

MITOCW | 3. Light Absorption and Optical Losses

The following content is provided under a Creative Commons license. Your support will help MIT OpenCourseWare continue to offer high quality educational resources for free. To make a donation or view additional materials from hundreds of MIT courses, visit MIT OpenCourseWare at ocw.mit.edu.

TONIO

BUONASSISI:

Today we're going to talk-- or it's the first technical discussion of the actual solar cell device itself. We talked last class about the sun and about the nature of the solar resource. Today we're going to be talking about the interaction of light with matter. In particular, we're focusing on light absorption. This lecture could alternatively be called "Light Not Getting Absorbed" or "Optical Losses." Both are important, and both are related, as we'll see.

So this is part of the fundamentals of the course. Just to situate ourselves, we're here right now in the fundamentals, the first third of course. Then we'll talk about the technologies and the cross-cutting themes. And what we're going to talk about is extremely important because it allows us to understand the technologies. Once we begin discussing them and we discuss cost trade offs of implementing this particular technique for the way for it to absorb more light, we can appreciate how much we can quantify the impact of that technology development, and we could also later on ascribe a cost to it, to determine the total cost benefit analysis.

So conversion efficiency is really what dictates the performance of the device, the solar cell device. It's how the solar cell device converts sunlight, the input energy, to some usable output energy, which is in the form of electricity, typically, from a solar panel. so the electricity coming out of these leads, for instance, right here.

And that conversion efficiency, that simple equation, for most solar cells, can break down into the following. You have inputs. Sorry for the small font here. This reads solar spectrum. That's your input. Your output, which is the charge collection, it's a collective charge coming out of your device, and a bunch of steps in between.

So from the solar spectrum, we have to absorb that light, then we have to excite

charge within the material. Then that charge has to move around inside the material to get to the metallic contact on the front side. Charge separation has to occur for there to be a voltage. And finally, the charge collection process. And so the total efficiency of this device is the product of each of these individual processes.

And so if you're making a solar cell device, and I know about a third of you are based on your background surveys, this diagram right here will ring true to you. It's Liebig's Law of the Minimum. What this is representing is a barrel that has water being dripped into it. And the water will flow out of whatever piece of wood is the shortest.

And in the case of a solar cell device, you can ascribe a certain name to each of these pieces of wood. We'll learn what each of those are with time. But one of the big ones is optical losses. And the optical losses tend to be rather severe on some of our lab scale cells. So one of the easiest ways of boosting efficiency is simply to take care of your optical losses and to minimize the amount of light reflected or not absorbed into maximizing amount of light that's actually absorbed.

And so to do that, there are a number of standard techniques and some cutting edge research areas. And I'll attempt to give you a broad overview and survey of both, assuming, of course, you've done your background reading.

So the learning objectives, the first is to be able to calculate the reflectance in non-absorption optical losses of a solar cell. So this is essentially all the light that's not absorbed. We want to be able to calculate that.

The second is to describe the physical underpinnings and the implementations of four to five-- there are five here. I added one at the end. Four to five advanced methods of reducing optical losses. So there are technologies, techniques that we've used that we've developed over time that we can use to minimize the optical losses, to minimize the amount of light reflected or not absorbed inside of a solar cell device.

So to think of this pictorially, we can come up with the following diagram, where we

have some incident energy, in this case incident light. Here's our medium. Here's the amount of light that gets absorbed. Here's the amount of light that gets transmitted right through that does not get absorbed within the material upon passing through it. And there's a certain amount of light that just gets reflected off the front of your solar cell device. We want to, obviously, maximize this part right here.

So to begin, we give a quick review of light, the nature of light. This is going back to the particle wave duality of light. It will be useful alternatively to think about light as a particle, quant of light, or to think about light as a wave, depending on what light management technique we're going to be describing.

And in particular, I'd like to just highlight these equations over here. The notion that one can define the energy of a photon coming in, and that photon has a certain wavelength, a certain frequency, a certain wave length associated with it-- frequency and wavelength-- related, of course, by the speed of light, Planck's constant, and so forth.

So just to situate ourselves with broad numbers, so when we dive in and talk about spatial dimensions in relation to the wavelength of the light, we're in a situation where we can actually have a horse sense, a common sense, about it. The visible photon wavelengths are usually in the hundreds of nanometers. And the solar spectrum peaks somewhere around 550, just good numbers to have in mind. So this was that solar spectrum, the integrated solar radiance versus wavelength.

And the second point that is equally valid, we can describe the wavelengths of the incoming light, wavelengths of the incoming light λ , or we can describe the energies of the incoming light, this E_{ph} , the energy of the photons. So just to situate ourselves again, the visible photon energies are typically in a range of 0.6 to 6 eV, electron volts, again, with the peak of the solar spectrum at 550 nanometers, somewhere around 2.3 eV. Good.

So a simple thing to keep in mind, for those high energy particle physicists in the room, that when we're talking about visible light, we're interacting with a very

specific type of electron inside of our system. It's the valence electrons. These are the electrons that are typically most loosely bound inside of a system or I would say in the outer shells of the atoms within the material.

You're typically not interacting with core shell electrons with visible light. For that, you need x-rays. So this is just something to keep in mind. When we start looking at the wavelength dependence of absorption inside of a material, you can have, for example, in the visible range, a decreasing depth of penetration of the light with increasing energy, whereas with x-rays, it's the exact opposite. It's because you're dealing with different types of electrons and the material. So just to situate ourselves, I know we have a fair number physicists and chemists in the room. That's a message geared toward them.

Let's describe how light interacts with matter. And first off, come up with a few variables. Define a few units that will make it easier for us to understand how light is interacting with matter. And so here what I've done for you is placed the equation that describes the complex index of refraction of a material. What this means, effectively, you can think about this refractive index of the material as being comprised of two different components. For now, it's going to be fairly cerebral, but I'm going to reduce it to practicing in a couple of slides.

The real component of the refractive index-- and the refractive index is material-specific property. So if I have, for example, silicon or if I have silicon nitride or if I have a particular type of glass, it'll have a particular refractive index. It's comprised of a real component which indicates the phase velocity inside of the material and an imaginary component, which can be thought of as an extinction coefficient. And it is related to the attenuation of the light intensity as it travels through that material.

The measurements for those who have already taken measurements before on a spectroscopic ellipsometer, this is how you measure that parameter up there. We don't have to dive too deeply into that for the purposes of the class. It's just for background.

Why these values are important-- these values here describe the interaction of light

inside of a medium, inside of a material. And we use that information to calculate engineering relevant parameters such as reflectance of light off of a surface. So if we want to calculate what is the reflectance of light off of the silicon right here, I can calculate it by knowing these properties right here, by knowing the real and imaginary components of the refractive index of silicon, in this case.

And the reason that's important is because we want to minimize reflection off of surfaces. So I've come up with the first equation right here which is describing the reflectance from air to a solid, in this case, from air where the refractive index is 1 to a solid, namely, say for example, silicon right here or glass, which has a finite refractive index typically greater than 1. And so I have an equation here that describes the reflectance. Let me dive a little deeper into it and try to understand what exactly that equation is telling me.

So from the folks who have studied mechanics, many of you are mechanical engineers in the room, you may recall studying a problem wherein you have two springs that are connected. They have different spring constants, different stiffnesses, shall we say. And you excite a wave over here. It travels down. And when it reaches the interface between the two, part of the wave is reflected back and part continues through.

The speed of the wave is changing as it goes from one spring to the other, because the stiffness is changing of the springs. And the amount reflected can be described by this equation right here, which looks awfully like the equation right above it, which is describing the amount of light reflected off of an interface. And in reality, those ends have a very similar meaning, the n and the z .

The n , in the case of light, which is the real components of the refractive index. Mind you, this parameter right here, this indicates phase velocity in material. It could also be thought of very loosely as the ability of an electromagnetic wave coming into material to slosh those electrons around. Not exactly a stiffness coefficient, but it bears some rough resemblance. So this is a method for you to gain a foothold in this new area of understanding the refractive index of a material based on

something you've already seen before.

So I would advise taking this analogy as far as it will go until it breaks down. Push it as far as it goes until it breaks down. And you'll see at some point it actually does, but it's a useful place to start.

So I'm going to ask you a couple of questions. This might be rather new for a lot of folks. But the purpose of asking these questions is to get you thinking. And eventually we'll get to a point of heightened understanding as a result.

Tinted windows. So if you have a tinted window, what is typically happening at that tinted window? Why can't you see inside? What would you imagine is going on? So let me go back to this reflectance equation right here, this one.

How would you modify a reflectance off of a window, let's say? And let's drop the k's for now. Let's leave those aside and just focus on this parameter right here, n minus 1 quantity squared n plus 1 quantity squared.

What would increase the reflectance off of that window, if I have a larger n or a smaller n ? If I have a bigger n , I would get bigger reflectance. Is that right? r goes up? Well, you'd have to plot it out, I guess.

So if I change the refractive index of the material that I am working with, I can change the reflectivity off of that interface, off of that surface. So if I add a coating, for instance, to a window that increases the reflectivity, then the amount of light that is able to escape from the inside to my eyes decreases.

Now, with normal incident light, there is a beautiful symmetry involved. That is, the amount reflected off of one side is equal to the amount of light reflected off the other side. So just the same way that I'm losing the ability to see inside, the folks inside are also losing the ability to see out. But they can still see out.

Why is that? Why is it that with the same reflectivity they're able to see outside and I'm not able to see in through that tinted window, through that car, for example, that's driving by with the tinted glass? Why can't I see insight but they can see out,

what's going on?

AUDIENCE: [INAUDIBLE].

TONIO Yeah, I hear somebody.

BUONASSISI:

AUDIENCE: The light on the outside is much stronger in terms of an absolute amount of light being reflected.

TONIO Yep, exactly. So yes, the reflectivity as a percentage is the same for both parties.

BUONASSISI: But the amount of light, the magnitude of the light from the outside, is much, much greater than it is on the inside. Can anybody give me just a gut sense. If I'm outside on a sunny day, how much brighter is it outside versus inside right here? Factor of?

AUDIENCE: 100, maybe?

TONIO Maybe a factor of 10, somewhere in that range. And so when you walk outside on a sunny day, you'll notice your eyes adjusting a little bit. It'll take a minute. And when we walk back inside, it will take a minute here for your eyes to adjust as well. That's because of the difference in intensities.

BUONASSISI:

So if you imagine being outside of that car and having 10 times the amount of light being reflected, that small amount of light that is actually transmitting through the window from the car to the outside world will be washed out by the amount of reflected light. Whereas if you're inside the car, there's a lot of light coming through that window, even though a lot of it gets reflected, there's still a sizable amount coming through. And the amount of light that gets reflected off that window of the internal light is small in relation to the outside light that is being transmitted through that window. So it's important to think about these processes, both in terms of their reflectance as a percentage but also the magnitudes of the light involved.

What if that glass pane was flipped around? Would it change anything? If I took that glass and just flipped it, would it change it? What about the symmetry argument, that the amount of light is reflected, the r reflectance, is the same from both sides?

AUDIENCE: Is it not the case that there's a coating on the outside? So if the change in refracted index is an abrupt change from the outside looking at this coating. Because on the inside, you're going through some median glass, which is more index matched than the outside.

TONIO
BUONASSISI: Yeah, so I would advise you to actually walk through that calculation. And what you'll find is it winds up being the same. And it's because you have to take all reflectances off of all these interfaces into account. There are, in fact, three interfaces-- the air, the glass; the glass, the anti-reflection coding; and the anti-reflection coding, the outside.

This, of course, without getting into quarter wave effects, which we'll get into a minute, there's some higher order effects that deal with phase change, which we haven't discussed right now. We're just assuming that all of these layers are well above the wavelength of the light in terms of thickness and that these equations, these linear equations, are valid. Very good.

So this is just to get us situated with this new concept of reflectance-- and again, very powerful equation. Keep in mind that this is a very specific form of the reflectance from an air into a solid. If you're going from a solid into a solid, you'll add your n_1 and your n_2 , depending on what material going into and what material are coming from. So we're happy to walk through that perhaps during recitation.

OK, so what we're going to do now is we've talked about reflectance off of surfaces. What I'd like to do is talk about a light absorption inside of a material. So let's imagine that through the techniques that we're going to be discussing later on in lecture, we manage to minimize the amount of reflectance off the front surface. And now the light that's incident on the material is actually going to go inside and get absorbed by the material inside.

We need to be able to understand how light gets absorbed inside of matter. And for that, we apply a very simple formulation inside of this class, which is called Beer-Lambert's Law, which is a very simple yet very powerful formulation that describes not only the interaction of light with the solar cell material but also light through the

atmosphere, light the water, many other forms of optical absorption.

And for that, I'd like to call Joe up for a quick demo that he put together that will allow us to actually plot out Beer-Lambert's Law. And I'd like to start with what I would think of as a simple hypothesis. What we're going to be doing, and Joe will explain this a minute, what we're going to be doing is taking many sheets of material. This is just some polyethylene material, a little bit discolored. And we're going to shine a laser down on to this photodiode. The photodiode current will be measured by this little current meter right here. And we'll be inserting these panes of plastic in the middle.

And as we increase the thickness of the plastic, applying good pressure in between to minimize the reflectance, the air gap, for instance-- as we increase the thickness of the polyethylene, we will plot the total transmitted light as measured by that photodiode. And so I'm going to come up with a hypothesis of what's going to happen. I'm going to say that if we double the thickness of the polyethylene that we're going to halve the amount of light going through. And if we triple, we're going to reduce it by a third. And if we quadruple, we're going to reduce it by a fourth. And let's see if the hypothesis is correct. It's not. But we're going to test it.

And it's a logical thing you might assume. And then we'll walk through a derivation that will correct our missed logic. So go ahead, Joe. Take it away.

JOE:

Sure, so if you guys want to play along, that's fine too. I know there's lines in the side of your notes. You can make little graph paper, and it comes out looking really nice. So basically what we have is a laser pointed and a photodiode. And the current out of this photodiode is directly proportional to the light hitting that photodiode. And it has a quant efficiency, which we're going to learn what that is in a few lectures, of about 60%. So of the photons hitting it, you'll get a certain number of electrons out, and that ratio's 60%.

And so first of all, we're going to see what it's like, what the power of our-- yeah. So right now we're getting about 1.32 milliamps. So Tonio's going to plot that. Then as we keep increasing and put one layer of polyethylene, that drops to 0.75.

TONIO So before we go onto the next one, what do people predict the next dot is going to drop the total intensity to? Is it going to be kind of a linear line like that? You'd expect it, right, because you're doubling it. So you'd expect the intensity to drop by another factor of 2. Why not? Where am I getting a mistake here? Somebody says exponential. There's kind of this sense that it should be exponential. What don't we add some more filter in front, and we'll see what exactly this comes out to be.

BUONASSISI:

JOE: This is with two.

TONIO Two.

BUONASSISI:

JOE: Now we get 0.43.

TONIO 0.43. OK. All right. Why don't we do one more just to see what sort of trend we're getting. Still 0.26.

BUONASSISI:

JOE: 0.26.

TONIO 0.26. Ah, wow. OK, so it didn't go in a straight line. It's actually starting to curve down. Cool. OK.

BUONASSISI:

JOE: And we keep going, 0.16.

TONIO 0.16

BUONASSISI:

JOE: 0.10

TONIO 0.10. OK. Look at that. What sort of curve is it? Exponential. It looks like one at least. And we can test whether or not the hypothesis is correct by an exponential fit, which happens to match pretty well. So--

BUONASSISI:

JOE: Now one other quick thing you notice is that if you look at the fit, the first point's a little bit higher than that fit. Anyone have an idea of why that might be the case? What are we ignoring in this experiment?

AUDIENCE: The reflection is [INAUDIBLE].

JOE: The reflections, yeah. So in the first one, you reflect light, and certain amount gets transmitted through that front surface than absorbs. And so right now we're ignoring this is $1 - r$ component. But it's so small that it really doesn't matter for this experiment. These things don't reflect a lot of light.

TONIO Cool. Well, why don't we give a quick rondo.

BUONASSISI:

[APPLAUSE]

Well done. Can I grab one of those?

JOE: Absolutely.

TONIO This is going to be important for the immersion scattering demo.

BUONASSISI:

JOE: Oh, sure.

TONIO Yep. Cool. OK, so we notice that we have some exponential character to be decay
BUONASSISI: of the intensity of the transmitted light through a medium. And the amount that's absorbed is following another trend, which is just $1 - r$. So it's the amount of light that's absorbed is following a curve looks something like that.

OK, so let's look through the formalism of Beer-Lambert Law and try to understand why it is that we come up with that exponential function right here. So if we assume that light is coming in a medium and light is decaying in some function to that medium and a certain amount of light is transmitted, we know, of course, from our little experiment that it follows some exponential function. But how do we justify that to ourselves?

Well, first off, we're going to ignore reflections off the front surface. We just talked about them. We can calculate them. Let's leave that aside for now as a parallel

calculation. We're just concerning ourselves with what's happening inside of the medium.

So if we assume that the change of intensity within that medium in each little delta thickness is going to be affected by some sort of scattering intensity within the medium-- and this sigma here can refer to a variety of processes. That can refer to absorption events that result in the generation of free charge. They can refer to absorption events that just heat the material up and generate phonons, so lattice vibrations.

There are a number of processes embedded in the sigma, and that's why this formalism is so powerful, because it doesn't care really what the physical nature of that sigma is. It just matters that there is an absorption per unit distance thickness traveled inside of the material that is constant throughout the entire material. So the sigma here is independent of thickness throughout.

And then as you integrate through, you wind up with that beautiful exponential function at the end, the sigma I times n . We collapse the n and the sigma here into an alpha. That alpha is an absorption coefficient. The I is the total length or the total thickness of this medium right here. So if we increase the total thickness, we're going to decrease the total amount of light coming through via that exponential function.

The alpha, on the other hand, is not a geometric parameter. It's an intrinsic material parameter. To put that in terms of mechanical engineering, for many of the mechanical engineers in the room, you recall from solid mechanics, 2001, that you have geometric parameters that determine, say for example, structural response and intrinsic material parameters like Young's modulus that determine the structural response of a system. And likewise in here, in the optical, shall we say, response, we have a fundamental intrinsic material parameter, α , the absorption coefficient, and the geometric parameter, l , which is the thickness.

And the beauty of this formalism right here is that we can measure, experimentally just like we did right there, our alphas for materials. And so from an engineering

point of view, we don't really-- to first order, it doesn't really matter what sort of scattering or absorption process is happening inside of a material for us to calculate the amount of transmitted light. We just need to know the alpha. We need to know the optical absorption coefficient.

This alpha will vary as a function of wavelength inside of a material because, obviously, the physical absorption mechanisms are varying as a function of wavelength. The resonances with different electronic states within the material, that light, depends on the energy of the light, depends on the frequency. So there's a wavelength dependence.

Yeah, and that general equation is the same one that drives the reduction of light intensity as it travels through the atmosphere. So if we increase the atmospheric path length, we'll be reducing the amount of light that actually reaches the surface of the earth. That's at air mass two or air mass three, there's less solar flux coming down than at air mass one or air mass zero.

The alpha, obviously, is going to be very different for our atmosphere than it was for these little polyethylene sheets. Because the nature of the scattering and absorption processes are very different for the atmosphere than it is for here, the density of the material and so forth. Any questions? Yes?

AUDIENCE: What was n ?

TONIO BUONASSISI: So the n , there's a certain scattering intensity, and then there's a certain number density, for example, of the material. So this alpha here is, I would say, density neutral. What we've done is we have the alpha encapsulating the physical parameters of the material and the absorption processes all in one variable, very nicely and succinctly. And the only geometric parameter that is of essence is really our l .

AUDIENCE: It's called an absorption coefficient, but is it more of an extension coefficient, really? Because it's kind of confusing that it includes scattering.

TONIO The extension coefficient, absorption coefficient, yes, in solar research, when we

BUONASSISI:

talk about an absorption coefficient inside of a material. Oftentimes we're operating in a wavelength regime of light wherein free charge is excited. But we can also keep increasing that the wavelength of light, say, out to 10 microns, very long wavelength light, very low energy light. And that can excite free carriers within the material-- carriers that are already excited, essentially excited them further, without generating any new free carriers inside of our material. So we won't necessarily be generating more current by shedding light on it but will be absorbing light, nevertheless, in our material.

So it's important to keep, let's say, the underlying physical processes that are occurring distinct. Later on we'll get to that. For now, it's important just to, I would say, recognize that we have an exponential decay of the intensity of the light as it goes through the medium. And then over the next few classes, we're going to get to exactly what physical processes are going on. But I'm glad people are asking those questions.

OK, so again, alpha is a function of the wavelength of light and the property of the medium. And let me just flash up some curves of alpha versus wavelength so people have some exposure to those numbers. Again, we're talking about an energy range quite broad here, from about 6.2 eV to 0.62 eV. The visible wavelengths range would be somewhere in this regime right here, so a very limited band. And the infrared out here, ultraviolet over here, and we can see for a variety of different types of materials what the absorption coefficient is.

So here we have germanium. The red would be crystalline silicon, gallium arsenide, indium phosphide, and amorphous silicon. So let's do a little quick calculation just to get us a little limber. We're starting to get into the semester, so the energy level starts going down. What we're going to do is we're going to pick a value, say 550 nanometers. Why did I pick 550 again? It's near the peak of the solar spectrum, right? It matters.

And we're going to look at two different materials. We're going to look at silicon, and we're going to look at gallium arsenide. And we're going to calculate the thickness

necessary to absorb 90% of the incoming light at 550 nanometers. What I want you to do is turn to your neighbor, and once again with your neighbor, calculate what thickness of material, what thickness of gallium arsenide, the yellow curve, and what thickness of silicon, the red curve, is necessary to absorb 90% of the incoming light at 550 nanometers. Why don't you go for it? I'll give you, say, a couple minutes.

To make sure people are setting this up right, I divided by i_0 to absorb 90% of the light, that would be 0.1, 1 minus 0.9. OK, so as you're finalizing your calculations, I just wanted to make sure set this up right. Again, if we're absorbing 90% of the light, it means only 10% of the light is going out the other side. That means their i is going to be $1/10$ of i_0 or i divided by i_0 is 0.1.

And then we would take the log of both sides, typically, and solve for our l based on the alphas that we have here. Again, units of alpha would be in inverse centimeters. And so the l 's that you obtained, let's go for gallium arsenide first. Did anybody manage to walk all the way through that calculation?

AUDIENCE: 20 micrometers.

TONIO 20 micrometers. For our gallium arsenide or for our silicon?

BUONASSISI:

AUDIENCE: Gallium arsenide.

TONIO Gallium arsenide. Did anybody get any other numbers for gallium arsenide.

BUONASSISI:

AUDIENCE: 0.4.

TONIO 0.4 microns. Yeah. That's sounding more in the ballpark. Anybody else?

BUONASSISI:

AUDIENCE: 23.

TONIO 23 as well. So I'm getting-- I would have guessed that the number would rather

BUONASSISI: small for gallium arsenide, so something in the range of, say, a micron, in that

order. Why don't we give folks enough time to walk through-- I know I rushed you on the calculations here. We have material to get through. And I wanted to see you perform under pressure.

But how about the silicon? Is it larger or smaller? Let's just for order of magnitude first and the general trend and then try to pick up the precise number. For silicon, crystalline silicon that is, with an optical absorption coefficient and order of magnitude less than gallium arsenide, is the thickness needed to absorb the same amount of light going to be greater or smaller?

AUDIENCE: Greater.

TONIO Greater. By an--

BUONASSISI:

AUDIENCE: Order of magnitude.

TONIO Order of magnitude, brilliant. OK. So whatever number you got for your gallium, **BUONASSISI:** arsenide you could translate it fairly easily. All right, so that was at 550. And there's a lot of solar radiation right around 550, so the numbers that I have on the top my head work somewhere out to be on the order of a micron, a little less for gallium arsenide, somewhere in the order of 10 microns or so for silicon out here.

But now if we go out to 800, there's still a lot of solar flux out there. If you recall the solar spectrum, the folks who have been doing their homework, there's still a lot of flux out around 800. As a matter of fact, it continues going all the way out to here, although decaying intensity a la black body.

And at 800 nanometers wavelength light, the optical absorption coefficient is dropped by about an order of magnitude relative to the peak of the solar spectrum. And that's why most of these solar cells that you see of crystalline silicon are on the order of 100 microns, typically a little thicker for some technological reasons, which we'll get to, make it difficult to handle very, very thin stuff.

But if you just assume one pass through the material, you'd need about that

thickness to absorb a lot of the light. And I'll pass around some of these materials right here just so you can get a sense of how thick they are. Here we go. Actually, here's what I'm going to do. I'm going to take out the big pieces and leave the small ones in here that are already broken. And you can actually pick them up if you like.

Just be aware that these little pieces of silicon are-- silicon's brittle material. It's like glass. So if you have a little shard of silicon, it can poke you just like a charge of glass can. So treat it with the same amount of respect that you would a very, very thin piece of glass.

But you can see here that if you look at the thickness of these materials inside of that little bin, these are small shards of silicon solar cell wafers. Their thicknesses in the order of 100 microns, those are particularly thin. You have other solar cells that are 170 microns is typical thickness for silicon. And for gallium arsenide, you can deposit thin films that are on the order of a micron thick or less. You can go down to a few hundreds nanometers and still make-- actually the record efficiency of gallium arsenide solar cell is a few hundred nanometers thick.

And our calculations right here assumed one pass through the material. That's all we gave the light. We only gave one chance to go through the material and get absorbed. What could you envision would increase the total amount of light absorbed? What could you do to your solar cell device to increase the total amount of light absorbed inside of it?

AUDIENCE: Put anti-reflective coating on it.

TONIO You could put anti-reflective coating on it. Let's do something much more simple.

BUONASSISI:

AUDIENCE: Put reflective coating on the back.

TONIO Reflecting coating on the back, absolutely. Yeah. So if the light goes through the

BUONASSISI: solar cell and doesn't get absorbed, that 10% of the light that didn't make it, that's going to get reflected back. It's going to get another chance to go through. So if you absorb 90% of the light on the first pass, you'll absorb 99% of the light on two

bounces, right? Or in one bounce, rather, and two trips, two optical path links through the material.

And so the term optical path length is a very important term here, because the optical path length does not have to be the thickness of the material. Ideally, the optical path length through the material is much, much thicker than the actual material itself. And over the next few slides, we're going to learn how we engineer that.

So methods to improve optical absorption- generally, these are called light trapping. Not all of these entail trapping the light. Actually, most of them do. We also call them light management as a more general term that includes reflection and absorption inside of the material.

So the very simplest thing we can do on the front surface-- so what we're going to do is take this step by step, as light goes into the solar cell from the front side, we're going to take step by step, what can we do to improve the amount of light that is absorbed? The first thing that we can do is texturize our front surface. If we don't have texture on our front surface, if it's absolutely flat, what we call specular surface-- specular coming from the root mirror. In Latin languages, for example, Italian specchio is mirror.

So a flat silicon substrate, a specular surface, would reflect some finite amount of light. And we can calculate that now because we know that it relates to the real component of the refractive index of the material. Now if we texturize our surface-- this is representing kind of a pyramid type texturization. If the light comes in and some fraction doesn't go into the material-- there's some component of that ray that's going into the material over here, but we're ignoring it in this drawing. We're just focusing on the lights, the rays that get reflected. That beam that gets reflected off, instead of just going back out toward the sun, it's now going toward the material again. So it has a second chance of getting absorbed.

So you just went-- for example, let's say if you have a 10% reflectivity on the surface, you went from a 10% reflectivity over here to a 1% reflectivity over here.

Because now you have the total amount of light that gets reflected is $1 - 0.9^2$ as opposed to $1 - 0.9$. In this case right here, the amount of light that gets reflected, assuming it's 10% reflective, would be $1 - 0.9$, so 10% of light. And over here, the amount of light that gets reflected would be $1 - 0.9^2$, so 1% instead of 10%.

So texturization increases the probability that light will enter the device. And what it also does-- this is a secondary benefit-- is it increases the path length, the effective path length, of the incoming light. And the way to understand that particular phenomena is called Snell's Law. Well, even in the absence of Snell's Law-- no, let's go there. Let's go there.

So we have a texturized front surface. What's happening? Well, as the material goes from one medium to another, the refractive index changes. We discussed this right at the beginning of lecture. So the way in which the electromagnetic wave oscillates the electrons instead of the system is changing from one medium to another, let's say from air into the solar cell device from air into our silicon, for example, right here.

Now, we can ascribe the refractive indices to air and to our silicon like so. And the light path will obey what is called Snell's Law, which is the product of the refractive index and sine of that angle, the angle relative to the surface normal. So a simple way to think about this is when the light goes from a low index of refraction medium to a high index of refraction medium, light bends toward or away from the normal?

So if I'm going from air into silicon, light would bend toward the normal, right? So here my θ_1 is going to be greater than θ_2 . My light has bent toward the normal, if this is my silicon and this white stuff over here is my air. So light came in. It encountered the surface. The θ_1 was defined as the angle of the light relative to the surface normal. That was my θ_1 . My θ_2 is going to be given as the ratio of the refractive indices. And because the refractive index of silicon is going to be greater than that of air, light would bend toward the normal.

And so what I have on a macroscopic view over here, if this is my surface texture,

light was coming in, it's now bent. And so the effective optical path length is now larger than the thickness of my device. It's kind of cool.

So there are two benefits to texturizing your front surface. One is you have an additional pass, additional bounce, an additional encounter with the material. So that reflected light gets another chance to go in. And the second benefit is that you're able to increase the optical path length by the delta in refractive indices and the fact that the path of the light will be Snell's Law.

Now another really interesting aside of Snell's Law is that if light is trying to go from a high index medium to a low index medium, and if it's coming in at a very oblique angle like this, if you run through Snell's Law, you don't get an angle coming out. It actually falls along the surface or actually bounces back in most often, depending on the angle. And you have what is called total internal reflection, which is this case right over here. That little bounce, that friendly bounce, of the light that went in bounced off the back side and then was reflected back in. That's a total internal reflection event.

And that happens in solar modules. Right here, when light comes in, bounces off of the white back skin right here, and then gets scattered off at an angle, it can have a total internal reflection off of the front surface glass and have a second chance of getting back into the solar cells inside. So that's one of the reasons why you see this white spacing, the white colored material, in between the cells, is that the light gets reflected off of there. It doesn't make it very aesthetically pleasing. You might want it to look all black. And if you do want it to look all black, what would you do instead?

Instead of changing the back skin, what other component might you change?

AUDIENCE: The front.

TONIO The front, right? You might change the nature of the anti-reflection coating on the
BUONASSISI: glass. We'll get anti-reflection coatings in a minute.

So even if the panel looks black, there are some really aesthetically pleasing solar panels out there that look completely black. They may still have white back skin, but

the glass is just very good at absorbing that light and preventing it from escaping.

OK, so to engineer front and back surface reflectances, you really have to carefully select your refractive indices and your materials if you put on either side. And it's very important-- extremely important. To make a long story short, the record efficiency solar cell that was announced this past year in gallium arsenide was achieved because of good light management. And we'll explain how that came about perhaps towards lectures, maybe lectures eight or nine.

So I'm going to play a little game with you, which is to look at a swimming pool. This is a pool filled with water, which is refractive index 1.3. Air is 1. And so that's the normal view, what we have. Light bends toward the normal, right? And so you're able to look down inside the pool that stuff that is not in your line of sight, not in your direct line of sight. That's because when you look down, the ray of light is traveling like this and it bends toward the normal and likewise symmetric.

So you're seeing material down there. What change of property would give you these two images over here. Let me give you a hint. In one of those two images, the refractive index of the medium inside the pool is not 1.3. It's 0.9. It's 0.9.

And in another one of these two, the refractive index of the medium is actually going to be negative. We'll call it a negative refractive index material, a negative index material. So which of these two do you think is which? Why don't you turn to your neighbor quickly and chat about it without peeking at your lecture notes.

So let me walk through, as you begin honing in on your answers here. Think about what would happen to the reflectivity of that front surface of the water and what would happen to the angle that the light travels, or the angle of refraction of bending, shall you say, as the light goes from one medium to another. So if we go to a refractive index material of minus 1.3, will we change the reflectivity at all?

It depends, but the answers here are shown, for this particular system. It would require sitting down and walking through the equations, but in essence right here, with the pool filled with the negative refractive index material, you're really affecting

the angle at which light is coming out of the pool. Here you can see the corner of the pool, which you shouldn't even be able to see. It's just that the light traveled this way and then came back because it was a negative refractive index material. Light actually did something like this, zoop, zoop.

AUDIENCE: What's in the pool?

TONIO
BUONASSISI: Oh, that's just a corner. So what is in that pool? That is a computer generated graphic. This is not a real pool. There exists negative refractive index materials but not in that volume yet. These are relatively small things and very much a study in fundamental science.

So in this case right here, we have less of an acute bending of our angle of light. So we don't get to see quite as many features right here toward the edge. And the reflectivity has changed as a result of having drastically modified our reflection condition.

AUDIENCE: Why does the reflectivity seem to have gone up and the index has gone down?

TONIO
BUONASSISI: In that particular case? I think what they were getting at-- this is coming off of an SPI website. I think what they were getting at is mostly just a change in the reflectivity. So they were trying to emphasize that you were modifying the reflection off the surface in addition to the angle at which the light was exiting the material.

I'm going to come back to Snell's Law in a minute. But for the time being, I want to move on to the next concept here, which is Lambertian reflector. You'll hear this topic or this word thrown around quite a lot in the solar cell community. And it's used rather liberally to mean a lot of things. Although in optics, it has a very specific meaning.

So I'm going to show you that very specific meaning and then describe for you what it has very loosely come to mean in the solar industry. So a diffuse Lambertian reflector will follow a reflectance that follows a cosine theta dependence. So if you have light coming into a sample, the surface normal, and the outgoing light ray form an angle theta. And if the two are perfectly aligned, you get a lot of reflectance off of

that angle. If the two are perpendicular to one another, you get zero reflectance in that angle. And so the reflectance parallel to the surface here is zero. In everywhere in between, the magnitude of reflectance is varying as cosine theta. That's the, I would say, pedantic definition of an Lambertian reflector.

Often in the solar industry you'll hear people, probably because of a lack of optics background, just call any randomly reflecting surface a Lambertian scatter. It's a very loosely used term. And it is wrong by the book, but nevertheless, it's one of these things that live on in our industry.

So the difference between a specular reflector, the one that we've just been analyzing right now, and a Lambertian reflector, is that typically the way these are made is that you do have a random texture on your surface. And that's probably where the origin of this misunderstanding comes about. We don't get a random reflectance of the light coming off, but the surface itself can be rather texturized.

So, for example, if you suspect that this little material right here might behave like a Lambertian scatter, you might put it inside of a tool and rotate the angle and measure the amount of reflected light as a function of the angle to determine whether or not it follows this cosine theta dependence. And the reason it's important is because the back skins of our solar modules can quite often be Lambertian scatters. And we have a certain amount of light that comes off at some angle here that will get trapped by a total internal reflection inside of a modules.

So if, instead of having macroscopic pyramids right here, you had very, very small pyramids-- still not sub-wavelength, but smaller features, for example, the texturization on the back skin right here. An it managed to scatter the light at a particular angle that got caught by total internal reflection. Macroscopically, we might be able to describe the scattering behavior of that surface as Lambertian scatter. But it's those waves, those rays that are bouncing off at those large angles that are causing the total internal reflection event.

And so the notion of a Lambertian scatter is important on the backsides of solar cell devices. We would obviously wants to even change the scattering profile. We

wouldn't want necessarily specular reflectance. We might want to maximize the amount of light reflected off at particular angles. And there is, of course, research being done to figure out how to make light do that. I'll show you one example at the very end of lecture, a paper that was just published in *Science* last week, as an example.

And so these scattering centers off the backs of the rear sides of cells would operate more or less in the following manner. You'd have incoming light. Let's ignore front surface texturing for now. Let's just focus on the backside. And if you have some random, as we call it, a random reflector, a randomly texturized reflector on the back that reflects off in, say, a Lambertian fashion, you'll have some fraction of that light scattered off at an angle that is large enough relative to the surface normal that it is trapped by total internal reflection.

And you don't only have to texture your back skin. You can also texture the bus bars. The bus bars are these little metal wires right here that are collecting the charge from each of the solar cells. And they're connecting essentially the front side of one cell to the backside of the next. If you want to think about it as the cathode to the anode, cathode to the anode, cathode to the anode, stringing all these cells together in series.

And this metal right here is just really shiny, and it's reflecting light right back out into space. What if we instead were to texture that metal so that when laser light shined on it a certain amount would be reflected off at an angle and then caught by total internal reflection. And that's exactly what you're seeing right here.

The light bounced here on a textured bus bar, bounced off of the glass more or less around here halfway, and then got a second chance to enter the cell over here. Obviously some of it is reflecting off so we can see it. But a lot of it's going in. And that little innovation right there, which was developed in the building right next door by Professor Ely Sachs, can gain module performances somewhere on the order of a few percent relative.

So that might not sound like a whole lot, but if you're a \$100 billion industry, 1% is a

lot of money. So it does add up. So that goes back to the total internal reflection.

So there is a limit to all of this texturization. There's a limit to how much we can trap light simply by modifying or corrugating the surfaces to enhance the optical path length with these types of bounces using Snell's Law and of course the general reflectivity equations.

And a gentleman by the name of Eli Yablonovitch, who's now a professor in Berkeley calculated these parameters I think back in 1982 and came up with an upper limit to the optical path length. He, after a long series of calculations, derived an expression for the maximum increase of the optical path length due to surface texturing, which was $4n^2$. And the Yablonovitch limit to this day is a pretty good litmus test for the ability of a material to trap light.

So if you have silicon, for instance, with a refractive index of, let's say, in the infrared some around 3.6, your Yablonovitch limit is around 50, which means that you can increase the optical path length by a factor 50, relative to the thickness of your material. If you have an organic material, which has a refractive index typically of around maximum 2, then that would be squared, 16, somewhere in that range. You can increase probably in the order of 20 the optical path length inside of the material through texturization.

So this is a useful parameter for those who are doing research in photovoltaics, the graduate students especially. And so I think the graduate students will have a question at some point on the Yablonovitch limit. And so that's a useful parameter to keep in your mind.

Let me touch upon a few other forms of trapping light. We've so far just assumed that light behaves like a continuous wave, doesn't interfere with anything, doesn't interfere with itself. Now we're going to discuss some anti-reflection effects which derives from the notion that light is a wave and can constructively and destructively interfere.

What we have right here is a layer of another material with a refractive index, say

n_1 , which is in between our n_0 which is at air and our n_2 is the absorber material, let's say the silicon. So we have a grading of refractive indices going from air, our anti-reflection coating, to silicon. And right over here we have a certain thickness, d_1 . And over here we have a certain thickness, d_2 .

So what is happening in these two images? Let me show you with another, a little bit more clear figure, coming from our beloved Wikipedia, and then go back to that other image right there. So what's happening is we have an incoming wave that for some reason is ignoring Snell's Law. It's beyond me. But anyway, the wave is going in a straight line. It should be bending toward the surface normal, obviously. But we have reflections off of this interface and this interface right here.

And because the thickness of this layer is in the order of $\lambda/4$, that means that the wave that's going in will be phase shifted relative to the wave that's reflected off the front surface, first by $\lambda/4$ then 2 times $\lambda/4$, in other words, $\lambda/2$, which means that the two waves are out of phase by $\lambda/2$, which means that they will destructively interfere.

The peak will be at a trough. The trough will be at a peak. So the two waves will be going to be destructively interfering when they come out. If you add these two together, due to the wave nature of light, you get suppressed reflectance.

And that's a really interesting property. You can begin varying the thickness of this layer, and of course changing the nature of the reflected light. You can constructively interfere if you like and enhance the amount of reflected light as a result of this interference effect. Obviously, in most solar cells, we want to suppress reflection. And so we go to great lengths to make sure that this thickness as well as the refractive index of the material is optimized for a particular system.

And so without going into the hairy math, to calculate this right here, it's definitely possible. It's definitely something that should be done. And I believe the graduate students have it assigned. It's the very last problem in the homework.

But for a very simple kind of conceptual understanding that is wavelength

independent, if we want to minimize the reflectance at a particular wavelength, let's call it at a λ_0 , which is the photon wavelength at the peak of the solar spectrum, we have to design the thickness of our anti-reflection coating to satisfy that equation right there, essentially λ_0 over 4. That's the phase shift we want upon one pass of the anti-reflection coating so that two passes, when it goes through and then back, it's phase shifted relative to the surface reflected light by λ_0 over 2, divided by n , n being the refractive index of the material. Obviously the frequency of light is staying the same as it goes from one material to another. But the wavelength would be changing.

So that's why the n parameter appears right here in this equation. The t is the thickness of the optimal anti-reflection coating thickness. So just to give us a sense, kind of an estimate, and to give us some confidence in these engineering methods, what I'd like you to do is to calculate the thickness of an ideal anti-reflective coating. This anti-reflective coating right here on these cells-- I apologize, they also have the metal on the front, so it's a little difficult to distinguish between the two.

But in my right hand, this one, I have a piece of bare silicon. And you can see it's rather reflective. In my left hand over here, I have a piece of silicon with an anti-reflective coating as well some contact metalization on the front. So that's why you see those grid lines. But it looks very blue. It looks very blue because the cell is absorbing very well at the peak of the solar spectrum which is in the yellow.

So calculate for me what is the optimal thickness of an anti-reflection coating of silicon nitride? And we'll give it a refractive index of, say, 2.1. Let me see if those numbers make sense, so refractive index of silicon nitride somewhere around 550. Let's call it 2, just make our lives simple. And the peak of the solar spectrum we'll again call 550. So why don't we run the numbers quickly. What should that thickness be?

AUDIENCE: Tonio, I'm sorry, could you repeat the constant again?

TONIO Sure. So the n , the refractive index, is going to be around 2 for silicon nitride. So

BUONASSISI: we're going from air, which is around refractive index one, to silicon nitride, the

silicon. And the peak of the solar spectrum, our λ_0 , which is the photon wavelength at the peak of the solar spectrum in vacuum or in air, is 550 nanometers. So what thicknesses are folks coming up with? Order of magnitude.

AUDIENCE: 70 nanometers.

TONIO BUONASSISI: 70 nanometers. That's almost spot on to the actual thickness, to somewhere on the order between 70 to 80 nanometer typically.

You're telling me that something that is $1/1,000$, the thickness of my hair, is deposited on the surface of this wafer and is absorbing all this light? That's pretty cool. And it's not absorbing the light. The anti-reflective coating is not absorbing the light, which is really important. We want the solar cell underneath it to be absorbing the light. The anti-reflection coding is enabling the light to be absorbed because it's suppressing the reflectance. The reflected modes at that particular wavelength are suppressed because of the destructive interference. That's cool. I really get a kick out of anti-reflective coatings.

So they're 70 nanometers thick. And you gain quite a lot in terms of cell performance. I'll show you some slides to drive that point home in a bit. This is really really briefly-- I'll post these slides online so you can have access to them. If you use the matrix transfer method, as described beautifully in [? Gonchen's ?] textbook, you can calculate the amount of light reflected across a broad spectral range for a given thickness of anti-reflection coding.

So what we did right now was to calculate a suppression of the light at a particular wavelength. But you can also calculate with the tools that are available to you the reflectance of your particular device over a broader wavelength. Range and that's pretty cool because now you can begin, say, multiplying this function right here against your solar spectrum and begin to calculate the total amount of light entering your sample and the total energy entering your sample. Equations, brilliant.

The important thing to note here is that it really, really matters. This is silicon under glass right here, for example, typical solar cell material in blue. It's better than the

bare silicon. Why is it better than the bare silicon, silicon under glass? Glass has a refractive index of 1.5 or so.

AUDIENCE: The index matching. You go from pairs 1 to 2.3 and then to [INAUDIBLE]. The difference is small between the classes.

TONIO BUONASSISI: Exactly. So if we recall that equation that described the amount of reflectance, there was that-- what was it-- n_1 minus n_2 quantity squared, right? So the bigger the delta between the ends, the bigger the difference in refractive indices between material one and material two, the more the reflectance is going to be off that interface. And so you can begin reducing reflectance off of a stack of light going both ways by grading the refractive index of the material. And that, of course, changes the reflectance in both directions.

And so you get a reduction in the total amount of reflected light when you put the silicon under glass because glass has a refractive index somewhere between air and silicon. And then you get a further reduction of the reflectance when you have an anti-reflection coating with a refractive index somewhere around-- for this particular system, silicon again has a higher refractive index. This used in anti-reflective coating of a refractive index of 2.3 of some thickness, probably somewhere around-- let's see, it'd be greater or smaller, probably around 65, 75 nanometer somewhere that range.

So what this is saying is that you can minimize the reflection of light off of the front surface of your sample by using an intelligent combination of the very first equation that we're exposed to in the class today, which was the reflected light as a function of refractive index, so essentially refractive index matching and secondly, by engineering by engineering an anti-reflective coating, which oftentimes in the lingo of solar cell science we call it an ARC, an anti-reflective coating. And those two things combined give us very low reflection off of the front surface.

Probably 5% of our R&D cells that we make at MIT use these sorts of technologies, which are pretty standard in the industry. And you can see what the hit is, right? Let's see, if I'm just using a bare material, if I'm getting 30% reflection, I'm getting a

30% drop in the current output of my device. That's pretty significant.

So these are simple ways to improve performance of devices. If you want to become fancy and actually do what's called a ray tracing to calculate the path of light through a medium, there is software available that will take all of what we've discussed today and calculate it for you so you don't have to walk through the expressions that we just walked through.

It is easy. In other words, you plug something in. You get some ray traces. You can calculate reflectance and so forth, transmittance. But it's as smart as what you put into it. It's really important to understand the fundamentals behind any simulation software because you will get out of it what you put into it.

You will not be able to pick up on obvious things that you might of-- for example, double clicked on this little material here and find the real component of the refractive index completely wrong. And you might not notice it. You might not pick up on it if you don't have some good intuition which is grounded in the fundamentals. And so it's important that you understand what we've presented today. It's important you understand the reading and, of course, do the p-set as well to really drive those fundamentals home.

So to kind of put a big umbrella over the entire lecture, light management ensures that the absorbance is high. The absorbance would be, essentially, the amount of light getting absorbed inside of the material, normalized by the amount of light going in, so $1 - r$. So we want to ensure that light enters the absorber. We want to minimize reflection. We want to ensure good light trapping inside of the absorber as well, the absorber being the material, our photovoltaic material, the ones absorbing the sunlight and ultimately going to be generating the charge. So we call it the absorber.

So we want to ensure good light trapping inside it. We want to ensure the maximum amount of light gets trapped inside. We want to maximize the optical path length within it. And we want to minimize reflectance off the front surface.

There are fancier ways of light management as well that don't involve light trapping necessarily but light manipulation or even semiconductor manipulation. You can, for instance, change the wave length of the incoming light. One very simple example of this is when you shine, say for example, red light on a phosphor and then it glows green in the dark. That's a wavelength change-- maybe not red. You'd probably have to shine blue to have it glow green. That's an example of a spectral down converter where it's taking a higher energy light and converting it into lower energy light.

Likewise, there are folks out there trying to do spectral up converters where they take two lower energy photons then somehow convert that into a higher energy photon. And so since our absorption coefficient is dependent on wavelength, if we're able to shift the wavelength of the light around by engineering materials near the surface, we can enhance absorption as well. That is a form-- a valid form-- of light management.

It has additional benefits as well. If we can eliminate the longer wavelength stuff out here, which is heat, performance of most solar cell suffers when they get hot. And we'll learn why that is about five or 10 lectures from now. And so if we manage to do spectral up converting or reflect that long wavelength light away from our device, we can improve performance there as well. That's another form of light management that doesn't necessarily involve light trapping.

So again, I wanted to really emphasize that light management is necessary devices. This is no light trapping, the blue curve, and with light trapping, light trapping being essentially just an engineered coating on the backside, on the backside of your device, of lights coming in through here. I've engineered a coating on the back to reflect the light back so that it gets a second bounce through the material. I've engineered the front surface, texturized it so that we have not only the benefit of two bounces, double the chance of light going in, but also the Snell's Law working in our favor and increasing the optical pathway.

And so all told, the one reason why this boost is so big right here is because I'm

increasing the optical path length, the effective optical path length, relative to the thickness of my material. And as a result, I'm getting a much larger current output. I'm generating many more free carriers instead of my material. I'm absorbing much more light inside of my material, just a very simple calculation versus cell thickness.

And obviously the thicker and thicker and thicker you go in your device, the less important this becomes. Because the less important light trapping-- I mean, you have the entire thickness. I can absorb the majority of the light in one pass. But if you have a thinner device, it really begins to matter. Once the thickness of your device starts approaching the optical absorption, or 1 over the optical absorption coefficient, which is the extension length, then it really begins to matter in the absorption length.

Light trapping can still matter for thick devices, though. Because if you manage to make the light essentially refract or bend, if you will, so that it travels near the surface, the distance that those excited carriers have to travel to be collected is shorter. And so you can get an additional benefit from thicker devices by engineering light trapping as well.

OK, any questions about this? This is kind of important. This is why we spent all this time in lecture today talking about light management is because of this plot right here. That's why.

I just wanted to show you a cross section of very high efficiency device. This is one of the highest efficiency silicon-based devices are out there. And we have these so-called backside mirror, which is really just a layer of dielectric material, typically, that reflects the light off of that interface using the equation that we saw at the very beginning of class, the r equal to $\frac{n_1 - n_2}{n_1 + n_2}$ quantity squared divided by open parentheses $n_1 + n_2$ quantity squared.

So that's benefiting here from the change of refractive index going through your silicon to that dielectric material in the back. They definitely take good advantage of it. Where you have your metal, you're going to be absorbing the light. Or you have a higher probability of absorbing the light than you would if you had a dielectric

semiconductor interface. So the device design can get pretty complicated for these super high efficiency devices. And they're worried quite a bit about trapping, other things as well.

AUDIENCE: Coefficient, is that one there?

TONIO This one right here? In the lab, 24.2%, in commercial production, 22% and change.

BUONASSISI: 22.4%, I think.

Just to throw some last things out there since we're five minutes to closure. Snell's Law assumes that there's no phase shift of the light as it transfers from one medium to another. If you introduce a phase shift-- this is just a paper published in *Science* last week by our friends over at Harvard, Federico Capasso. If you introduce a phase shift of the light as it goes through one medium or another, now you can start doing some fun things.

If you introduce a constant phase shift gradient throughout the surface of a material, let's say right here, then you can cause each node, each point within your material, to lag by an increasing amount, so that your wave front now bends. You can think of these as kind of a Huygen wavefront forming as a result of these small nodes here.

And if you can tailor the phase independently at each one of these points, you can cause an increasing delay as you go across. And that will cause the light, essentially, if you trace through the points of maximum intensity, say the pink, you'll see that the light is bent. And that's pretty cool. Because now we can, in principle, if this is hot off the press-- and then of course there's a whole flurry of researchers out there trying to figure out how to use this to our advantage, but with anomalous refraction, in principle, now you can tailor the angle at which light bends inside of the material. Perhaps you can even exceed the Yablonovitch limit inside of the material as a result of this.

And so it's really exciting. There's stuff coming up every day. This is the point. There's stuff coming out every day on light trapping and light management. Mostly it's for photonic devices. But they can be transferred over into solar cells as well. So

it's going to keep your eyes open.

And another example of the photon up/down converters, there's recent reports in SPIE, a lot of interest in the optics community. There was a TR35 award given to a person who studying this topic. So it is, as well, a very exciting and up and coming field. Again, the opportunities there of manipulating light are large, are vast.

So the laws, if you will, that constrain us, that we've discussed today in class, don't let that constrain your thinking. That's my final message. Thanks.