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PROFESSOR: Welcome everyone, today. Today we're going to be talking about advanced concepts. These are kind of like what I would consider the next generation of solar cells if these ideas pan out. Some of them are very near and dear to my heart because it's what my research is mainly focused on.

Also another quick realization I had last week. Probably Tonio mentioned this to me at some point, but do you guys know where 626 comes from, why the course is called that? So 6.26×10^{-34} is Planck's constant. So haha, funny. Thought that was kind of cool. It's a little joke put in there.

So anyhow without further ado, one of the cool things-- cells are done. Yay. This is great news. I was very, very happy. So it didn't go quite as well as expected. I think most of you are finding out that these are incredibly [INAUDIBLE] limited. I'm going to talk about why that might be in a second.

Hopefully that will help you guide you through your analysis, which we'll be doing for the final part of the quiz 2.3, which hopefully I'll be able to post by tomorrow afternoon-ish. I'm still working on that right now. But just to give you guys kind of the processing that you didn't get to see, this is what the contact firing looks like. It's a very, very, very fast process.

It's really remarkable to me that this combines so many photolithographic steps that if you wanted to make this in the lab using photolithography, and condenses these six or seven steps into one process. So it's pretty remarkable. So DuPont, the people who made the pace-- so we used PV16A if you guys are curious for our front contacts for silver paste.

And we actually get-- the really important part is this peaking temperature, and you

can see we actually got pretty close to the ramp times. Where it really starts to deviate is here, and we hold it around 400, a little bit longer, which is several reasons for that, and I'll go into that in a second.

But what's important is that all these are fired in an oxygen atmosphere. So normally in these belt furnaces, and this is again what's used in industry-- this is actually the same exact tool that I use at Harvard-- it actually looks like this with the giant CRT monitor on top. The only way to get the data off is with a three and a half floppy drive.

I can't tell you how difficult it was to find a working three and a half floppy drive. Most of them are demagnetized at this point. I had to buy new ones. They're still being made, by the way. If you want them, go to Staples.

So anyhow, it's done in an oxygen atmosphere, so they generally force airflow into these giant belt furnaces, and these are really long. Like that's probably about a foot wide, maybe 18 inches wide. So this goes on for tens of feet, or several meters, depending on where you're from. And it's done in an oxygen atmosphere, an air atmosphere, because it needs to burn off a lot of the binders and some of the organics that might still be there.

And so those organics burn off, and what you're left with are the little metal particles, the frit, and some metal oxide glass. It's usually lead oxide, although DuPont will never tell you, but from papers I've read this is generally what's used.

So when that happens-- this is that burn-off period. When it spikes, the frit will actually burn through your silicon nitride layer. You guys didn't have a silicon nitride layer, but if it was there, it would help eat through it. And so that way, you've removed the dielectrics so you can actually make metal contact with your silicon surface underneath.

That firing will-- during that peak also simultaneously, these middle particles will melt and form this triple eutectic point with the silicon underneath it. And so the triple comes from the silver, the silicon, and the lead. The lead actually dissociates from

the glass. This lowers the melting temperature of that mixture, and you can make good ohmic contact with the surface.

So it's actually a pretty remarkable, incredible process. It's still almost kind of magic to me on how the whole thing works, and a lot of it's just kind of guess and check and still very proprietary. So the science is still a little lacking there.

You don't find a lot of good articles explaining the science of it. I have a few if you guys are interested. NREL's put out a lot of really interesting stuff, and some of the ways they actually figure out the actual profile underneath the contacts versus you measure the temperature on the side of the contacts, so actually touching the silicon or the silicon nitride surface, is you actually measure hydrogen diffusion underneath it.

And so they'll actually etch off the contacts and using secondary ion mass spectroscopy measure the hydrogen concentration off the contact and underneath the contact, and that'll actually tell you what temperature it saw based on that diffusion profile. So there is some good science going on, but there's not a lot of great papers on it.

So anyhow, that just kind of gives you what I was working on over the weekend, trying to get these cells fired. So I aggregated a lot of the results and tried to make sense of what was going on. I think I showed some of you different firing temperatures and the fill factors that we got and there was kind of just noisy data, so I couldn't get any real trends. The best trend I could find was that if you take the median of all the short-circuit currents of the cells and you look at the ones with four millimeter and two millimeter spacing, the four millimeter spacing has a slightly higher short-circuit current, presumably due to shading losses.

If you look at the relative areas that each of these cover up, you would expect a 4% increase. This is about 3%, so I'll take that as fact. It's certainly within the noise and the error of the number of samples that we have, but I thought it was interesting nonetheless.

Additionally, I plotted the series resistance that I calculated from your dark IV curves and plotted your maximum power. I also removed all the cells that were broken. I'm sure if I actually normalized them-- some of the cells that were broken actually performed a lot better, and I'll get into maybe why that was the case in a second. But really the take-home message is that our really best performing cells are all clumped over here.

And so you can see that our best cells have a very low series resistance. That's not always the case. There's some outliers, like this guy here, and I don't know how that happened. So some really interesting things going on, and I'm still trying to sift through it.

So I talked about this I think yesterday in the analysis section, but there's several sources of series resistance. Any of you guys familiar with what they are?

AUDIENCE: [INAUDIBLE] resistance and emitter sheet resistance.

PROFESSOR: Emitter sheet resistance, and then--

AUDIENCE: [INAUDIBLE].

PROFESSOR: So there's line resistance along the fingers and then there's contact resistance, so I'm going to draw this out really quickly. So if you have-- this is your emitter. You have a contact here and a contact here.

If you generate an electron here, it'll diffuse, hit the junction. Then it has to flow through the emitter to the contact. There's an associated resistance with that. That's the series resistance that we taught in class that has to do with the emitter resistance.

Additionally to hop over that metal semiconductor junction, there's actually a resistance there. That's called a contact resistance. So this is emitter and this is our contact, and then it has to travel from the line to the busbar here, and that's our line resistance.

And I think what's really limiting us, because when I looked at both the shallow and deep emitters, the series resistance didn't really have any noticeable trends. So I really think that this is what's limiting us completely, is our contact resistance, which is kind of too bad.

So one of the reasons I think that that's the case additionally is that the cells that performed the best-- I know Joel's did particularly well. What was your fill factor? Do you remember?

AUDIENCE: Well, on the one side it was 0.5, and on the other it was 0.64.

PROFESSOR: OK, so one side was better. So again, the inhomogeneity of doing the measurement is also another indication that our series resistance across the contacts is really poor.

So some of the other contacts if you look on the-- where's my good piece of chalk? Right. If here's our busbar, some people saw delamination. Who saw their contacts delaminated?

Yeah, so a couple people. And so what that means is that these contacts actually peeled up, and that's usually showing that the-- what's funny, though, is that these areas in the middle didn't delaminate. It was only the edges here, and so that's showing that some parts are being properly fired and some parts are being underfired because when I fired at higher temperatures, I was getting shunting.

And that was due to shunting through the center area. So I think that the RTA that I was using-- this wasn't the case on some of the earlier cells I had processed, but is rather inhomogeneous in terms of the temperature profile it's delivering to our cells. So I think that could be part of our problem, as well.

AUDIENCE: How many cells did he fire up at the same time? Just one, or--

PROFESSOR: Yeah, it's one at a time, and there's some variability in the peak firing temperature. So I've learned a lot about when we're going to buy an RTA for our lab, what to look for. The temporal resolution of the data you get out of it and how it records it is 0.6

seconds. And when this thing's ramping at 100 C per second, your variability is quite large.

So the temperature I read is not just from the data point, but I do a linear interpolation to actually figure out what the peak is on both sides of that peak, and it ends up being about anywhere from 20 to 40 degrees Celsius higher using that technique. And so the variability varies. It's about 20 degrees plus or minus 10 degrees Celsius in terms of what I want the peak to be and what it actually is.

So the RTA that we're using now is not incredibly reputable. Also, better RTAs will have a different heater on top and bottom, and so you can actually heat one side more than the other. And generally belt furnaces, so commercial ones, will have that same kind of control.

I know at 1366, they've actually done optimization to do heating the top and bottom differently because they use different pace, they have different heat requirements, thermal requirements. And so nailing that temperature and that profile actually takes a lot of iteration and a lot of time. And it's really just learning the tell as opposed to, the again, good science behind it. So it can be rather difficult and time-consuming to do.

So that's what I have to say about the cells. I think overall, though, I think the efficiencies are on the order of 6% to I think 9% for some of the cells, so that's not too bad. I'm still rather pleased with that.

Last time I think Tonio stopped right before he was going to talk about performance of modules in the field and kind of what's the difference between your cell efficiency and your module efficiency. Modules are put out in the sun. They heat up.

They can get shaded by snow, rain, clouds, trees, and also the modulus are made up of many different cells that are connected in series and parallel, and how does that affect their overall performance of the module? And so that's what we're going to talk about really quickly.

So first off, why does temperature matter? So all solar cells when they're measured

either at NREL or in our lab, are measured under standard operating conditions-- or standard testing conditions, sorry. Certainly not standard operating conditions. Standard testing conditions are done at 25 C.

Generally the cells are actively cooled to maintain that temperature of room temperature, and most semiconductor simulations you perform are generally done at 300 Kelvin. I know all the calculations I did for fitting your [INAUDIBLE] diode curve were done at 300 K. Typical operation can actually be pretty hot, so 50 to 65 degrees Celsius. I actually don't know if that is in Fahrenheit, but it's hot. It's hotter than Phoenix, and I'm sure they get even hotter in Phoenix.

So the effective temperature-- so how does it affect Voc? If you recall, this is our diad equation. We have our illumination current, which we'll get to how that's affected by temperature in a second. But for now, just ignore that. Assume it stays constant.

So one of things that's really affecting your Voc-- so remember, your Voc is going to make your current go to 0, and the main thing that's being altered is your saturation current, so your intrinsic carrier concentration, your diffusivity. So who here thinks your Voc is going to go up with temperature? Anyone? And who thinks it'll go down? Who has no idea?

OK, so who raised their hand for it'll go down? Sorry. Ben, do you have any ideas why that might be the case?

AUDIENCE: No.

[LAUGHTER]

PROFESSOR: So what's going to happen to your I_0 with increased temperature?

AUDIENCE: The intrinsic carrier concentration, n_i , is going to increase, and that should increase I_0 ?

PROFESSOR: That should increase I_0 , so therefore it's going to take a smaller voltage to counteract $I_{sub L}$ to make I equal to 0. And so why does $N_{sub I}$ increase with temperature?

AUDIENCE: Greater thermal energy present increases the film probability that electrons can be excited from the [INAUDIBLE]?

PROFESSOR: Right, so it increases the number of thermally-promoted carriers. And so that effect can actually be pretty stark, and now we go to a demo. Yay.

All right, so what we have here is our favorite solar cell. This came, again, from those small little toy cars that we pulled off, and again, these solar cells, the cars will assume were nothing, and these are about \$10 apiece, so pretty cheap. Probably cheaper than your solar cells that you guys made.

And, well, certain I know they are cheap. The wafers themselves, by the way, were \$16 apiece, so saying they were a dollar was a little inaccurate. So anyhow, we have this hooked up to a multimeter and we're going to measure the voltage off of it. I'm going to illuminate it with our desk lamp, and we can actually get a pretty decent voltage.

I can't actually see this. So it's about 0.57 volts, and now we're going to subject it to temperature. This is obviously a gross overestimation of what's actually going to happen, but can someone read off-- Joel, can you read the temperature for me?

AUDIENCE: The temperature, or the voltage?

PROFESSOR: Sorry, the voltage.

AUDIENCE: Yeah. We're at 0.561 and decreasing down to 0.55, 0.54, 0.53--

PROFESSOR: So it's going down. So congratulations the people who said it would go down, correct. Wow, that's actually quite hot. Anyhow, so that's what happens in the field. So when these cells heat up, you actually lose on your V_{oc} .

And if you really want to, you can go through all the math. You know what the

equation is for your Voc. It's shown here, and you can go through this if you like. It's all on PVCDROM if you want to go through the derivation.

You then can take the derivative with respect to temperature. And if you plug in values for crystalline silicon, it comes to about 2.2 millivolts per degree Celsius, which sounds like a small number, but it's at around 0.1 volts if you go up to 65 C, so that's actually quite a substantial amount. And again, when you're going from 0.6 to 0.59, these small margins can make or break a lot of installations, so that's an important one.

OK, now this one's a little harder. What do you think will happen with your illumination current, or your ISC? Who thinks it's going to go up? Anyone? Who thinks it's going to go down? Who thinks it's going to stay the same?

Who has absolutely no idea and didn't raise their hand? OK, that's totally fine. This confused me, as well, by the way.

So when we think about it, what is our short-circuit current proportional to generally? Anyone?

AUDIENCE: [INAUDIBLE].

PROFESSOR: Right, so generally your illumination intensity. And what photons generally are we collecting?

AUDIENCE: Super bandgap.

PROFESSOR: Super bandgap. So what could be happening is our bandgap could be changing. I sub L, as Ben pointed out, should increase the flux of photons above the bandgap, and EG actually decreases the temperature. So your bandgap actually usually increases-- the true bandgap of silicon defined-- most properties of semiconductors are actually defined at 0 Kelvin, and semiconductors are technically insulators because they don't conduct electricity at 0 Kelvin.

That just means semiconductor is a class of materials that have a small enough bandgap that they can thermally promote carriers that they can actually conduct

some electricity at room temperature. But the true bandgap of silicon's around 1.17. And as you increase temperature, you get a reduction of the bandgap. And so what should happen is your ISC should increase, but only very, very slightly.

So if you go over the derivation for the actual decrease in the overall efficiency, there's a few things. One, remember your maximum power is your Voc times your ISC times your fill factor. So if you want the derivative of your max power with respect to temperature, you need to do the partial derivatives and sum them up for all of those different components. So that's what this calculation's doing.

And again, this is what it is for fill factor. This is all in Martin Green's paper down here and also on PVCDROM if you guys are interested in that. Martin Green's tabulated a lot of this, making these general expressions and also fitting it to experimental data to get that information. And then it ends up being not a negligible percent, but about half a percent per degree Celsius for silicon.

So if you go up by 40 degrees, you can see that temperature's a non-negligible effect in terms of performance.

AUDIENCE: [INAUDIBLE] silicon's kind of below the ideal bandgap for a single-junction solar cell?

PROFESSOR: Yes.

AUDIENCE: If you had a semi-conductor with one that was above that, would an increase in temperature increase the efficiency because it's getting simply closer to that bandgap?

PROFESSOR: Oh, that's a good point. Generally temperature's a lot worse because you're really going to hurt your Voc. You would increase your J_0 tremendously with temperature because you're creating more thermal carriers, so your diffusion current that's counteracting your illumination current is going to increase dramatically, so temperature is always your enemy.

There was a great picture on PVCDROM of a solar install in Antarctica and its

perform well above spec, which is kind of cool. So yeah, temperature's generally an enemy. And so a lot of people's ideas have often been like to do active cooling and use that for waste heat, and there's a lot of reasons why that doesn't necessarily economically make sense. But when you do, let's say concentrated solar, for example, and I think Tonio will talk about this in the next lecture, but concentrated solar is you're putting in not just one sun but about 1,000, maybe 10,000 suns on one small device.

And the idea there is you can have a really small device, have it be really expensive but incredibly efficient, on the order of 40% efficient because you have these stacks of different semiconductors that absorb different regions of the light preferentially. And those heat up tremendously when you're being subjective.

It's like an ant under a magnifying glass or something. It can burn it. So they actually active cooling to cool those cells. And they also have to track the sun, as well, in order to concentrate it.

And the last thing which you guys did for your exam number one was the effect of light intensity, where you looked at light intensity throughout the day, assumed some sinusoid for the incident light, and you measured how your efficiency changes. And you remember, your V_{oc} decreases with light intensity with your JSC, and that's due to the decrease in the photon flux. And your efficiency goes down according to those two equations there, and I think the derating factor if you assume a sinusoid that hits at one sun and then declines, you should derate your-- if you use instead of using peak sun, you want to derate that by about 20%. So it's actually pretty substantial. I was kind of surprised at that finding.

So when V cells go out into the field, they are not just one individual cell. So oftentimes you string these in series and then in parallel. So right now we're just going to look at series and in parallel solely, and what you see here are your three different cells all mounted in series. So the top of this cell is connected to the bottom of this cell, the top of this cell is connected to the bottom of this cell.

Our bad cell, marked here with the I guess the denim pattern. I don't know what that

was in PowerPoint. But what's important here is that because the current flowing to this one is also flowing to this one is flowing to this one, the voltages add and the currents are all matched.

So the current out of this stack of cells is limited by your weakest cell. It can't exceed your short-circuit current of your weakest cell. So you can see that your operating point for these three cells is not ideal for this one. It's definitely way off the peak operating point for this cell and way off the peak operating point for that cell.

So it can be a pretty detrimental effect, and this is why often in industry when you do a series of testing on your cells, each cell gets tested either using sun's Voc or a very, very fast IV measurement. You can [?] cells based on their performance and then match them so that if you all your cells are perfectly matched, they're all operating at the peak power point and you're getting the most out of all those cells.

And so that's why reducing the variability within your process can really, really increase your module performance, and that's something a lot of companies work really, really hard at. Now, the other reason why series is important to study is the effect of shading. So when you decrease-- so let's say a leaf falls on your solar panel or it's partially shaded because you put it near trees.

If you look at the BigBelly Solar ones right near campus, they're always in shade. It makes no sense to me. I think they might get one hour of sun a day in certain times of the day. And so if you partially shade one of the cells, you can see that the IV curve drops down, and now this cell is running in reverse bias. And when you're in reverse bias, you're running a lot of current through your shunts.

And for those who were here this morning, we know that shunts are really, really bad because that's where all your current's running through. And if your current's running through one localized spot, that's where it's heating up the most, and it can heat up to temperatures that can actually melt the encapsulant or completely destroy the cell, so this can actually be rather destructive.

And generally once your cells are made and encapsulated in the module, it's really

hard to remove them and replace that module. Pretty much the whole module's kaput at that point, so it's pretty destructive. So what people generally do for-- yeah?

AUDIENCE: So in maintenance, like yearly maintenance, you should clean the panel because of the dirt, or is there any other thing that you should do [INAUDIBLE]?

PROFESSOR: There's important things. So you don't want-- it helps if they're angled so snow and other things will fall off of it. You don't want to put it in areas next to a chimney, for example, where certain parts of the day it will be shaded, or things like that.

So I've seen some studies on cleaning, and it all depends on if it economically makes sense. If you want to pay someone to clean your panels, that's expensive. Is it worth it for them to do that if you're only saving just a little bit? Obviously, the shading's so bad that it could detrimentally ruin and destroy your module. It's really-- you want to do that?

Ways to prevent the destruction is actually a lot of cells will have bypass diodes. So if a string goes down, the current will just [? flow ?] through that diode and won't destroy the cell, and so that's one way of kind of fixing that problem. That's a great question.

So now we're stacking ourselves in parallel. Normally, again, in a module, you have them in series and then these stacks of cells in series are actually put in parallel, but there's just an easy illustration. Again, cells in parallel, you're matching in voltage and the currents are what add in. And so if one cell let's say has a low output voltage, it's going to shift the operating power point for the other two cells off of their maximum power point and you're going to get a reduced output.

And so this is actually very analogous to this idea that when you make your cells larger, generally their efficiency and performance go down. You have a higher chance of inhomogeneities and other things that might detrimentally hurt your cell. And this is kind of analogous to saying when you hook a whole bunch of cells in parallel, you're limited by your worst cell. And in this case, you're limited by your

worst region of that cell, and so that's the same kind of analogy.

And I think it's kind of cool, and so you can see this for a lot of different cells. So these are actually getting pretty big. So when you're getting to-- I don't know if they make cells this big. But it's 100 by 100. That's a meter squared. Wow, so maybe Cad-tel can get that big. Actually, they do. Look, here's First Solar right here.

AUDIENCE: [INAUDIBLE].

PROFESSOR: I'm sorry?

AUDIENCE: [INAUDIBLE].

PROFESSOR: Oh, OK. [INAUDIBLE] modules. So some of the cells you can see. So here's cells-- amorphous, submodule. Anyhow, so the idea is that you're, again, limited by your most defective region in the cell. And again, illustrated by this idea here is that if you take a cell, you split it up into a grid, and you model it as a bunch of many cells operating in parallel, you're again limited by that bad region.

And so this looks a little outdated. So this is 2006. So this is cell performance versus module performance, and you can see that it's also quite significant. One of the other things that's different about cells and modules is that you have glass in front. So when you optimize-- for example, in class we optimized our silicon nitride coating for an air-silicon interface. Modules, you optimize at silicon nitride coating for a silicon to glass interface.

And the glass, which has an index refraction of about 1.5, you're automatically going to reflect 4% of the light, so that light's lost. But it does help with your reflection losses because you now have a graded index of refraction. So it does reduce some of those reflection losses from that interface. Yeah?

AUDIENCE: Is this just silicon?

PROFESSOR: I'm guessing yes because this is from Richard Swanson. This is Tonio's slide. My guess would be yes, but don't quote me on that.

AUDIENCE: So for the modules, how is voltage and current controlled? I'm assuming that they control it at a specific point.

PROFESSOR: Yes, so that's a great, great question, actually. So your modules are hooked up to an inverter. The output of your solar cells are direct current, and so you have to convert that to alternating current. And the inverters are actually rather intelligent. They'll actually constantly scan at a very high frequency where it should be operating and taking the derivative and finding where that optimal point is.

And so one of the other ideas is that if you have a bunch of modules, usually those are also hooked up in parallel. And the idea is to have instead of just one inverter, a microinverter-- so small inverters for each one. So that way, each of those are operating at the maximum power point.

And I think problem is that inverters are expensive and the larger they are, generally the more efficient they are and cheaper can be. So I don't know how far that idea's been realized, but it's a good question. Does that answer it?

So we have-- good, plenty of time. So now we're moving onto advanced concepts, which, again, area that I'm working in. Kind of exciting. These are ideas that are very, very high efficiency, potentially very low-cost, and that's kind of the allure to them. And they're great science and research projects, so they're really exciting to be in.

So one of things that kind of motivates this work-- I think you guys have seen this equation. I know I've used it before. But you know that the defining metric for the performance of a cell in terms of its economic cost is dollars per watt, so dollars per watt peak. This is all defined at your peak sun elimination. This makes it location-blind, right?

The really important thing when integrating it onto the grid is how much are you paying in terms of cents per kilowatt hour. But to make it location-blind, you put it into dollars per watt, and dollars per watt is a function of many things. It's how much does it cost to make the module itself? So how many dollars per given area?

You divide it by the insulation. For dollars per watt peak, you'd set that to aim 1.5 or 1,000 kilowatts per meter squared. Multiply that times your efficiency, and then by your yield, which is a manufacturing parameter.

So for some cells where if you can reduce this number quite dramatically, so for example, suppose you decide to go to very, very thin wafers for silicon. You want to move to 20 micron wafers, let's say, which is something that a lot of companies now are working on. What happens is that those become very, very fragile.

And when you handle them and using all these pick and place operations to move them to different processes within the cell fab, oftentimes they'll break. And so that yield parameter can come very important and [INAUDIBLE] interplayed with this number here, and that's why it's there.

So anyhow, what this graph is is this is the dollars per meter squared, so the cost of producing that cell. And then you have this efficiency here, and each of these lines represents a certain dollars per watt. And so I think the DOE has wanted us to get to \$1.00 per watt, and you can do that by either producing incredibly efficient cells, around 50%, which seems a little unreasonable. And they can cost \$500 per meter squared, and that would be actually a cheap panel.

Or the other idea is to go to very, very low cost and low efficiency, and you can try to hover around in here. And so this nomenclature I'm about to use is a little outdated, but I think still some people use it, although rather loosely. What's known as first-generation-- and again, these terms I've read papers now they claim that they're third-generation where they used to be classified as second-generation. It doesn't really matter, but the ideas behind them are still relevant.

So the first-generation with the single bandgap, it's crystalline silicon still [INAUDIBLE] the market leader, and they're on the order of 15% to 20% efficient, but they're still relatively high-cost. And there's actually a lot of work now that says that this can move in this direction, moving to thinner wafers, increased laser processing. Just tighter manufacturing can really bring that cost down.

So your second-generation are your thin film. So this is either CIGS, amorphous silicon, organics. A lot of these very, very cheap to deposit, cheap to manufacture, but they generally suffer in efficiency, so they hover around in this area. And so far, this idea hasn't really fulfilled itself except for maybe cad-tel, which is a thin film material.

And then what we're about to talk about is our third generation of cells. So these are potentially low-cost and potentially incredibly efficient. So we're going to talk about only a few types today. I encourage you to look up. There's a whole different types of solar cells you can look up, ideas, research being done.

But I'm going talk-- this is what I work on, our intermediate-band solar cells, specifically impurity-band photovoltaics. And I'm sure you're all familiar with this picture, but if you want to create free mobile charges within your semiconductor, you have to shine light on it that has energies greater than the bandgap. And so you lose these low-energy photons. They're not collected, and what's a way that we can collect these?

Well, one idea this guy had was if you can create a material that has a density of states that looks like this, you can create a stepping stone by putting a half-filled band within your bandgap that allows you to promote to that band and then from that band into the conduction band. So the idea is that your voltage output can still be maintained for the host material, but you can collect that extra current. So your ISC will increase substantially, and so that's the promise.

And if you do some theoretical calculations similar what Shockley and Queisser did, assuming the radiative lifetime is your limiting factor-- and again, that's certainly not the case in some of the materials that are worked on for this idea-- and the idea is you can actually get up to around 63% efficient. And so what this graph is here, here's your single gap limit. This is a calculation similar to what Shockley and Queisser did. I think this is using blackbody radiation, which is why the curves are so smooth.

And it can actually outperform a tandem cell, which is again a multi-junction cell that

are two cells stacked. And it turns out the best is something that has a gap level that's about 0.7 eV from the conduction band and has a larger band gap, so that distance between your valence band and your conduction band of around 1.9 electron volts, and that's kind of the ideal material for an intermediate-band solar cell.

So theoretically, this idea is a great idea. Problem is, how do you make a material that has this band structure? And that's really the challenge where people are working right now, and it's actually rather difficult. And so there's three approaches.

One is the impurity band, which I personally like because it's a much cheaper method. Other one is this band anti-crossing idea where you can actually split the conduction band, and it's generally done with these mixed metal oxides and these highly mismatched alloys, and they're really cool. And this is currently the most successful material there for intermediate-band solar cells.

And then there's quantum dot arrays and quantum structures that are also a possible fabrication method. OK, so idea behind an impurity photovoltaic is you start with let's say a material like silicon or some other high-bandgap semiconductor, you put in impurities that have these deep-level states. Iron would be an example. So iron in very low concentrations can be incredibly detrimental. But as you increase that concentration above some critical limit often called the [INAUDIBLE] transition limit, you can actually form a band within the bandgap.

And so the idea what's going on here is that each of atoms this has some electron wave function and some radius that it sees. And then as you increase that concentration, these wave functions overlap and you can have conduction through those mid-level states. So that's one idea, and I like it because you use what I could consider very dirty materials. The concentrations you can put in here around are one atomic percent, so your silicon's only 99.9% pure at this point.

Other idea is to use either quantum dots or these quantum wells. So I think the idea here is that these are localized and then this becomes delocalized. So as you bring these quantum well structures or quantum dots closer together, you can actually get

tunneling through these states, and it basically essentially forms a band within your bandgap. Similar idea is to do this locally-- is that you have one photon promote to one of these confined states in your quantum structure, and then another photon to keep promoting up into your conduction band to create carriers.

AUDIENCE: [INAUDIBLE] would there be quantum [INAUDIBLE] embedded in the silicon, or these are solar cells made out of [INAUDIBLE]?

PROFESSOR: It's usually stacked between two other semiconductor materials. So you have semiconductor, quantum dot, semiconductor. If you look up this paper among-- if you look up anything-- so Antonio Luque-- sorry, yeah. Luque and Marti are two people in Spain who've kind of promoted a lot of the theory around this. And look up their quantum dot papers, and they'll really go into the device structure if you're curious. I'd recommend doing that, Joel.

AUDIENCE: So the x-axis on these figures are--

PROFESSOR: Real space.

AUDIENCE: So there will be some portions of the device where this is possible in-- it kind of depends upon how many quantum wells you actually put into your structure.

PROFESSOR: Right, and that's one of limiting things, is the EQE of these devices because they can't grow so many are pretty limited. And again, these also provide pathways for traps and other things, which is again a huge problem for these types of devices and ideas. And people are working on that quite extensively from the theory side and from the experimental side, and trying to merge the two.

OK. Sorry, Ben?

AUDIENCE: The quantum well [INAUDIBLE] on the right, where [INAUDIBLE] functions don't overlap, do those act as recombination centers?

PROFESSOR: It seems to me that they would act as traps. Again, I'm not an expert on these types of materials, but that would be my inclination. I guess the idea is that you have a

very, very short well and then you have a field across it so there's not something else to hop to. And it just pulls it right out, so that would be one device structure. Again, these are generally just like a few layers of quantum dots.

Oh, I didn't put up the [INAUDIBLE].

So this is the band-anticrossing model. So this is they're using these quaternary alloys. So these are, again, very, very hard to grow, and they've done these awesome measurements where they can show your valence band, conduction band, and your impurity bands, and they're using a technique called photomodulated reflectance, so basically the reflectance under oscillating fields.

And from that, you can get these kind of resonance points between the different transitions and you can figure out where your energy state lie. It's a really cool technique. But what they did is they've done some very, very careful engineering and grown these very, very carefully. And they can actually demonstrate the sub-bandgap response where if they have, let's say a photon that's able to drive this transition but it's too low in energy to drive that transition, they will get no current out.

And then as soon as they add the higher one, the current will increase. And then if they turn off that low-energy photon source, the current decreases but doesn't stop because the other high-energy photon can do both promotions. So this is actually one of the only successful devices of impurity-band solar cells, and it was quite an awesome feat.

So I think one of the few ones we'll talk about for another advanced concept is hot carrier cells. This is something I think Martin Green pioneered, and I believe it still working on. I haven't heard much about them recently, so I don't know what the progress is there.

So the idea is that one of the biggest losses, as I'm sure you guys know from I think homework 1 or 2, is thermalization in your solar cells. When you promote an electron well up into the conduction band, it then gives off heat or phonons, which

are just lattice vibrations, which is another way of thinking about heat.

In that process, the problem is that's incredibly fast. If you look at the time scales here, so you come and you promote this electron way up into your conduction band. This is what it looks like prior at that promotion, and then it slowly decays, and that decay happens over about a picosecond. So if you want to move your carrier in a picosecond, if you know what your field is, you can see how long that length is, and that length scale is also incredibly short.

And so one of the ideas is, OK, how either we can decrease our path length, or we can somehow slow down thermalization, and that's actually one idea. And to slow down thermalization is something that they call carrier cooling. And basically making certain types of device structures or material structures, you can inhibit certain phonon modes. So when these electrons get promoted, they want to give off heat. They basically give off lattice vibrations, so they want to shake the atoms around them and distribute that motion.

If you prevent that from happening somehow, through certain types of structures, you can allow that process to go slower, and that's one of the ideas. Extracting the carriers-- also kind of difficult. You need to have contacts that are selective that can take the hot carriers at all the different energies that they're promoted at, and that's also a really difficult idea.

And some of the ideas that they've been working on are these resonant tunneling contacts. So again, this is kind of hairy stuff. I think these slides are rather old and I don't know what's come of this research. So it's a really exciting idea and I encourage you guys to look more into it.

OK, so now we're going to move a little bit away from advanced concepts and talk about kind of bulk thin film materials, and I think we're actually going to end quite early, which is fine. So the most common commercially-available type of material are these wafer-based materials, so monocrystalline, which you know, which is what our cells are made of. This CZ, or Czochralski growth, probably pronouncing that wrong. Silicon, multichrystalline silicon, which I think Tonio was showing you what

that looks like. You can see the different grains. They're actually quite pretty.

Ribbon silicon, which was pioneered by Evergreen, and I think now that technology's gone. Evergreen went out of business, so I don't think that technology's still around. The [INAUDIBLE] still might be making modules.

Anyhow, so thin films. Cad-tel is still currently-- or First Solar is still one of the cheapest module makers. Their process was so cheap that their efficiency really suffered because they didn't even have an ARC coating for the first 5 or 10 years of development. And they said we didn't need it, and they were right. They were still outperforming silicon people.

That's becoming less so the case and one of the big problems with Cad-tel, as you guys know, is the [INAUDIBLE] and also the toxicity, which some people are really concerned about. Yeah?

AUDIENCE: Just a note on that. So if we're debating in this class whether the should be allowed to be imported into Japan. And my understanding, from the reading, was that Japan actually does not allow cadmium telluride imports. Is that correct?

AUDIENCE: I guess so, then yes. I don't actually know. I do know that Cad-tel is a very stable compound and I know people who work with it here and they actually work on recycling it, so how to dissolve it and separate the two elements. And they're not worried about the hazards of the actual raw material because it's a pretty stable compound, but a lot of people do worry about it and it's certainly a valid concern.

But one of the thin film replacements, well amorphous silicon-- you think you guys know that is, but that's deposited silicon. It has no real like lattice structure to speak of. It's kind of a disordered mess, which means it has a lot of dangling bonds. It has very, very low lifetimes as a result, and also in [INAUDIBLE] low mobilities. You also deposit it and you deposit with hydrogen to passivate all of those dangling bonds, and that's usually done with either plasma-enhanced chemical vapor deposition, and it's done on either metal or glass. And so it has the potential to be very cheap.

And then one of things I think was aimed to replace Cad-tel was CIGS-- so copper, indium, gallium, diselenide. I'll get to some of the problems with CIGS in a second, but there are few startups around it. I think Nanosolar is one, Heliolt, and I think Solyndra was one, although I don't really want to say their name out loud.

So problem with CIGS is if you're looking for Earth-abundant films, again if we want to scale-- if we want solar energy to scale to terawatt levels, if we want it to provide all of human energy needs-- then we're going to need to use elements and materials that are Earth-abundant, cheap to find, cheap to produce, and CIGS isn't going to get us there. It's got indium and gallium.

Indium, which is highly used and the price has skyrocketed now because I think it's used in your displays and televisions. There's indium in here.

AUDIENCE: [INAUDIBLE].

PROFESSOR: OK, so that's where it comes from then. Thank you. So what people have been working or trying to look at replacements-- so this is CZTS. So it's copper, zinc, tin, it's sometimes sulfide. This is selenide, but they are also working on replacing the selenium with sulfur, something a little more Earth-abundant.

And this was done at IBM and it was pretty remarkable, actually, because I think within a very, very short period of time, they were able to get efficiencies around 9.6%, which for a fledgling material is incredible, and I'll get to why that was so incredible in a second.

But again, when thinking about Earth-abundant materials, I really recommend you guys read this paper. This is a paper by Cyrus Wadia. It's "Environmental Science and Technology" and it looks all of these different semiconductor materials and it looks at in yellow, this is what you could get if you look at annual production of that semiconductor material now in terms of what is being produced to produce the raw materials that make it. And then the known economic reserves, what can we mine and get economically today, how much could it produce?

And your worldwide consumption is on this line, and you can see Cad-tel is just

barely eking it out. And the ones of note for this discussion are Cad-tel, CIGS, which is slightly better, and then CZTS, which is rather plentiful even with reserves that are currently being mined now, and so that's kind of the take-home message.

The other thing also really interesting is the actual raw material cost. Cad-tel, turns out, it's not that great when you compare it to CIGS and then CZTS. It's a whole lot cheaper.

So one of the other things about CZTS that's so cool is that there's basically this huge growth parameter space for making these quaternary alloys, and IBM on their first shot just kind of nailed it. So they didn't really look at this whole parameter space. It was just kind of their first shot was right there, and so it might already be optimized, and a lot of people are kind of concerned about that. But I think it's certainly a very interesting field and really cool to work in, so I think hopefully there's hope here.

So actually we're ending way early, but that concludes the lecture today. If you guys want to stick around for more questions, that's totally fine, but that's all I had prepared for today. So thank you.