

MITOCW | 7. Toward a 1D Device Model, Part I: Device Fundamentals

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PROFESSOR: What we're going to be doing over the next few days, today and on Tuesday, is really diving into the device fundamentals, and then on Tuesday, the materials fundamentals, of how a solar cell device really works. And what we've done so far is skimmed along at a very high level using only the necessary physics and nothing more to describe how solar cell works. Because we want to give you an intuition about solar cell device operation.

PROFESSOR: The alternative way of teaching PV is that we go heavy on the device physics upfront, you're completely overloaded, your RAM is completely full, and by the time we actually get to IV curves, you're completely lost. So hopefully you have some intuitive sense now about how a PV device works.

Now we're going to be doing some deep dives into some advanced concepts so that we really have a sophisticated understanding of how a solar cell works.

So let's dive into the lecture material for the 1D device model, we want to be able to create a one dimensional model that describes how a solar cell operates. So we want to capture all of the necessary physics from the materials and the device to describe the IV characteristics of a solar cell.

So we'll do at the very beginning is start a little bit of nomenclature so we understand what we're talking about in terms of energy conversion efficiency and quantum efficiency. And then we'll start describing the different parameters that effect energy conversion efficiency and efficiency here.

So one of the first key concepts that's very, very important to understand is that energy conversion efficiency is not the same thing as quantum efficiency. You'll here these two terms used quite frequently the PV community.

Now, I would say we're really starting to get sophisticated about their use. In the very beginning of the field-- well let's put it this way, in the third wave of PV, which began at around late 1990s early 2000s, which was really when, say, some of the novel materials-- quantum dot-based solar cells, some modern organic material based solar cells-- really started to take off, there wasn't that sophisticated of understanding of some of the nomenclature in PV. And so terms were used in a confusing way. When you read some of the papers back from the early 2000s, you might pick up on some of this.

And So that's why I have this slide right here describing very clearly what is quantum efficiency and what is energy conversion efficiency. So energy conversion efficiency is pretty easy to understand. We've been talking about that all class. We've been talking about how photon comes in with a certain amount of energy.

And you extract electrons for your solar cell device that of a certain amount of energy. And that ratio would be the energy conversion efficiencies, essentially the energy coming out divided by the energy going in.

So if, for example, one photon comes in with three eV and generates an electron hole pair, which is then extracted from the device with a voltage of say 0.6 volts, we would have an energy conversion efficiency less than 1, somewhere around 15% or so. Whereas if we looked at quantum efficiency and define quantum efficiency as the number of electrons out per incident photon, that means if we have one photon coming in and one electron coming out of our device, we have a quantum efficiency of 1, or 100%.

So quantum efficiency can be thought of as collection efficiency. It means how many electron hole pairs were generated inside of the device, and how many were collected coming out of the device. There's a little bit more to it than that dealing with reflectivity off the surface. I'll get to that slide or two.

But it can be thought of roughly as collection efficiency, as whereas energy conversion efficiency is really what you think of in terms of thermodynamic efficiency

of a device.

Why is this important? Well, there are papers out there-- this is an old one, I think, in nature of materials, if I'm not mistaken, that started using a bunch of terms, right. So under 5 volts bias and illumination from a 975 nanometer laser-- so nothing like a polychromatic solar spectrum, this is a monochromatic light source-- our detectors show an internal quantum efficiency of 3%.

The photovoltaic response under this monochromatic light results in a maximum open circuit voltage of so and so, a short circuit current 350 nanoamps-- very, very tiny-- and a short circuit current internal quantum efficiency of 0.006%.

So what they're talking about here is a quantum efficiency of 0.006%. As we've already done just by the simple example the 3 V phonon coming in and exciting electron hole pair, quantum efficiency of 1 but energy conversion efficiency below 20%, we can already guess that the energy conversion efficiency of a device like this, even for monochromatic light, is going to be very low.

So the reason I'm highlighting this abstract right here is because it's a great example of the plethora of different terms that you can find in reading a paper. And if you focus on just a few of them, like oh, 3%-- wow, that's awesome, 3% device efficiency.

No, it's not energy conversion efficiency. That's the quantum efficiency under a very specific bias condition, reverse bias is like a photo detector, not a solar cell, not under forward bias conditions.

OK, so what does this really mean, this 0.006% short circuit internal quantum efficiency? Well, we defined our energy conversion efficiency or solar conversion efficiency as power out divided by power in. That was done in the previous lectures.

The power out would be the power and the current and the voltage product at the maximum power point divided by the solar flux coming in. And that would be equivalent to the fill factor times the short circuit current times the open circuit voltage.

And typical values for energy conversion efficiency are in the 12% to 20% range, I would say. Maybe less than 10% for emerging technologies. But these are typical values. And the solar flux, the illumination intensity might vary as well. But typically we talk about one sun, or AM 1.5 illumination conditions, right. So that's our spectrum at AM 1.5 conditions, what we did on homework number one.

Now the quantum efficiency has two flavors. One we'll call external quantum efficiency and the other internal quantum efficiency. And basically the difference between them is the reflectance off the front surface of the device. The internal quantum efficiency essentially factors out the reflectance. The external quantum efficiency is really taking reflectance into account as well.

So external quantum efficiency is defined as electrons out per photons toward the device. We say photons in, but this is really how many photons are impinging upon the device itself. Some of those photons will be reflected off the front surface. Other photons will go into the device and generate electron hole pairs. Or some will go straight through the device and be absorbed in the back surface or so forth.

So the EQE, external quantum efficiency, typical peak values range between 60% and 90% depending on the reflectivity for moderate efficiency devices. So the reason peak values ranging 60 to 90 is because there's going to be some band of wavelengths at which the solar cell really responds well.

It's really efficient at converting those photons into electron hole pairs. And were the sun-- instead of a beautiful polychromatic blackbody emission source-- if the sun were a monochromatic light source tuned to that particular wavelength, the solar cell would be wicked efficient. But it's not.

So this is why EQE is an interesting parameter is because it tells you the response of the solar cell to different spectral conditions. And that's why we sometimes call it spectral response of a solar cell device.

By the way, those who need notes, if you would be so kind as to raise your hand, Joe will pass them around as well so we can have enough for everybody to write

down. Any questions thus far on EQE, external quantum efficiency, the difference between QE and the difference between ECE, or shall we say, the energy conversion efficiency? Okay.

AUDIENCE: Quantum efficiencies, they also include [INAUDIBLE] photons, right? Or do they just include photons which have a potential to make an electron [INAUDIBLE]?

PROFESSOR: In principle, QE, or sorry, EQE, should have EQE as a function of lambda, really. And the photon in is going to be, obviously, at a certain wavelength usually. I've rarely heard EQE given in a polychromatic sense where they take an entire solar spectrum and measure the quantum efficiency average.

Usually quantum efficiency is measured wavelength by wavelength. And so you might change your monochromator settings 20 or 30 times over, or even more, over a quantum efficiency measurement to really map out the entire solar spectrum from short wavelengths in the ultraviolet all the way to longer wavelength and the infrared.

And you're absolutely right. Some of those wavelengths, the photo response of the solar cell will be very close to 0 because it just doesn't respond well at that wavelength. Maybe the wavelength is too short and is being absorbed by some surface layer.

Or maybe the wavelength is too long it's just going straight through [INAUDIBLE] photon. Whereas energy conversion efficiency is really taking the entire solar spectrum and matching or testing the energy, the power coming out of the solar cell versus the power going in.

So a typical quantum efficiency curve might look something like this. Let's walk through the axes first and then talk about the curve. So the axes, we have wavelength on the x-axis, on the abscissa. Then on the ordinate, we have quantum efficiency. Wavelength is varying from, let's say, the ultraviolet to the infrared and beyond. Well, beyond the red into the near infrared and probably ending somewhere on the mid-infrared.

And the quantum efficiency extends from 0 to 1, in other words from 0% to 100%. And we have this box that's represented by this maroon line right here entitled Ideal Quantum Efficiency. And this would be if at the band gap energy, all of a sudden our quantum efficiency turned on to 100% and cut across. And this was the assumption that we made in our homework, that the solar cell device would respond in this ideal manner.

In reality, at longer wavelengths here, what's going on? Why would there be a decrease of the quantum efficiency at longer wavelengths? What effect is happening there?

AUDIENCE: [INAUDIBLE].

PROFESSOR: Yeah, the absorption coefficient is dropping. And this light is starting to go straight through the device. There's a growing fraction of photons that are not being absorbed by the solar cell device.

In the very short wavelengths right here, as I said before, oftentimes there's a dead layer right near the surface of the device that's impeding good electron hole pair charge separation and eventually a collection. And right here in the middle, there's a slow but steady decrease of the quantum efficiency typically.

These are photons that are being absorbed in the absorber layer. If you think about your solar cell in cross section, here's your solar cell in cross section, these are photons being absorbed in the absorber layer generating electron hole pairs which are then being separated by the junction.

And as we go to longer and longer wavelengths, if you remember your optical absorption coefficient begins dropping, that means that the penetration depth of the light, the average penetration that the light is increasing. And so the average distance that the electron hole pairs are being generated from the junction is increasing.

So in other words, as we go from short wavelengths to longer wavelengths, the

distance from which the electron hole pairs are being generated from the junction is increasing. That means that the electron hole pairs generated at these wavelengths have further to travel to reach the junction than those electron hole pairs generated at these wavelengths closer to the front surface.

And since there's a finite probability that the electron hole pair will recombine as it travels through the material, that's why you get this very slow but steady decrease of quantum efficiency over the mid-wavelength range. And on Tuesday we'll talk more about that.

Internal quantum efficiency. So for those who say, well you know, there's a certain delta right here between 1 and my maximum response, here my maximum quantum efficiency. And I suspect that's really due to the fact that a certain percentage of my photons are being reflected off the front surface. I know how to calculate reflectance. We did that in lecture number two or three, I believe.

So we know how to calculate reflectance off the front surface. We can also measure reflectance using a spectrophotometer. And what we can do is normalize the effect of reflectance out. By dividing our external quantum efficiency by $1 - R$, what in effect we're doing is we're normalizing the effective reflectance out of our measurement. So now we're only considering those photons they get into the device.

If you want, you can think about the extreme cases there. If reflectance is 0, that means your EQE is equal to your IQE, your internal quantum efficiency is equal to the external quantum efficiency. But if reflectance is, say, 50%, if 50% of your photons are being reflected off the front surface of your device, now your IQE is probably going to be double your external quantum efficiency.

And so now this is an interesting parameter because, for example, in our lab scale devices when we're testing them, oftentimes we don't optimize for optical properties. Sometimes we do, but many times where we're focused on the material, we're focused on the junction, and we don't bother to put the perfect entry reflective coating on it.

It would take too long to fabricate it. And so IQE gives us a good metric of how the solar cell is responding if we were to go through all the effort to make the light capture ideal for our device. Okay? And that's why we sometimes use a report IQE in studies.

And typical peak values are between 80% and 98% for moderate efficiency devices. So it would essentially-- the curve would look very much like the EQE curve. It would just be boosted up by $1 / (1 - R)$. Okay? So any questions so far? Make sure we're on the same page here. Yeah?

AUDIENCE: [INAUDIBLE]?

PROFESSOR: Absolutely. So IQE is a function of wavelength. R, reflectivity, is also going to be a strong function of wavelength because the real component of the refractive index is changing as a function of wavelength. Yeah, absolutely.

OK, so this gives you a sense. Sorry for the poor choice of the reflectivity colors right here. This baby blue, which is almost impossible to see, but I've just traced it out with my finger, that denotes the reflectivity as a function of wavelength from some data that it took as a graduate student. So you have some typical quantum efficiency curves right here.

And then the quantum efficiency curves that are shown are for a pretty poor quality device. And in this particular case, I measured quantum efficiency under short circuit conditions, but with different illumination intensities. So going from 0 sun illumination all the way up to 1 sun illumination.

But the device was still in short circuit conditions. So what I was doing, in effect, was flooding the device with more and more and more carriers, and I got this boost here in the middle wavelength range. I still was limited by my surface. I was still limited by my band gap and non-absorption effects over here.

But in the middle, I was able to get this boost in performance simply because I was filling in trap states inside of material. This is an advanced concept that we're going

to get to over the next few lectures. But it gives you a sense of what a QE curve might look like for device, what the reflectivity might look like, and these curves right here were IQE, or internal quantum efficiency.

OK, so take efficiency with a grain of salt. When you hear somebody reporting an efficiency value, ask-- think about what efficiency is being measured. Is it energy conversion efficiency? Is it quantum efficiency? Internal, external? What wavelengths? What is the nature of the light being used, right? Is a 1 sun illumination source that has been well calibrated to within 2% spectral fidelity, spatial uniformity, temporal stability?

Is it a really bona fide good light source? Or is this some monochromatic light source that somebody set up because they knew, aha, my solar cell really responds well to, say, 500 nanometer lights, right? So I'm going to test my-- I'm going to report my values right at that wavelength. You have to take it with a grain of salt.

Yeah, exactly. And what is the intensity of the light that's being used as well. That's very important as we just saw right over here because the bulk material is going to respond differently. There are certain trap states for electrons inside of the material.

And as you add more and more light, you're flooding those traps. They become filled, and the electrons can move through the material more easily. That's why you get this boost of response as you increase the illumination intensity in this particular experiment.

So these are all questions that you should ask yourselves when you see quantum efficiency-- internal quantum, external quantum efficiency values reported and/or energy conversion efficiencies. What is really happening? What are they measuring?

This right here, a paper out of Paul Alivisatos' lab from 2002 was, in my humble opinion, an excellent example of honest efficiency reporting. First off, they picked their highest values and put their best foot forward, and said look we have a quantum efficiency over 54% , and a monochromatic power conversion efficiency of

6.9% under very low intensity light at 515 nanometers, right.

So first off, they put their best foot forward and said, under optimal conditions monochromatic light that's what we get. But also under air mass 1.5 global solar conditions, under the standard solar spectrum, we obtained an energy conversion efficiency, or a power conversion efficiency of 1.7%.

So both values are put there out on the table, and they say look, here's a characterization of our device. So I really like this paper. It was back in 2002 right at the beginning of the new wave of new materials in PV, so to speak, this third wave of PV in the United States. And it was a beautiful example of a really well-reported, carefully described efficiency.

Any further thoughts or comments before we jump on to the next topics of the day?

AUDIENCE: How do you have a QE curve for 0 suns, I noticed on your plot? Or is that kind of an extrapolated?

PROFESSOR: Yeah, so this is the bias condition-- sorry the bias lighting condition, not the bias voltage as in battery, but bias lighting as in I shine a light source, a polychromatic light source at my material. I believe in that case it was a halogen lamp with a series of filters to simulate the solar spectrum.

And obviously you can't measure a quantum efficiency without having some light involved. And so the light that was being generated by the monochromator was much lower in intensity than these illumination intensities here. And so it was more of a perturbation on top of a steady-state background.

And we ran the measurement exactly those conditions. We had a steady-state background light, and then we chopped the monochromator light coming in, and used a lock in amplifier to track that particular frequency. So we were able to detect the small perturbation due to the monochromatic light coming in on top of the steady background. Yeah?

AUDIENCE: There's no international centers to report efficiency or convention?

PROFESSOR: There are. There are conventions, international conventions, to report energy conversion efficiencies. And I believe there might also be for quantum efficiencies as well. Let me look into that. Why don't we take note of that and bring back the precise ASDM standards next time.

And I believe also there are other entities like IEC that have their own systems for it. There about four laboratories worldwide that are authorized to give standard efficiency measurements. So they have very carefully calibrated quantum efficiency measurement devices, very carefully calibrated solar simulators.

And if you really think you have a record efficiency cell, you should get it checked at one of those laboratories. You shouldn't just report what you have coming up your lab-based system. You may even want to go around to a few different labs at MIT first because one might have a better calibrated solar simulator than another.

What we're going to do now is dive into some of the common factors that cause solar cell IV curves to deviate from normal ideal diode model. We're going to talk about shunt and series resistance, recombination currents-- maybe we'll get to current crowding, some other effects.

Basically what we're doing now in number two, is we're beginning to say, OK, now that we understand an ideal diode, now that we have an ideal picture of how our solar cell works, let's bring it down to real life and talk about all the things that can go wrong. Because when you try to make a solar cell in the lab, these are the things that are going to start nipping at your heels, so to speak.

So we'll start out with an equivalent circuit diagram of a solar cell device. And this might be new to some folks, but it's all stuff you've seen so far. What we have over here is the current generation source of the solar cell operating under forward bias conditions, under illumination, generating a voltage and a current.

We have a diode here that prevents the back flow of current, and forces the current to go out through the external circuit loop. And it forces it to drive the external load, which would be attached to that little circle over there, and that other little circle over

there. So you can imagine external circuit attaching itself right there.

So the diode-- if the diode quality is high, if it's good, it will prevent the backflow of current. If the diode quality is poor, you will have so-called leakage current, current leaking into the diode back-- if you want to think about under forward bias conditions, here's your solar cell forward bias.

You have light, your electrons coming in, separated by the electric field. Instead of powering the external load and coming back into the device through the back, leakage current would be the electrons going back up the barrier, going back into the base of the device, the so-called diffusion current.

So this is that diode right here representing the diffusion current, or in that particular case, in the ideal, the equivalent circuit diagram, this is representing the resistance to diffusion, if you will. So we have this voltage and current being generated by the solar cell, and that would be described by the ideal diode equation. My apologies, there should be actually a x of this minus 1 right there. We should take note of that and correct it. I just happened to notice that.

OK, so the ideal diode equation is right here. And this is the current density versus voltage. So we have in linear log scale or axes, we have a straight line. That would mean on a linear scale, we would have an exponential curve. So an exponential function, exponential curve up here, and a straight line in linear log scale.

I'm trying to sensitize you to the two ways of looking at this, both a linear scale and a log scale of current in the y-axis because both will tell us something. From the linear scale up here in the upper right, it will be very easy for us to see the fill factor. We can just glance at that curve and see, oh, it looks really box like. It must have a large fill factor.

From this curve down here we can begin to see deviations from ideality. If anything causes this curve to bend up or down, either down here or up here, we're going to see it really quick on the log scale. And that's why looking at the IV curve in both ways is helpful. It's a method of diagnosing the problem quickly.

So what we're going to do now is to take our equivalent circuit and begin adding a few things to it that represent realistic effects that we might see in a real device. So the first thing that we might do is say, well listen, a real device has a finite series resistance. And that can come from a variety of sources. We'll talk about those in a few minutes.

But we might add a series resistance component right up there. So let's look back. I'm going to flip back and forth between the two slides just so folks can really see what the difference is. This was the ideal case. That's the with series resistance, again ideal with series up there in the equivalent circuit.

Great. So what have we done? Well, we've added a series resistance component which is essentially dropping the voltage output of our solar cell. And notice what else happened. Now we have a nonlinear equation. Our current density is a function of our current density.

So this is becoming more difficult to solve analytically. And what is happening to our IV characteristics? Well, let's look-- we'll go back once again to our ideal diode equation right here. We have a very sharp box-like IV curve under the ideal conditions.

Now when we introduce the series resistance component, we begin smoothing out that IV curve. The fill factor has dropped. Take a look. Ideal conditions, sharp, very large fill factor. Now we've added the series resistance component, the fill factor has begun dropping.

If we look at it in log scale, it's very easy to detect that series resistance. We can see it right here. This used to be our curve, right? So again, this was the ideal case, straight line. Again, this is log of current verses linear voltage. So the x-axis of the two plots here are the same. I'm only changing the y-axis from linear scale up there to log scale down here.

And notice what happens. If I add the series resistance component, now I begin dropping off. So this is a telltale sign when you take an IV curve and you see that,

then you have some series resistance effect inside of your external circuit or your solar cell, or some combination of the two. Yes, Ashley?

ASHLEY: So from this curve it looks the series resistance really only starts to have an effect once you have a higher voltage.

PROFESSOR: Absolutely. And that, you can begin to see directly from the equation right here as well. Take the limit of low voltage and the limit of high voltage. Or another way to put it would be the high current, really. And the high current to voltage ratio only begins to take on up at higher voltages because of the exponential function of that curve.

So that's a very, very important and astute observation that the series resistance begins to kill you at high forward bias voltage conditions. You hope that you design your solar cell in such a way that the series resistance only really begins to kick in above the maximum power point voltage. That's the goal.

AUDIENCE: This is not voltage out, this is voltage applied to the [INAUDIBLE]?

PROFESSOR: This is the voltage that is being measured across the solar cell.

AUDIENCE: The output voltage.

PROFESSOR: The output voltage, yeah. Yes, you can think of this as the biasing condition of your solar cell device. The two are almost equivalent. The only difference is you have that series resistance in series there. So you have to be careful whether you're talking about the voltage here at the solar cell itself across a junction, or the voltage coming out of your device that is effected by that series resistance as well.

So think of it is doing that IV sweep that we did in class the other day. So you're taking the IV sweep of your device, and you're seeing the impact of the series resistance in the output voltage you're measuring of your solar cell device, just like we did in class.

So again, series resistance will effect you at some point. It is almost inevitable. But you have to design your solar cell such that it effects you only after the maximum power point.

Likewise, we're going to introduce another resistance term inside of our equivalent circuit diagram, what we call a shunt resistance. Let me back up one step here. This was just a series resistance, now I've added a shunt resistance term here as well.

And whereas we wanted our series resistance to be small, right? The smaller our series resistance, the less this effect would be, the more ideal this curve would be. We want our shunt resistance to be large, because we want to prevent the current from flowing inside of the device back to the base.

Instead, we want the current to flow through the external circuit. So we want the shunt resistance to be large. In other words, we don't want our solar cell device to full of shunts. That's pretty obvious.

OK, so what does shunt resistance do to you? Well, if we compare the IV curves once again between the solar cell just with the series resistance, we had a very low forward current here under low forward bias conditions. If we have a very poor shunt-- if we have a plethora of shunt pathways in our device, we're going to get current flowing through our device even at low bias conditions. That's because the pn-junction is weak.

And even though we have a very large field in there, there are some regions where the field is much smaller because of the shunt pathway, and current is going to be flowing through there. Diffusion current will be flowing through that shunt pathway. So think of this as being a very strong diode, right.

In the absence of shunt resistance, you have a very strong diode. You have in your p-type region and your n, and that large barrier is preventing the diffusion of electrons back into the device. It's preventing this from rising. It's keeping it low.

And that can only happen when the pn-junction barrier is uniform throughout your entire device. If you have one region in your device that is poor that has a shunt pathway, maybe you have a piece of metal that fired through the junction and is making good ohmic contact to both sides. If you have a shunt pathway, now the

current can flow even under small bias conditions. The diffusion current can flow into your device.

And that, of course, drops on the linear log scale right up here, you hardly detect it. Notice, if we go back and forth between with and without shunt resistance, you can hardly detect it right here until you start getting to some really leaky diodes, in which case you begin to impact your fill factor as well.

So shunt resistance is important for a solar cell device that it not be too, too high. Because at some point it does begin impacting your fill factor. Sorry, the shunt resistance not be too, too low. Yes, your shunt resistance can't be too, too low because at some point it will begin impacting your fill factor.

But more importantly, shunt resistance is usually indicative of some localized failure in your pn-junction. It's usually not homogeneously distributed throughout the entire pn-junction. Maybe your first solar cell device you ever make might be effected by that. But as you get better and better, you'll start making higher quality junctions.

And usually the shunt resistance is indicative of one little spot. And what happens at that one little spot? Well, current is flowing in from the entire emitter region into that one little shunt and locally heating up your device.

And so that's why people worry about shunts in industry, is because if you have current crowding into that one little spot, it's heating up, it's becoming a hotspot, and it can even melt the encapsulated materials in your module. Perhaps even create a fire in extreme conditions.

And so when you test the solar cell devices, typically the IV tester will measure the shunt resistance in a solar cell by looking at what's happening under very small bias conditions right here, and comparing it against the healthy cell that it would expect. And if it finds cells with high shunt leakage current, in other words, low shunt resistance, it will advise the tester and sorter to throw out those cells, and so they'll be put into the scrap pile.

And so the shunt resistance manifests itself right here in the ideal diode equation in

this term right there. And so it's essentially an add-on term after your exponential, looking something like this. Essentially, at low bias conditions, you can extrapolate this point right here, determine the slope of that point, and find the shunt resistance.

And likewise, you'll notice that the shunt resistance really isn't impacting you up here. The shunt resistance really isn't impacting you at higher forward bias conditions. That's mostly series resistance in the illumination current that's overwhelming any shunt pathway. Ashley, yeah?

ASHLEY: Do you know for, I don't know, a high-quality manufacturer, what percentage of produced cells get tossed because [INAUDIBLE].

PROFESSOR: Very low. The manufacturing yields of a well-oiled manufacturing line- I say oiled in a figurative sense. We're not typically-- yeah, some of the parts, I suppose, use oil. In a well-functioning manufacturing line, the yields are upwards of 95% for cell fabrication. So it's a very small percentage.

You typically see this when you're developing a new process. And that's why I'm informing all of you about this is because we're all developing new processes here, right? We're all working on new solar cell devices. And it's very important to be aware of what's going wrong in your device, not just that you're getting a low efficiency because this is the first step to troubleshooting. Yep?

AUDIENCE: [INAUDIBLE] but why is it bad that we have a high current density? [INAUDIBLE] current density [INAUDIBLE]?

PROFESSOR: Why is it bad that we have a high current density? Why don't we go back to simple case right here where we have a series instance, for instance, right? And so at, say, 0.5 volts forward bias, we now have with the series resistance, a higher forward current-- we'll call a dark forward current because we're measuring this in the dark. That's why we have 0 here.

And it's forward current, meaning it's like a diffusion current going from the emitter back into the base. And so we have a higher dark forward current here in the dark with the series resistance, then if we didn't have the series resistance, right? So let

me do that again. We're up here at, say, 1 times 10 to minus 2 milliamps per square centimeter, whereas before we were down at around a quarter.

So why is that bad? That's bad because when we illuminate our solar cell device, we are going to be shifting that curve down, and that's going to reduce the total current output at the maximum power point. So anything that goes up here when it's shifted or transposed by a finite fixed amount, it will be closer to the 0 point of current than it used to be. That's why it's bad.

So anything that increases that blue curve and shifts it up in the dark is going to be bad for our solar cell. In an ideal case, we want our dark forward current to be as small as possible. We want our J_0 to be as tiny as possible for a good solar cell device.

OK. Good let me show you dynamically what happens in a solar cell. Oops, sorry about that. Here we go. So this is a PV CD-ROM again in a beautiful example of, in this particular case, looks like series resistance. So now we're at 1 ohm series resistance for the entire device.

The ideal solar cell is shown in red. The IV curve for the ideal solar cell is shown in red. It would be a short circuit current of 35 milliamps per square centimeter, an open circuit voltage of 624 millivolts, and a fill factor of 83%, ideal solar cell. The real solar cell now with 1 ohm series resistance, the fill factor has dropped by 5% absolute down to 78%.

And now I'm going to increase the fill factor. What would you expect to happen to that curve? Flattens, right? The fill factor drops. So let me start increasing the series resistance by manually dragging this forward. So now we're at around 2, 3, 4, 5, 7, 8, 9, 10.

So now we're at 10 ohms series resistance. That means we have a large resistance inside of our solar cell device at some point. And our fill factor has now dropped precipitously. And if you remember that efficiency is proportional to fill, factor that means we have a problem with our device. We're really dropping the maximum

power point. We're really dropping the operating point of our solar cell.

So if you were to do an extreme condition, you might have so much series resistance that your IV curve looks like a straight line, you have an ohmic resistor now. The resistance component is swamping out any diode-like behavior of your solar cell. And that's why you have a line. Likewise, you're dropping the total current output of your device, right, because you have a resistor in series now that's preventing the current flow.

OK, so that's, again, an extreme case of what can happen in a shunt resistance. Let me show you that as well. So we have another beautiful example shunt resistance here.

Now we start out with a very high shunt resistance, because in our equivalent circuit diagram, if we go back up here, we have a large barrier that prevents the current from flowing back internally inside of the device. The current is forced to go outside through the external circuit.

But as we drop that red shunt resistance component right there, as we decrease the magnitude of the shunt resistance, we will allow the current to flow inside of the device. Now we have internal current loops, and that means that we no longer are forcing the current go outside through the external circuit.

And somewhere around between 1,000 and 100 ohms for our shunt resistance, we really begin to see that drop in fill factor. And as expected, it's really begin to impact us at the lower bias voltages down here like we saw. And at some point, we drop the shunt resistance so much that now the voltage across our solar cell is even suffering because there's not enough separation of charge sustained to make that voltage large because the current is being shunted back inside the device.

And again, we have what appears to be very linear IV curve. So you can see when you measure your solar cell and you test it, and you get a linear IV curve instead of that nice exponential, you have to do a little bit of troubleshooting to figure out what exactly is going on.

OK. Good. So key concepts so far. We can add the effects of parallel resistance. What we typically refer to a shunt resistance is also called parallel resistance because it appears in parallel with the diode inside of the device, right. So we can have a parallel or shunt resistance and series resistance in our devices.

And as an advanced concept, I really wanted to expose you once, and we can talk more about this in office hours, to the notion that in addition to just having one saturation current, you could envision different saturation currents coming from different regions of your solar cell device. Let me walk you through that.

Under low bias conditions where we have a large built in field, and we have very low bias conditions. Before bias, obviously the field is going to be decreasing, the barrier height's going to be decreasing as well. So under low forward bias conditions, current is going to have a hard time getting all the way up into the base and recombining inside of the base, but some of the current could recombine in the space charge region of our device.

And that's why under low forward bias conditions, we might have what is called a J_{02} current, or recombination current in the space-charge region. And then there are high forward bias conditions when a lot of the carriers can diffuse into the bulk, and recombine inside of the bulk, we might be driven by different recombination mechanisms, bulk recombination mechanisms.

So that's sometimes where you see what is called a two-diode model for a solar cell. And the two-diode model for a solar cell would look very much like this, except you'd have two diodes one right next to the other. One that would effect you at low bias conditions, another one at large bias conditions. You might see this in your research. It's really an advanced concept more targeted towards the graduate students here.

Another thing you might see pop up is this ideality factor showing up right down here. The ideality factor is a slope factor. What that means is-- here if we go back to this, if you change your ideality factor, you're changing the slope in log scale. It'd still be a straight line, but if your ideality factor increases, you would get something like

this. If it decreases, the slope would increase, right? Because you have the equation dependent on 1 over this parameter.

So the ideality factor is important as well because it indicates the type of recombination mechanism that's driving the current inside of that region of the device. If anybody ever comes across this in their research, come talk to me. I'd be happy point to the right directions.

Or you could look up the thesis of Keith McIntosh from University of New South Wales. Excellent, excellent thesis entitled, "Humps, Lumps and Bumps: Three Dimensional Effects of the Current Voltage Curve of Silicon Solar Cells." Some of which might apply as well to other material systems as well.

And you can tell where the lumps, humps and bumps comes from. It's really these lumps, humps and bumps in the IV curve he's talking about. Excellent read, very good thesis. Highly recommended for those who want to look into their IV curves a little bit more. It's kind of like looking to the tea leaves, right? Because there are a number of things that can be effecting the IV curves. We'll get to some of those on Tuesday as well.

These are IV curves, again in log scale on the ordinate, linear scale on the abscissa. You notice there's little commas here because I took this data in Germany so the decimal place is written as a comma. The IV curves vary in shape and in style. Let's look at this one right here, this black one.

It starts up like this, and then it goes flat for a while, and then it becomes series resistance dominated way up at higher bias voltages. Whereas this blue curve right here, this one again, you have the effect of shunt resistance at lower buys voltages.

Then you have one diode, two diodes, and eventually the series resistance component coming in as well. Or perhaps it's a large shunt as well. You don't really know until you start fitting it, and modeling it, and maybe measuring the temperature dependence and so forth.

So this gives you a sense of the real life diode IV curves that you might get over the

course of your research, and it gives you some tools to use to begin parsing through and figuring out what's going wrong. Let's talk about that. Let's talk about solving problems.

So fill factor. What can impact the fill factor? Well, we talked about the need for a high fill factor to produce a high power cell. Very easy to understand. The larger the fill factor, the larger the maximum power point. If you have a low fill factor, your maximum power point is going to drop.

Let me show you back and forth. Good device, bad device, large fill factor, low fill factor, high maximum power point, lower maximum power point.

OK, we talked about this. OK, so causes of shunt resistance, physical causes. I alluded to this earlier, but let's imagine you have that weak spot in your pn-junction. This is meant to represent pn-junction in two dimensions now.

So, so far we've only taken a cross section like this. Now you have a real device in 2D. And what this is meant to represent to some local weakness in the pn-junction. And the current is now flowing through that local weakness. So that's a representation in a 2D energy band diagram E versus x versus y of a shunt in realistic conditions.

So shunt series resistance, on the other hand, we talked about the effect of high series resistance, and we're going to calculate the series resistance for a solar cell. In part, because this is asked for you on your homework assignment. At least the graduate students have a problem pertaining to this.

So let's talk about the different components of series resistance. We have a bulk current and then a lateral current inside of a typical solar cell device. So sunlight comes in, shines, generates electron hole pairs. These electrons will diffuse to the junction region, and then they'll drift across the junction, wind up in this emitter front surface region. And eventually through lateral diffusion reach the contact and be pulled out of the device.

So we have to consider these two different components, and pretty much the current all the way from the back contact to the front contact. Any one of those things could contribute to series resistance in an additive sense.

So to put that pictorially, we have bulk resistance, emitter sheet resistance, the contact resistance, and in line losses out of plane as we travel along those front contact metallization.

So bulk resistance. This is another way to state how to choose an absorber thickness. So we've talked about choosing absorber thicknesses, in other words, we've talked about choosing the thickness of our solar cell device based on how much light we want to capture, based on the optical absorption coefficients.

Well guess what? This is a co-optimization problem. We also have to worry about the finite resistance of the bulk material, and we have to spec the thickness accordingly so that we don't wind up with too thick of a bulk material and the series resistance component will be too large.

So how to choose the appropriate absorber thickness. Let's talk about that for a minute. So you can measure a parameter in the bulk called resistivity. Resistivity will be given as a function of q , which is the charge, u , which is the carrier mobility, which means how easy is it for that carrier to move around the lattice, and n being the carry density.

So let's think that through. Resistivity-- if our carrier density goes up, if we have more carriers to transport the charge, the resistive should go down. That makes sense. Check. If the mobility goes up, meaning it's easier for the carriers to move around the lattice, then the resistivity should go down. Check. OK, so that makes good, intuitive sense.

Now the base resistance, in other words, the resistance that we should have as current travels across the base, across the absorber of our material, which we also call the base of our solar cell. So as the total resistance, as current goes across the base, should be given as R_{ho} , which is a fundamental material parameter combined

with some geometric parameters that define the size of our solar cell.

So l is going to be the length of the conductive path which typically would be given as the thickness of the device, and A is the area of current flow. In other words, the dimension or size of our solar cell device.

So to minimize base resistance, we want to have a very thin solar cell device. But wait a second. If we make it very thin, then what happens?

AUDIENCE: [INAUDIBLE].

PROFESSOR: You get less absorption. So you have to make it a certain thickness to get a good enough absorption. Then we can compensate. If we still need to drop the base resistance, we can increase the area of the base.

And so far that makes good sense. There's nothing else tugging for the area to be the other direction, right? So we can make this solar cell infinitely large, thick as we want to be to absorb all the light. Great, OK. Hold on to that thought because we're going to have another constraining parameter that pushes us in the opposite way in a few slides.

All right, so the emitter sheet resistance. In other words, how to design front contact metallization. Emitter sheet resistance refers to the resistance of lateral current that the carriers will experience as they move laterally to reach the front contacts.

And again, we go back to this fundamental material parameter where we have resistivity as a function of mobility, and total dopant concentration. Sorry, for some reason, I used the big N here and a little n on the previous slide. But it's the same thing. It's carrier density.

So again, our resistivity is a function of carrier mobility and carrier concentration, how easy it is for the carriers to move, and how many of them are there. For a thin layer, a sheet resistance can be described as the integral of the resistivity by the thickness of that layer.

Or to put it more simply, if you have a uniform layer, you simply multiply the

denominator here by thickness. So this can be thought in the following way. If we have a thicker emitter, we will be dropping the emitter sheet resistance.

We will be dropping the resistance component that carriers experience as they travel laterally through this. And that makes sense because, in effect, as we increase the thickness of this emitter region, we're increasing the total cross sectional area for the charges to travel through.

So folks with me so far. For the emitter sheet resistance to be low, we need the thickness to be good enough, the thickness to be thick enough, the carrier density to be high enough, and the mobility to be large enough. And oftentimes, the resistivity of a material, you might spend months trying to optimize the resistivity of your emitter region.

For those doing thin film materials, you might be working on zinc oxide, aluminum doped, or fluorine doped zinc oxide, for instance. And after months of tuning the temperature and the oxygen partial pressure during the deposition process, you're there and you have what you have. You have a certain carrier density and a certain mobility. And you can't do much more than vary the geometric parameter varying the thickness.

So what next? If my thickness is too big on my emitter, if my thickness is too big, I'm going to be absorbing all of my short wavelength photons in the front surface of my device. And maybe the current collection probability from that layer up here, that has a very high carrier density, is not going to be as large-- in other words, the current collection efficiency won't be as large as if I generated the carriers here in the bulk because of an effect called Auger recombination, which we'll get to a few lectures.

So this front surface region here oftentimes is considered a dead layer to a solar cell. Its electrical properties are very, very poor. So if I make this layer too thick, sure I get rid of my emitter sheet resistance term. But at the same time I'm killing my quantum efficiency in the short wavelengths. Because I'm not able to absorb those short wavelength photons and convert them efficiently into electron hole pairs. So

this is a story about co-optimization of different device parameters.

So let's keep this thought for a minute. And let's now try to calculate the total power loss due to the emitter sheet resistance, because now we have this weird unit of ohms per square. In reality, it's ohms. But when we think about emitter sheet resistance, we're thinking about a square of the material.

We have units of ohms per square, square being a unit-less parameter. So it has, let's see, resistivity had units of ohm centimeter, we divided our resistivity by our thickness of that emitter region, so our units became ohms. And ohms per square here is the units typically given for emitter sheet resistance.

And now we have to convert this into some meaningful parameter for actual solar cell device. So if we want to calculate the fraction of power lost due to this emitter sheet resistance, it's fairly straightforward. We would have to think about the current. Since power is $I^2 R$, we have to think about the current as a function of the resistance, right? As a function of the position here, we're integrating over y , y being the lateral dimension.

And we're integrating-- imagine the separation between contacts is S . So here's one contact metal finger. Here's the next contact metal finger. It's extracting charge from the material. And we have a certain distance, S , right here between them.

So the maximum distance that the current would travel in principle would be S divided by 2, since any current that reaches the emitter over here will be collected by this contact grid, and any electrons reaching the emitter over here will be collected by that contact grid finger.

OK, so now we have our current. We can translate that into here where we have our b , b being the vertical dimension, y being the horizontal dimension here. And we would get this equation coming out right in the other side, which is a function of the separation of our contact metallization fingers to the cubed, to the third power.

So the power loss coming from the solar cell device, as we separate our contact

metallization by small amount, this power loss is going to go up very quickly. That's a really deep point to recognize here because what this means, in effect, is that we can lose a lot of power very quickly in our solar cell device if we place our contact fingers too far apart, due to this emitter sheet resistance effect, due to the row sub s, which is our emitter sheet resistance right here.

OK, so then if we divide the power loss by the maximum power point, we essentially get a normalized power loss. And so if we want to, say, limit this ratio to a certain fraction, say 4% of total power is lost due to emitter sheet resistance, now we can define the geometric parameter, the distance between the contact metal that we need to do an actual solar cell.

And if you run through the calculations with a typical set of parameters for a silicon-based solar cell, you'll find out that your metallization fingers should be separated on the order of 4 millimeters. And if you remember the real solar cell devices that you saw embedded in that module, the separation of the fingers is just about 4 millimeters. So this is where that finger separation comes from.

In one case, you'd want to have your fingers spaced really, really close together to minimize the emitter sheet resistance. But on the other hand, if you place your fingers too close together, your shading the front surface of your solar cell with metal and light's not going to get in to generate electron hole pairs. So that's the optimization function that's run right there.

Wow, so far I'm counting three or four of these different parameters tugging in different directions, right? So you can begin to sense how constrained the solar cell device is in terms of optimization of all these parameters, and how easy it is to make a very low efficiency device as a result, how difficult it is to make a high efficiency device.

So this is interesting. So we have now the spacing, the appropriate spacing between fingers. It's about 4 millimeters. Which means if we're going to be making a solar cell device, say a thin film solar cell device on a sheet of glass with some transparent conducting materials [INAUDIBLE], and then we have our source of

device, and we have their front surface here, and we have, let's say, something else on top, we have to limit how wide we make that device. Otherwise, we could be limited by our sheet resistance in, say, the zinc oxide layer of our device.

And this is interesting now because previously for the bulk resistance-- let's think back over to our bulk resistance. We wanted our area to be large because we wanted to minimize the bulk resistance. Now we want the area to be small so that we minimize our emitter sheet resistance.

So you can see how the current traveling in two orthogonal directions inside of our device is really causing us problems because we're having to optimize the same parameter in different directions for each. It's tricky.

And I'm providing you the tools here to be able to sit down and calculate out what is the optimal thickness, what is the optimal thickness of your emitter, of your base, and what is the optimal lateral dimensions of your solar cell device to simultaneously minimize your bulk resistance and your emitter resistance instead of a device. And you can do it all now with equations that I just gave you. So it's pretty cool. At least to first order.

AUDIENCE: How did you define B, again, in that?

PROFESSOR: Yeah, absolutely. So B was a vertical dimension. B is just given as the distance here. Yeah.

AUDIENCE: And that's going across like if you look down on your model?

PROFESSOR: Yeah, you're looking down on your solar cell. So the pn-junction would be planar to this view right here.

AUDIENCE: [INAUDIBLE]?

PROFESSOR: Yep. It's a bird's eye view on the solar cell. Any other questions?

OK, so contact resistance. This is the next thing that can kill a solar cell device.

Contact resistance-- we want to minimize the contact resistance, but the first step to

minimizing is to measure, to know what your contact resistance really is.

And one simple way to measure contact resistance is to take a cross section of your solar cell device. We have deposited, say, four metal fingers on it, and they're appropriately spaced by, I don't know, how many millimeters or so.

So you have a certain contact resistance right here between the metal and your semiconductor material that's denoted as $R_{sub C}$. And then there's a certain emitter resistance that we just talked about, $R_{sub em}$ right here.

And if you were to measure the current passing through here to here, or another way to say it is, the resistance for current to pass from this point to that point, you might get, let's say, this data point right here, a total resistance value of some value, and a distance between the two probes of, say, $1 \times d_{sub f}$ we're $d_{sub f}$ is the unit distance between two adjacent contact metallization fingers.

Now if we measure the resistance between this point and that point, we might wind up with that data point right here. And if we measure the resistance between this point and that point-- we already did that-- to this point and that point, we might wind up with that data point right here, and so forth.

And what's happening? Well, as a current goes into the device, it passes once through the contact resistance, a certain n times $R_{sub em}$, n being the number of metallization, number pops, the number of times we travel distance df . And then it goes out the other side, again traveling through the contact resistance.

So the slope of this line here should be equal to the emitter resistance. And the offset, the intercept at x equals 0 here, the intercept should be 2 times the contact resistance. Because in principle, that would be the equivalent of current going in and going back out through this contact resistance right here, through the same one, not traveling at all through the emitter.

Obviously since that's impossible to measure, we have to determine that through extrapolation back to the y -axis. So this so-called TLM method, the transmission line method, is a method that is used to determine the contact resistance of a solar cell

device.

You could either perform it linearly in this fashion right here, or using a circular, essentially an array of concentric circles. And the latter method is typically preferred, especially in thin film devices. So this is how you measure the contact resistance.

And then there are line losses. So what can-- let me back up one step-- what can effect the contact resistance? Typically, what effects contact resistance is the atomic interface between your metal and your semiconductor, whether it's an organic or an inorganic semiconductor. Bless you. So the interface here is what determines the contact resistance, typically. And of course, the dopant density within your semiconductor.

So components of the series resistance in the line losses. So line losses are essentially the losses in the contact metallization lines out of plane. What can cause a resistance in the contact metallization line?

Well, intuitively we know that, OK if the line is too small, if the cross section that line is too tiny, then there's going to be a high resistance to current travel along that line. And indeed that's the case. Whoa, we have the same exact equation as we had for our base resistance.

Now it's applied to the line, because in principle it's the same thing. We have current traveling through in one direction along a constrained cross sectional area, a certain distance, a certain length.

So we have now a resistivity given by the metal obviously, because now we're talking about the metal itself, not the semiconductor anymore. Currents traveling along the contact metal so that the ρ becomes the resistivity of the metal, the A becomes a cross sectional area of the contact finger, and the l is the length of the conductive path.

In other words, how long does the current have to travel along that contact metal before it reaches a highway, a bus bar, one those really thick strips of metal on our social device, in which case it's home free.

So the R, the row rather, the metal resistivity, resistivities of several metals and non-metal materials are given here. That's typically why you see silver contact metallization used for solar cells. It's because it has a very low resistivity, which means that the resistance line losses will be small.

Now, what is the problem with silver? Does anybody know what percentage of the world's silver right now manufactured each year is currently being used for contact metallization on solar cells? Take a number. Guess.

AUDIENCE: 30.

PROFESSOR: A little lower, but in that order of magnitude. So he said 30. Somewhere upwards of 10%, right, would be your guess? So around 10%. And of course PV is growing at a cumulative annual growth rate in the several 10s of percents per year. So silver utilization is expected to continue to increase.

So either we mine more silver, or we venture to another contact metal material. And that's why you see folks looking into copper. Nickel, which is similar in electronic structure. It's one element to the left of copper on the periodic table, and another metal alternatives. Yes?

AUDIENCE: Yeah, where does nickel fall on the resistivity chart?

PROFESSOR: I have to give you the exact number, but if I were to venture a guess, what you're noticing over here are several of the metals that fall in the noble metal category. These are far to the right on the 3D series. So if you picture the periodic table again, far in the 3D series you have that d-shell orbital completely filled.

And those outermost electrons are then screened by all the other electrons in the system and very loosely bound. And so you can remove the electrons fairly easily. It's one of the reasons why these elements in that class have a higher conductivity, a lower resistivity. Yeah, question?

AUDIENCE: Copper doesn't seem that much worse than silver. [INAUDIBLE].

PROFESSOR: So, yes, absolutely. Copper doesn't seem so much worse than silver. So the contact metallization pastes to date have mostly been using silver. Copper can oxidize fairly easily. So that's one downside of copper.

Another problem with copper is that it's a very fast diffuser. It's very tiny. And so the elastic strain energy turn as it tries to move through a lattice is very small. And as a result, it goes deep.

So when you fire your contact metallization when you create the contact between your metal and your semiconductor underneath, you run the risk of having atoms diffuse into your device and hurting the efficiency, hurting the ability of the solar cell to collect carriers. We'll be more about that on Tuesday.

AUDIENCE: So it becomes an impurity.

PROFESSOR: Yeah, exactly. It becomes an impurity. In this case, unintentional. So just remember where the contact is right here in the emitter. OK, if it diffuses into the emitter, it's OK. The electrons at this point are the majority carriers. But if the metal diffuses all the way into the bulk, the electrons inside of the bulk in here are minority carriers. And they can be impacted by the presence of that copper there.

All right, so I wanted to get through at least one more point to really set us up well on Tuesday. We want to be able to calculate the Fermi energy of a solar cell as a function of dopant concentration, illumination condition and temperature.

So, so far we've really talked about the Fermi energy, the chemical potential inside of a solar cell in hand wavy terms. We've talked about general trends, about how as we add more electrons to our system, say by doping, we shift the Fermi energy up because the average ensemble energy of the electrons is increasing.

But now we're going to be calculating it and determining how to calculate it. So the question is calculating Fermi energy. So let's introduce a new concept here.

So far we've talked about an energy band diagram, and drawn our valence band, and drawn our conduction band, and of course the band gap in between them.

We've drawn the valence band and conduction bands as if they were just continuum density of states, as if they were just these blocks where electrons could pile in.

In reality we have what's called a density of states in the valence band and a density of states in the conduction band. If you want to think about electrons as cars, the density of states could be considered the number of parking spaces there are per floor in a parking garage.

As you increase the energy in the case of a parking garage, you increase your potential energy as you move your car higher and higher. In here, you would be increasing the energy of the electrons as you go higher and higher. The increase in the energy of holes as they go lower and lower.

So we have a certain density of states that is allowed inside of our semiconductor. And there's a very small density of states right at the band edge. And that density of states typically increases as you go deeper and deeper into the bands.

So now at absolute zero, and the person who probably knows more about absolute zero than anybody else here in this room is Kristy Simmons in the back, who for her Ph.D. would work on very low temperature experiments down into the, what, 10s of millikelvin range. 10s of millikelvin range-- it's very, very cold.

And then if you cool things down a lot, all the electrons that were excited will drop down, say, into the valence band right here. And what this is represented is as a filled valence band right there. And as you begin heating your system up, some of the electrons will have the thermal energy to be excited across the band gap.

So thermally excited electrons here represented in your conduction band.

[WHISPERING]

So we have a certain number of thermally excited electrons here up into the conduction band. Oh, and these carriers we'll call intrinsic carriers because they're not added by dopants. We're not adding anything to the semiconductor to create dopants to generate new carriers. There are intrinsic carriers because they came from the valence band, went up to the conduction band.

So if we plot intrinsic carrier concentration as a function of temperature, we see a curve that looks like this. And it follows this expression right here, which is called in an Arrhenius equation in a generic form. In this case it would be intrinsic carrier concentration as a function of temperature.

We'd have to substitute this big N here for intrinsic carrier concentration, some exponential prefactor, and then an activation energy, the activation energy being the energy needed to create that free carrier. The band gap energy in this case. The activation energy divided by $k_B T$, the $k_B T$ being Boltzmann's constant times temperature in Kelvin.

Now, if we plot the same functions that we just saw in the previous slide a little differently, we plot $1/T$ -- see $1/T$ right -- and there-- and we plot the log of this value. So again, log of this value, we can read the activation energy off of the slope of this graph.

So that's why you typically see Arrhenius plots plotted in this way-- $1/T$ versus log of parameter-- because you can read the activation energy straight off of the graph. It becomes very easy to see the carrier concentration.

So again, at absolute zero we have, here the valence band completely filled, the conduction band completely empty in our semiconductor. And the probability of occupancy of a state inside of our semiconductor is given by this box function right here.

Now let's look at what happens when we heat this up. When we heat the sample up, some of the electrons that were in the higher energy states are going to be excited. So they used to be here in lower energy states. They are going to be excited to higher energy states.

In the area of this little shape right here is equal to the area of that little shape right here because of conservation of number of electrons in our system. If we multiply this by the density of states, this is the density of states in the valence band minimized here at the band edges, and increasing as we go deeper into the bands

for the valence band and the conduction band. So we take our probability distribution function, multiply it by the density of states, and we get the occupied density of states in our semiconductor.

So now we see that there's some number of missing electrons that are now in the conduction band. They used to be in the valence band at very low temperature. But now as we increase the temperature, they've had the thermal energy to excite across given this probability distribution function. And these carriers are now free to conduct charge inside of our system.

So what do we do with this framework, with this understanding? Well, we can look at this function here and ask ourselves, what is the name of that function. It's called the Fermi-Dirac distribution, and it's given by this equation right here.

We'll notice in the Fermi Dirac distribution, we'll notice that this equation approximates to an exponential equation as we move further and further away from the Fermi energy, the Fermi energy being defined as this energy right here. If we move further way down here, or further way up here, this starts looking an awful lot like an exponential. Meaning this right here and this right here start looking like exponential functions.

OK, so let's do a quick little Gedanken experiment is a quick little thought experiment, about what happens when we heat up a semiconductor. And how would this impact, how these free carriers right here impact the noise, say, in a camera, in a CCD-based camera.

A charge couple display camera, which functions not so different from a solar cell device, except that it's biased a little differently than an actual solar cell device. But it could be like a pn-junction, p-i-n, to be more precise.

So we have our little camera right here, and the camera's typically placed inside of a liquid nitrogen dewar if we want very high performance. These are not your typical handheld cameras that you would use for shots in the street. These are cameras that we use in the laboratory for detecting very faint signals inside of our

semiconductor systems.

And we typically cool our cameras down. Why? Because we want to minimize the density of these intrinsic carriers. Because any photon that comes into our system, we want to be able to count it and to detect it. And not have to detect a very small signal on top of a large background noise of thermally excited carriers.

In a solar cell device, the intrinsic carrier concentration is typically much, much less than the dopant concentration. So the intrinsic carrier concentration matters less for our semiconductors than it does for a photo detector like this. And that's why, thankfully, we don't have to cool our solar cells with liquid nitrogen.

So in terms of have intrinsic carries, let's dwell there just a little bit longer.

Transistors are made of what semiconductor material to have less electronic noise to experience? OK, so what semiconductor material, germanium or silicon, would experience less electronic noise at room temperature?

And let me give you a hint. Silicon has a band gap of 1.1 eV. Germanium has a band gap of 0.67 eV. Which of the two is going to have greater electronic noise at room temperature?

AUDIENCE: Germanium.

PROFESSOR: Germanium because it has smaller band gap, it's going to be easier for the carriers-- we go all the way back here-- it's going to be easier for carriers to hop across because the band gap is smaller. Another way to look at it is on the Arrhenius plots, you'll have a higher carrier concentration because your slope is smaller, your activation energy is smaller.

And as a result, you'll have a higher-- if the band gap shrinks-- you'll have a higher carrier density here in the conduction band. Let me show you that in pictorial form.

So this is the silicon band gap. This is the density of thermally excited carriers for silicon. Now we shrink the band gap. Boom, we shrunk it. Same probability distribution function because we're at the same temperature. But now we have a

smaller band gap so we have a higher density of free carriers.

And true story, germanium was one of the first crystals to be purified during the early days of semiconductors, and silicon was following germanium. And silicon was ultimately chosen as the material of choice for transistors because the intrinsic carrier concentration of germanium was just too high for most applications.

And so you can see the intrinsic carrier concentration at room temperature of silicon is around 10^{10} whereas for germanium is around 10^{13} , three orders of magnitude higher. So, yes, question?

AUDIENCE: [INAUDIBLE]?

PROFESSOR: Yeah, it would be most costly. Absolutely. And so you do see solar cells like Concentrics is one company that's commercializing gallium arsenide-based solar cells. But they have to concentrate the sunlight into very small area devices because the devices cost so much to make per unit area. So they take cheap plastic and concentrate the sunlight down.

Yeah, and here's a gallium arsenide. The intrinsic carrier concentration is even less than that of silicon because the band gap is 1.4 eV instead of 1.1.

OK, so I think this is a good place to stop. I'm still not through all the material. Oh, we wanted to do one demo.

JOE: Yeah.

PROFESSOR: Do you want to do it first thing next lecture?

JOE: That's fine. We've got five more minutes. Ah, we do have five more minutes before 10 after. OK, why don't we do a quick demo then. So what we're going to do as Joe sets this up, is I'll verbally describe what's going to happen here.

We are going to take this-- actually let me go back to be Fermi-Dirac distribution function. This function right here, as we increase temperature, what happens to this? This will look more and more, shall we say, flat. It won't actually go flat, but it'll

become more and more diagonal opposed to box-like in function.

What that means is the density of carriers, the density of free carriers will increase with temperature. And because of the Arrhenius dependence here, we have an exponential increase of the number of free carriers with temperature.

Because the function right around this region right here, which impacts the electron concentration, the conduction band, this small portion of the Fermi-Dirac equation can be approximated by an exponential. If we have an increasing temperature, we should have a drastically increasing carrier density.

And let's see if that's indeed the case. What we have is a piece of intrinsic silicon just with a battery pack attached so we have a field across that piece of intrinsic silicon. Whoops. Here we go.

And we are going to apply, again, that field across the intrinsic piece of silicon. A certain current will flow through it. And then Joe has a heat gun, so he's going to heat up the silicon and see what happens as the Fermi-Dirac equation here is effected by temperature, we should have an increasing density of carriers in the conduction band.

So let's see if that's indeed the case. Can somebody read off what the current is currently measuring there on our current meter?

AUDIENCE: It's about 9.8 microamps right now.

PROFESSOR: 9.8 microamps. So this battery pack of 3 volts right here is it is forcing a current of 9.8 microamps across that little slab of silicon that is sitted right here. And so Joe is going to apply the heat gun, and if none of the contacts pop off, let's see what will happen.

So we expect the resistivity to go what?

AUDIENCE: [INAUDIBLE].

PROFESSOR: Down. And the conductivity to go up. All right, so let's see here. So what's

happening there folks? It's going up? So that's the --

JOE: So it went up to around 50 microamps, and can see it's dropping rather dramatically now [INAUDIBLE].

PROFESSOR: So the current that the material's able to pass through is increasing as a result of the increasing temperature, because you're exciting more carriers into the conduction band, leaving more holes in the valence band, and these are free charge carriers are able to conduct charge through the material.

Cool, OK. So with that, I will leave you, and I will return Tuesday. And Joe give a fantastic lecture on device physics as well since I will be at a kickoff meeting for a big NSF-related center in Phoenix, Arizona. But it will be great lecture. You won't want to miss it, and look forward to seeing you on Tuesday.