lecture focused on the broader general topics. But if somebody is interested in learning more, I'm happy to kind of dive into there.

All right. So readings are strongly encouraged. I have interacted with several of you. Joe has interacted with probably 3n, n being the number of people I've interacted with so far, and really tried to impart the wisdom of pn-junctions. So please, please, please come to us if still things are going over your head. You should be able to explain to your roommates exactly what is going on in a pn-junction.

Define parameters that determine solar cell efficiency. So now we have a qualitative sense about where current is flowing, where electrons are moving around, what defines the power output, how the power output is changing with illumination condition.

We're getting an intuitive sense of all this. Let's start putting some discrete variables to all of that. And there are a bunch of two-letter or three-letter acronyms with some subscripts here that we'll get to know and we'll become very familiar with over the next few lectures.

So how is solar cell conversion efficiency determined from that illuminated IV curve? That's our first question. And what I'm going to do is start with our source IV curve right here. This is just the IV quadrant. OK? So notice the current starts at 0 and goes to some negative value. So we're looking in the IV quadrant. Voltage is going from 0 to a positive value. So again, IV quadrant.

We have our ideal diode equation here. And oh, notice one thing. I just changed I to J. What just happened? Well, I and J look very similar, but they're, in fact, two different variables. Most often, PV researchers will report a current density, in other words, a current per unit area instead of the actual current coming out of a solar cell device.

So what you've been measuring here off of the DAC has been current, total current output from that device. And it might be a really tiny number, and it might be difficult to compare against other-sized devices. And so what solar cell researchers often do is they say, OK, let's normalize the current by the area to get a current density. And we'll call current density J, and we'll call current I, right?

So for calculating power, we'll have to use I. We'll have to multiply I times V. But if we're just looking at one solar cell versus another, we can use J as a very convenient way of comparing one solar cell versus another. Cool. OK.

So the illuminated IV curve looks something like this, right? It's in the IV quadrant. It goes out a certain amount, then it the curves up. We just determined that here in class. And that's essentially the ideal diode equation with a superposition term, this J sub L right there.

So let's parse through this. We have the y-intercept over here. At the y-intercept, there is maximum current flowing through the circuit but no power because voltage is equal to 0. So remember, the Fermi energy is the same on either side. The chemical potentials are the same on either side of the device.

So there's no energy gain of the electron traveling through the external circuit, but there's a maximum current. And no power flowing through that external circuit because there's no potential to be dropped across the external resistor.

The opposite happens over here at this point called Voc, which we'll call open-circuit voltage. The oc stands for open circuit, V, voltage. Open-circuit voltage is just as you would think it is. When your solar cell is in an open circuit, when you-- say you took a pair of scissors-- please don't this-- and cut the leads so that your solar cell wasn't outputting the current through an external load, there would be a bias voltage built up across the p and the n side of the solar cell.

And it would be the maximum voltage that could be supported by that solar cell device under illumination conditions. That's the open-circuit voltage, open circuit because there's no current, again, traveling through the external circuit. That's why current is 0, open circuit. And voltage because this is-- well, it's an interesting point because it's the maximum voltage here represented in the IV quadrant.

And somewhere in between the point of open-circuit voltage and short-circuit current-- short-circuit current, again, because you're short circuiting your device-- current is flowing through, but there's no resistor. There's no external load. There's no power being deposited on external load.

Somewhere between these two extreme conditions where there's no power flowing through the external circuit, you have a maximum power point where there is a power being deposited across your external circuit and a lot of it, right? That's the maximum power point. This is the point at which the solar cell is producing the maximum amount of power output.

And to represent that slightly differently, what I've done-- so if I were to take current times voltage right here using IV quadrant data, my power would be a negative number. Why? Because voltage is positive, but current is a negative number, right? So I'd multiply a positive and negative number together, you get a negative number, and that just sounds weird. Who talks about power output from solar cells being negative? It almost sounds like power's going into the device.

So this is another convention that you're going to have to get used to is looking at the IV curve in the I quadrant. So all we've done is taken the y-axis and multiplied by a negative 1. So we flipped it up, right? So bear with me here. It's a bit tricky to keep all this in your RAM.

But here's our short-circuit current point now. Here's our open-circuit voltage point. Our IV curve now is pointed down. Before it was going up because we were in the IV quadrant. Now, we flipped, essentially just done a-- we've done a flip vertical, if you will, on our IV curve, and we have our current increasing here going to higher bias voltages.

Now we can take the product of the voltage and the current to determine the power, and we obtain a curve that looks very much like this blue curve right here that you can see. And the maximum power point is truth in advertising. It's at the maximum power. It's where this blue curve reaches a maximum. That is the maximum power point of the solar cell device. That is where the solar cell is outputting the maximum amount of power.

And so at this maximum power point, there is a voltage and a current associated with it that you can read right off the IV curve. And this we call Jmp, or current density at the maximum power point, and Vmp, which is the voltage at the maximum power point. So, so far, we've learned essentially four variables here. We have our Jsc, our Voc, and our Jmp, and our Vmp at that data point right there. Questions, since I know you have them.

AUDIENCE: To ensure that the device is working in the maximum power point, does an external voltage have to be applied to it?

PROFESSOR: So to ensure that the solar cell device is operating right here, a couple of things need to happen. You need to have the right illumination conditions, and you need to have the right load. So the two need to be matched to each other. Absolutely. And that's where some of the power electronics come into play. Yeah?

AUDIENCE: So in the last problem set, where [INAUDIBLE], we assumed that output voltage would be [INAUDIBLE] volts.

PROFESSOR: Yeah.

AUDIENCE: Is that, in general, a safe assumption for [INAUDIBLE] solar cell?

PROFESSOR: Yeah, yeah. So it's a very interesting question regarding the homework question. Let me repeat it so that the microphone can hear it. The homework question in the last homework, there was one question that inquired, assume that the voltage at the maximum power point is the band gap voltage equivalent minus 0.5 volts.

And the rationale for that assumption is as follows. The open-circuit voltage, this point, is generally between 0.35 and 0.4 volts minus the band gap, or lower than the band gap. So you have the band gap energy minus 0.4 volts. And I can show you a very nice little paper that describes why that is. It essentially has to do, in part, with losses inside of the solar cell at thermodynamic limits of conversion inside of the solar cell device.

Then what we've done is we've done another additional discounting from the Voc to the maximum power point, which we've assumed is around 0.1, maybe 0.2 volts. Notice the shape of the IV curve right here. The maximum power point is interesting because the voltage at the maximum power point is almost the Voc, in a good device.

And the current at the maximum power point is almost Jsc, but not quite. All right? So the discounting from the Voc to the maximum power point voltage is not that much, as is the discounting from the short-circuit current to the maximum power point in a good device.

In a bad device, this maximum power point here could be dragged all way down here. You could have an IV curve that looked something more like this instead, almost like a resistor, at which point the maximum power output would be a lot less, a lot less than what's shown here in blue curve. Cool.

All right. So let's continue moving on. The efficiency of the solar cell. Eta, this Greek letter eta, is our power out versus power in. Our power in is the illumination intensity given in units of watts per meter squared. So we calculated this in our very first homework assignment and realized that the AM 1.5 spectrum is around 1,000 watts per meter squared. So that's our input power right here.

Our output power is the voltage at the maximum power point times-- whoopsy-- times the current at the maximum power point, not the current density, the current at the maximum power point. So take this current density and multiply by area, and that's effectively-- the units work out better that way.

So it would be either V times I at the maximum power point or V times J times the area, the area of the device, the area of the solar cell, at the maximum power point. And that's the total power out.

Actually, yeah, yeah. So as long as the units are in units of watts per meter squared-- yeah, down here-- if this is not total watts but, watts per meter squared, you could still use current density. Those units would still work out. So be very careful whether you use total power in or normalized by unit area power, right? Just keep track of your units. Don't do like the professor.

OK. So we have efficiency here as power out versus power in, the power out being the maximum power point power and the power in being the illumination from the sun. Now we're really talking. This is starting to get interesting because it's beginning to click. Pieces from lecture number 2 come together with what we're seeing now. So this is solar cell output power at the maximum power point and sunlight coming in. OK.

So what I'm going to do next is I'm going to take this maximum power point and I'm going to draw a box that starts at the origin here, and the kitty-corner corner of my box is going to end at the maximum power point. So it'll have some rectilinear shape that will comprise the maximum power point and 0, 0, the origin, as two of its corners.

And that box looks like this blue one right here. The area of that box is Jmp times Vmp. OK? And notice I have another box around here. I have this clear box that starts at the Voc point and the Jsc point. And now I have two rectilinear shapes, this blue one and the clear one right here, the bigger one. The bigger one has an area of Jsc times Voc.

And I'm going to define a parameter called fill factor, which will be the ratio of these two areas, the ratio of those two boxes, the Vmp times Jmp divided by the Voc and Jsc. If this is 1, which is virtually impossible to do, but if this were 1, it would mean that these two boxes were the same size. And the current and voltage at the maximum power points would be the current and voltage under short-circuit and open-circuit conditions respectively.

In real life, this blue box is smaller than the square box right over here. And so the Jmp Vmp product is less than the Jsc Voc product. And by consequence as well, the Jmp is less than the Jsc, Vmp is less than Voc.

So the ratio of the two boxes is defined as the fill factor. The fill factor indicates the quality of your diode. If your fill factor is very poor, that means that that sun right over there at its maximum power point is being dragged toward the origin. That means that the area of this blue box is growing smaller relative to the area of this clear box. The fill factor is going down. That means you're filling less of this maximum square box function defined by the Voc Jsc. OK.

So we have defined efficiency as power out divided by power in, power out being the current voltage product of the maximum power point divided by the solar insulation, fill factor being defined as the ratio of Vmp Imp product divided by Voc Ioc product.

Notice that here I've written this in terms of total current, here in terms of current density. The areas essentially just cancel out because you have an area in the numerator and denominator. They cancel. These ratios should be identical.

Thus we obtain an expression for the efficiency in terms of fill factor, Voc, and Ioc. Simply by using this fill factor definition right here, what I've done is I've multiplied this side of the equation-- let's just focus right here-- where we have fill factor equals Vmp times Imp divided by Voc times Ioc.

I moved the denominator up to the side over here, multiplied it by fill factor, and that's my Vmp Imp. Now, I go back to that top equation and say my Vmp Imp is now going to be substituted by fill factor times Voc times Ioc, and that's how I get to this equation right here.

Why? Why do I go through the effort of this little numerical manipulation? I do it because these parameters right here are fairly easy to measure using the solar simulator that you just put together. So I can measure the point at which my voltage is at open-circuit condition. I can measure the current at short-circuit condition. And simply by taking the ratio of those boxes, I can determine what my fill factor is as well.

And these break down roughly into the current is going to be a function roughly-- again, I'm really painting broad brush strokes here-- the current is going to be roughly a function of illumination condition and bulk material quality. The Voc will be roughly a function of the interface and the diode characteristics. And the fill factor is going to be a function of the interface diode characteristics but also of the resistances within the device.

And so from an engineering point of view, when we break the solar cell output down into these three parameters so that we can better understand what's going wrong with our solar cell. If we have everything lumped in terms of Vmp Imp, it becomes a little bit more obscure to figure out what exactly is going wrong with our solar cell device. Ashley?

AUDIENCE: You said the fill factor also an easily measurable parameter?

PROFESSOR: So the fill factor you would measure essentially by doing the little analysis we just did right here. Yeah, exactly. So you'd have to do a voltage current sweep. Mm-hmm. Coolness. OK. So we have an expression for efficiency in terms of fill factor, Voc, Ioc and our incoming power. So power out, this right here again is power out, divided by power in.

Why does efficiency matter? Why do we care so much about efficiency? Well, the conversion efficiency determines the area of solar cells needed to produce a certain peak power, or to think of it differently, the area of solar panels that is necessary to produce a certain energy per unit time.

And many costs scale with area. You have glass, encapsulants, the absorbent materials within the solar cell devices themselves, the metals that are used to make contacts, the labor that's used to install the panels. If you have a larger panel area, you need more labor to install it. The aluminum and racking and framing materials that go into holding the panels up in the field either on a roof or out in the field.

So efficiency affects pretty much everything but the inverter and possibly some of the soft costs of the project. That includes the architect and the people who you pay to handle the money, financing, and the lawyers perhaps. So pretty much all of the real material and labor costs are scaling with area. And so efficiency determines that to a large degree, and hence it's a highly-leveraged way to reduce the costs of solar energy.

If you do a sensitivity analysis, which you will do in the second and third parts of the class, and look at the costs of solar and how it scales with efficiency, you'll see that efficiency is one of the determining factors for cost in a solar cell device. And that's why we focus on it a lot.

To put it into perspective, if the efficiency up there is determined by the output power versus the input power, if we had 100% conversion efficiency, which is impossible to achieve, thermodynamically impossible to achieve, we would produce a certain amount of energy per unit time, or a certain amount of peak power, with this panel right there. Say that's the size of our field installation.

If we had a 33% efficiency cell, which is closer to the space-grade solar cells, we'd need three times that area, so three times the encapsulants, three times the glass, three times the labor to install it.

And if we had a 20% efficiency, say, high end but still commercial solar module, not something you'd need to get from NASA, but something that you could buy from a supplier, you'd need five times that area. Whereas if you had a 10% efficiency module, which is more approaching the area of some relatively inexpensive solar cells, you would need 10 times that area.

So if you're doing a cost analysis, this is why efficiency matters. It might still be cheaper to use this instead of to use this over here. That might very well be more expensive when you do the math and figure out how much it costs to deposit those materials with a very low throughput deposition process and very high cost. It might still be, but it might not. The material costs might end up whopping you.

And so a simple equation that calculates all these parameters in, the material costs, the module efficiency, essentially the material [? and labor ?] costs, are being calculated in dollars per meter squared, just saying, how many dollars go into producing a meter squared of this material?

And the efficiency is over here. And this is just a very simple back-of-the-envelope calculation type of way of estimating the cost of a solar system. So if you say, OK, I'm willing to pay more for a high-efficiency cell because I'm using less area, you can use this type of calculation to get to the answer quickly.

It's not a levelized cost of electricity analysis. It's not using discounted capital flows and so forth, which we'll get to later on in class. This is a really back-of-the-envelope envelope engineering approach to estimating costs of a solar system.

So I think this is a great place to stop. And if anybody has a pitch concerning their project ideas, class project ideas, I'd like to invite them to the front now. The class project, mind you, is really the capstone of this class, 2.626, 2.627. So if you have an idea, a fun idea, for a class project, I'd invite you to give a pitch up here at the front of class, or you're welcome to send it on an email to the class listserv.