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PROFESSOR:

So folks, we're going to get started into thin films for a moment, but I saw two of you, at least, in the class at Eli Yablonovitch talk on, gosh, what was it, Tuesday? Tuesday is was. How many attended the talk-- show of hands? Three? OK, three, awesome. I must have missed one of you-- very interesting talk. This was a talk about solar cells given from the perspective of somebody who does light management.

And so I wanted to share with you a book that is essentially from where he takes his efficiency calculations, which are based largely on thermal dynamics and less on the continuity equations-- Peter Würfel's book *Physics of Solar Cells*, a brilliant, brilliant book. I'm going to pass it around. On page 33, very easy number to remember-- 2 times 3, 3. On page 33, he starts delving into the derivation that Eli Yablonovitch presented during his talk, so folks can follow along from a thermodynamics point of view and maybe read up a little more and understand that perspective.

But he very, very briefly touched upon essentially the same physics but from the perspective of what we've been talking about a class in terms of carrier densities and current flows. He had it on the bottom of a slide, perhaps halfway through the talk, on four different bullet points. Does anybody remember what those were? Why did he achieve such a high efficiency conversion efficiency with the gallium arsenide cell? Anybody remember that one?

He had a thin device, so by thinning the device down, if he's able to concentrate the carriers, in other words, if he's able to collect all of the charge carriers inside of that very thin layer, he'll have a higher charge carrier density. And the charge carrier density is what influences the separation of the quasi Fermi energies, which is what influences the voltage output of the device. So he was able to obtain a higher

voltage output because he had a thinner solar cell. He was able to concentrate the carriers in that thinner region by light trapping, by light management.

And so as a result of having a higher carrier concentration, he had a higher separation of the quasi Fermi levels and hence a higher voltage output of his device. So in reality, it was very simple from the perspective of what we've been learning in class here, how he was able to obtain the very high efficiencies of gallium arsenide. The physics is well known; it's not new physics. It's actually quite old physics, and that that approach has been used within the crystalline silicon solar cell community for some time as well. The back surface reflectors off of the devices are highly optimized and the texture, as well, to scatter the light.

So I would invited you to take a look, and this is another example of how technologies can flow from one photovoltaic system into another. So you can learn a lot from material systems that you aren't working on necessarily yourself. That's another take-home message from the talk, at least what I walked away with. Any other impressions that folks would like to share before we dive into the lecture? Yeah.

AUDIENCE: I just have question about carrier collection. How is it possible to extract any energy from carriers which are generated in front of the junction? Because even if they diffuse another junction, they have nothing to fall down?

PROFESSOR: OK, so you have to think about it always from the perspective of the minority carrier. So if you generate an electron-hole pair, your minority carrier is now a hole, in the n plus region. And that hole diffuses across the junction. The electron stays.

AUDIENCE: I see, OK.

PROFESSOR: So did anybody else pick up on the point at the very beginning of his presentation? He said a P-N junction isn't necessary to separate charge. OK, that's fine. We've talked about heterojunctions. We all agree there are other ways to separate charge.

And he said an electric field is not necessary to separate charge, but then he immediately went into discussing how the chemical potential was slightly lower in the

contact than it was in the semiconductor, which would result in a charge imbalance, which would result in a field. And I think Gene Fitzgerald from material science and engineering department-- Professor Fitzgerald called him out on it and said, isn't there a field there at the metal contact. He said, quiet, wise guy, we'll get back to you later.

But essentially his point was a very small electric field is necessary. So his point was a matter of degrees, that you don't need a massive electric field. A very slight field is all that's necessary to start driving a current through your system. I just wanted to make sure we didn't leave that talk thoroughly confused with our head on backwards.

We're going to talk about thin film materials today. Why thin film solar cells? Well, we've been talking about crystalline silicon solar cells that have a lower optical absorption coefficient, so you need a larger amount of material, or a larger optical path length, to absorb a significant fraction of the light.

Already, in lecture number two, we saw how other material systems that have higher optical absorption coefficients are able to absorb this equivalent amount of light in a thinner amount of material and less material. So to put this in perspective, what we're talking about on one hand with the crystalline silicon devices is we might have a device that's maybe three or four times the thickness of your hair in crystalline silicon, and for the other materials, so these thin film materials, you might be talking about a material absorber that has maybe 100th the thickness, so something under a micron or a 50th of the width of your hair. So that's the perspective of scale that we want to have in mind. When we're talking about thin films, we're talking about thin materials, really on the order of one micron or so. And even brittle materials, at one micron thickness, if deposited on compliant substrates, can be flexible.

Another thing to keep in mind in thin film technology is that the scale of the thin films industry is about 1/10 that of silicon industry right now. So the crystalline silicon industry is going full force, gangbusters right now, and the thin film is a growing

fraction, but it's on the order of 10% of the total world market. And many, many, many startup companies, which are young, dynamic, fun-- and that's why today I'm not wearing a tie; I'm in startup mode. I'm a lot more relaxed. We're going to be talking about thin film technologies and diving into some fun work.

So we'll talk about these specific technologies of thin film materials, and before we get into those, I'm going to address some general topics about deposition and, of course, general parameters that affect all thin film material systems. We have to appreciate the sheer diversity of technologies that are out there on the market. We have a variety of different solar cell materials that are available, some of which are thin films, other ones, wafer-based crystalline silicon. And all of these technologies have to consider cost resource availability and, eventually, environmental impact as well. So these or some of the things I'd like you to keep on the forefront of your mind as we talk about these different technologies. Think about the broader picture, and ultimately, this cost, or the amount of money per unit energy produced, is really paramount in determining marketability and determining the scales to which they'll penetrate the market.

This is the one slide that you have printed out. You have one per pair of students, or you should. So if you don't have access to that particular slide, feel free to share it with the person next to you. This is representing as a function of time, going back to the 1970s, the record solar cell conversion efficiency.

The chart is maintained by a certain Larry Kazmerski at NREL. Actually, he used to be the head of NREL's solar program. He stepped down a few years ago after a very successful run-- many years. And he's a bit of a father of the US PV industry. He's been around for a long time and has been tracking the growth of the PV industry and, of course, the improvement of performance over time.

Many of these devices-- many of these record efficiency devices-- are very small area, and many of them were actually grown for the intent, the explicit purpose, of getting onto this chart. And so when you're trying to make a record efficiency device, you do things a little differently. Let me give you an example; you'll optimize

your anti-reflection coating for air not for glass, right? So if you want to minimize the reflectance off the front surface, you'll be optimizing it for air, which has a refractive index of one, as opposed to glass, which has a refractive index of 1.5.

So there are some tricks that one does and engages in, some are a little bit under the table, too. It has been done in the past that people would do an HF dip of their silicon-based solar cells right before measuring the efficiency. The hydrofluoric acid would result in surface passivation, but, of course, it would result in a very low surface adhesion of the metal, and so the metal flake off afterwards. It wouldn't pass the tensile, but you would nevertheless achieve instantaneously higher efficiency. Those practices have largely been weeded out. These were the early days, when it was a wild west of solar cells.

In more recent times, there are some very strict standards, and there are only a few laboratories around the world where you can take these standard measurements. The one at NREL is extremely well staffed in terms of the quality of the people. They're notoriously under resourced, but that's another issue.

But in terms of the quality of the people there, very, very good, very thorough, very pedantic and careful about taking their measurements. And if you ever have a question about how to perform a solar cell efficiency measurement, they're a very good resource. Their website would be an excellent place to go.

So these data points here versus time represent the record cell efficiencies. They may be on very, very small pieces of material. They may be on a centimeter squared, perhaps even smaller, so they're not necessarily representative of what is in commercial production today.

Let me give you one example; the record crystalline silicon cells, which are in blue here, has been around 25% for about a decade-- actually, a little more than a decade-- and the record efficiency crystalline silicon device has, in essence, not been so planted for many, many years. There are a number reasons for that. It's very much approaching its theoretical efficiency limit. People haven't necessarily tried specifically to get a record efficiency crystalline silicon device. They're more

intent on making lower cost silicon devices than record efficiency ones, and the average module efficiencies are somewhere down at around here-- actually, somewhere in the 13% to 15% range for module, average module efficiency.

You have some modules that are in the 18%, 19% 20% range, but most of them are significantly lower. And the record cell efficiencies, as you can see, is 25%. So there's a significant delta between what is commercially available and what the record cell efficiency is. There are several reasons for this. To make a record efficiency cell, you have to throw everything at Liebig's law of the minimum. You have to make sure that every plank is really, really high. That costs a lot of money typically, and so doing that cheaply is a big challenge.

Some companies, like First Solar, for instance, has some of the lowest cost models in the market. We'll describe how they're made in a few slides. First Solar forwent the anti-reflective coating on their glass for many years, because it just didn't make cost sense. It didn't help optimize this function right here. Although, you'd get more energy out, the dollars that it took to add that component just didn't make sense for them.

So you have to think about a few different perspectives. You have to think both in terms of cost, and in terms of performance. The performance, what it does or what it tells you is that this material system has potential. It has been demonstrated we can get the high performance. It's a proof of concept. The trick now is to get there at low cost, and that's pretty much what you should walk away from this chart having seen.

Another thing to keep in mind is that it takes a long time to improve the performance of a new material. If you're starting out somewhere down around here, it's going to take you a while to reach higher efficiencies. Granted we can learn a lot from the previous material systems. We could learn a lot by reading those old NREL project reports that are available online of all the people who were working towards these record efficiencies-- what they did differently, how they advanced, and how they improved cell performance-- and leverage that information as you try to develop

your material. But the fact of the matter is, it'll still take a bit of time to develop new technologies, and you can see that by some of the newer materials that are coming along down here, for example, the organic-based solar cells.

So thin films, general issues-- so we talked about the advantages here, that we're squeezing the cost of the absorber layer out of the module, which is excellent from a cost point of view. But obviously, there are trade-offs involved. If it was all a walk in the park, we would be 100% thin films and have abandoned silicon by now. There are both advantages in this advantages with thin films. Instead of disadvantages, perhaps a happier way of looking at this is challenges and opportunities for getting PhDs and other advanced degrees.

So let's go up into advantages. The advantages of thin films, quite simply, is that you're using a very thin amount of material, so thin, in fact, that it's virtually insignificant in terms of the total cost structure of your module. One perspective is that if you're depositing a thin film using a fairly low-cost technique, like a c spaced sublimation type process, you may be able to deposit the material for as much cost as it takes the cardboard that separates the modulus from each other in the stack that's being loaded onto the 18-wheeler out of the factory, to put things in perspective. It's very cheap to deposit these thin layers.

Now let's hop down to the disadvantages real quick. If you're depositing a very thin layer, and it's not high efficiency, then you need more glass, more encapsulants, more framing materials, more labor, and everything for the same amount of power out. If your efficiency is low, your costs will be higher. Even if you have a dirt cheap absorber layer, you might as well get the absorber for free. If your efficiency is too low, all the other commodity materials are going to outweigh that cost advantage because the commodity materials scale with area. If you have low efficiency, you need a larger area module to make the same amount of power.

So, at some point, if you look at the cost of the material versus efficiency, you start entering negative territory. You actually have to be paid. If you're producing like an 8% or a 7% module, typically, you would have to pay your customer for them to

accept your module. So you really have to achieve a minimum efficiency target to be cost competitive, and as a rule of thumb, that's typically 10% to 12% for today's cost of glass encapsulation framing materials and labor and installation and so forth.

So back up to the advantages-- there's a potential here for a very low thermal budget. If we're able to print, say, a micron-thick layer onto a substrate, remember, we go back to that the high speed printer analogy, there's a potential for a low thermal budget, which means thermal budget is the amount of heat that you're introducing during the processing. As a result of a very low thermal budget, you have a potential cost decrease. Instead of heating things up to 1,400 degrees C over several hours, having all that massive amounts of electricity that go into producing the crystalline silicon wafers, here, potentially, we could be printing stuff on flexible substrates. So that's the thermal budget argument.

In terms of conformal deposition and flexible substrates, there's a potential here for roll-to-roll deposition. Picture a newspaper plant, where you have one roll of paper on one side being pulled on to another spool in the other, with some deposition process happening in between. If you can deposit on a flexible substrate, this is the vision. And if you're not depositing onto a flexible substrate but onto hard substrate like this one right here-- this is glass, a thin film material deposited on glass right here, a very small one. Oops, some tape on the front. Let me get rid of that for you. Here we go.

It's in a nice little protective coating here, so you can have a look at it without worrying about getting your fingerprints all over it. And the company name is fully removed-- check. This is an example of a thin film material deposited on glass without any anti-reflective coating, just the absorber material, so you can get a sense. It looks great. It's about a micron thick. It's about 170 times thinner than those wafers that you saw on Tuesday. So that's an example of a thin film material. It will be making its rounds.

There's a large amount of technology transfer with a thin film display, the flat panel display industry, with deposition on glass like that one right there. And there's a

potential it'll be very nice for building integrated PV applications. If you're able to get rid of the glass and deposit on a conformal substrate, you could envision roof shingles or other flexible substrates that would allow you conformal coverage on undulating roof tops and so forth.

Radiation hardness-- this is just a small aside, but there are some materials that have better radiation hardness than silicon. What does radiation hardness mean? It means that if I send something to outer space, where we don't benefit from the radiation shield of our own atmosphere in the Van Allen belts on earth, and we have proton bombardment and other forms of radiation striking are module and creating damage within the absorber layer, some compounds are naturally better at resisting degradation of performance than others, and that's what radiation hardness means. So there are some thin film materials that are exceptional for space applications.

The challenges and-- oh, go ahead, Ashley.

ASHLEY: Is gallium arsenide one of them?

PROFESSOR: We're going to show you in a few slides. We'll compare them all as a function of radiation exposure time. The disadvantages, or shall we say challenges and opportunities for PhD and master's students, lower efficiencies in crystalline silicon potentially larger module costs. If you're able to improve the performance of these thin film materials, wow, you have now equivalent performance of crystalline silicon but at much lower cost. Good for you-- you have a marketable product.

Potential for capital intensive production equipment-- not all of the production equipment is as low cost and as low thermal budget as simply printing on a piece of paper. As a matter of fact, that's one of the more avant garde and R&D type of deposition processes. Most deposition processes and the vast majority of companies used are actually quite capital intensive, and the cost of the equipment can add up.

Sometimes, not always, but sometimes scarce elements are used. We're going to have a debate about that on next class, on Tuesday. Put an asterisk next to that. I'll

get back to those as soon as this slide is over. And spatial uniformity is a challenge during deposition. Imagine trying to deposit a film one-micron thick over glass that is one meter in size.

You're talking about a six order of magnitude aspect ratio here. So we have to somehow deposit a film a micron thick in layers that are even thinner, that might be only a few tens or hundreds of nanometers on top of that and below that absorber layer to separate charge, for instance, and that's really challenging to do on a very large scale, and that is an engineering challenge or a process engineering challenge that had many startup companies flailing for a long time.

Think of spatial homogeneity in the following manner; if you have one region of your solar cell that's producing a lot of power, and the region next to it is not, and they're connected in parallel through the contacts, power will flow from the good region into the bad region. So you have internal current loops inside of your module. That is essentially decreasing the power output of your module itself. So that's why homogeneity is important.

This is just to represent the vision of a roll-to-roll process in the upper right-hand side there. Kind of a visionary cartoon that is being enacted by one company, in particular, Uni-Solar, based out of Michigan. They do have a roll-to-roll process and PCBD-- we'll describe what that is in a second-- deposition of this material, so-called amorphous silicon.

And here are some building integrated solutions, just showing you what you can accomplish or what the vision would be. If had have this really flexible substrate that you could literally take it as a roll from Home Depot, bring up to your rooftop, splay it out on your roof, much like you'd lay down a piece of tarp or plastic, and take a staple gun or a nail gun and drill it into location, that would be an example of a much reduced installation cost. So you have the potential here of reducing the installation cost of solar as a result of the form factor of your module.

And this here is another example of a building integrated photovoltaic solution within films. The fact that it looks really nice, is really sleek, you'd never guess that those

are solar panels there, and that's, of course, from an aesthetic point of view, a huge benefit.

Common growth methods-- how do we make that sample of copper indium gallium diselenide, that thin film material that happens to be making its way around the classroom right now, how do we actually make it? Well, not only the material I just described, there are other materials as well. We'll talk about the general classes of growth method. So this is the material science processing class condensed into a few slides. Bear with me; this very high level, but it aims to highlight the techniques that are most commonly used in PV today.

We're going to start with what are called vacuum-based thin-film deposition technologies. And the reason I'm separating vacuum from non-vacuum is because if you have a system that is comprised of these large stainless steel chambers that you typically see when you go walking in the physics building, if you have a vacuum chambers, those are typically quite costly, at least the large scale ones that are in commercial production.

As the name would suggest, you need to have pumps to suck out the air inside of the chamber, and that's how you create the vacuum. The vacuum is necessary because typically you're transporting atoms from some sort of source, either gas or a solid target, onto the substrate. So you're transferring individual atoms or clusters of atoms from some source onto the substrate that will ultimately hold your thin film device. And that process requires a limited number of interactions of those atoms or clusters of atoms, in other words, a large mean-free path, as these make their way to your substrate. And that's why the vacuum is typically required in these deposition systems.

There are a variety of ways to accomplish this goal. One class of techniques is called Chemical Vapor Deposition, often referred to as CVD. This typically involves flowing in some form of gas into your chamber and then allowing that gas to react on the surface of your sample or above the surface of your sample and ultimately depositing on the surface. The chemistries involved in CVD processes can be quite

complex, and the reaction process itself can be very difficult to master. So you might have some friends who are involved in spectroscopy shining lasers at their system and looking at the absorption lines and trying to figure out how these molecules are evolving between when they're inserted into the chamber and when they actually wind up as your film, because understanding the reaction, the chemical reactions, that take place is essential, is key, to really controlling the CVD process.

The other class of technologies involved is called PVD, or Physical Vapor Deposition, and this tends to be a bit more straightforward. We tend to have atoms of a specific type. They may be ionized, or they may be charge neutral, and they're making their way to your substrate. And the chemistry tends to be much more simple, but the apparatus around it to give the incentive for the atoms to leave the target and deposit on your substrate, that tends to be more complex. And so some of these tools, especially molecular-beam epitaxy can be very expensive, very slow, but very high quality, but very expensive as a result.

And so a very simple way to think about the vacuum-based deposition technologies is a compromise-- this is an oversimplification indeed, but it's an easy way to get started about thinking of the parameter space of all these techniques. It's a compromise between speed and quality. Some of the techniques that are fastest also tend to be the lowest quality materials, and the other ones that tend to be the slowest tend to produce the highest quality materials.

How do you optimize somewhere in between, somewhere in that parameter space, to get reasonably high material, just enough that you can produce a high efficiency device-- remember that saturation of device performance versus diffusion length. At some point, it just doesn't make sense to keep optimizing your material. You've got it good enough. You're good to go. So that's one of the things to consider when you're choosing your deposition system.

So let's go into a few examples of these vacuum-based deposition systems. Within the PVD techniques, within the Physical Vapor Deposition techniques, one of the most commonly used in manufacturing, at least in some startups-- you have

examples like MiaSole-- is sputtering.

And this sputtering process is essentially very, very straightforward. You have a plasma. The plasma consists of atoms that are charged. These are accelerated toward your target, which is comprised of the elements that you want to deposit onto your substrate. Your substrate is sitting up top. And this target material is sputtered off and eventually makes its way up and sticks to and eventually grows the film on that orange platen up here at the top. That is your substrate.

The substrate is facing down. Why is the substrate looking down? Why wouldn't you invert this and put the target on top and in the substrate in the bottom? What could happened then in terms of purity of the deposition process? Let's go to Kristy.

AUDIENCE: Things could fall onto it.

PROFESSOR: So stuff, gunk, could fall onto your substrate. You're trying to grow a thin film a micron thick, and you're trying to avoid any imperfection, and now gravity is working against you in that case. Because, if you were to invert this, your target would be on top. You could have stuff raining down onto your substrate.

There are a few people who sputter down. It's very tricky. You have to be able to control your process very well and avoid flakes from coming off. There are folks who sputter sideways, saves some ground space in their factory. They might load things vertically, put them in.

And many people, at least in R&D, sputter up. So again, you're creating this plasma. The charged species are accelerated toward the target. They sputter off atoms, which are then deposited on to your substrate, which is there at the top.

And the film that was just being passed around is an example of a sputtered film. The spatial uniformity of sputtering over large area depositions can be in the order of a few percent. So the ability to control this process in terms of spatial uniformity is fairly good.

You could also employ radio frequency modulations to the bias voltage. That's

called RF sputtering for Radio Frequency. Industrial applications usually involve large rotating targets. So for those of you-- how many people actually work with some sputtering materials or have done it in the past? One, two, three, four, five, six, OK. So you know that, at least in the laboratory, if you have a fixed target, you wind up with that race track, right?

So if you have a fixed target in the lab, and you're trying to deposit your films, if you wear it down several hours, eventually the metal that you're trying to deposit, or the ceramic that you're trying to deposit, will usually wind up having a bit of shape to it. Instead of being flat on the surface, you'll have what's called a race track; it'll dipped down near the edges, and that can result in a change of the deposition rate of the species that you're trying to deposit. And from a homogeneity point of view, that might be disastrous in the company, and so there are methods to move your target to avoid that sort of effect from happening. And when we talk about large targets, we're really talking about large targets, right? These aren't your lab scale two-inch or three-inch, these are much, much bigger in commercial production.

So in terms of comparing sputtering against other growth technologies, there are technologies that are more conformal. Because this is more of a line-of-sight deposition technique, the atoms are moving toward your substrates. But if you have some shape to your substrate, maybe you have a ledge or a ridge, in that case, you won't necessarily coat that uniformly. You might have less being deposited on that edge rather than the flat sections. And so conformality of coverage, or conformal surface coverage, can be an issue with sputtering.

Let's talk about the next technique that is commonly used in inorganic thin-film deposition. Excuse me. This is called metalorganic chemical vapor deposition. So again we notice the CVD appearing at the end. We know it's a Chemical Vapor Deposition process. MO in this case, standing for Metalorganic. The reason metalorganic is because we typically have a metal, like this representing the indium right here, and then little organic compounds on the outside. Those are methyl groups. The little gray and the two white dots, those represent three methyl groups around the indium, so trimethylindium.

And what we do is we flow these molecules into our reaction chamber and control the temperature gradients inside in such a way to have those molecules deposit on the surface, leaving the indium behind, or the metal behind, and the reaction products flow away out the back, and that is represented chemically here on the surface. This is zooming in right at the surface of our sample so right where the gas interacts with the thin film material that you're depositing.

This is representing the incoming metalorganic molecule reaching the surface. This represents, right here, the separation where we have the indium shown in black right here, and then the methyl groups are moving off, and essentially, those will be sucked out of the chamber, leaving behind, in this particular case, you have a layer of indium forming, probably another layer of material underneath. Say, for example, your other species comprising the thin film may be phosphorus, so it would be indium phosphide growth.

This metalorganic chemical vapor deposition is very nice from the point of view that you tend to form homogeneous films-- very good surface coverage. The disadvantages would be that many of the inputs and outputs are toxic-- not always, but many of them are. They have to be volatile and reactive so that you can crack the metal on your surface and create the thin film. If it wasn't reactive, you would just have it flowing through and leaving, not having a reactant with your substrate.

But because of the reactivity involved, oftentimes these are not very friendly for human beings or for other organisms. It was not uncommon in the early days of MOCVD reactor development where they'd have this little stack going up to the roof, and then when they'd do maintenance on the roof, they'd find all these dead birds lying around. That obviously has improved since people have put up the appropriate filtration on the output of their growth system, so-called scrubbers, to prevent toxic gases from being released into the atmosphere. But you do have some old stories.

So the proper design of metalorganic precursors is essential. You can easily see how if you change the molecule that you're bringing in, all of a sudden now, your reaction temperatures are changing. The rate of deposition is changing, and you

have to optimize your growth process all over again.

So part of the trick of doing good MOCVD is knowing your chemistry, being able to design or synthesize these metalorganic precursors. And the deposition process is very sensitive to temperature, pressure, the precise surface orientation, and preparation, what carrier gases, as well, are mixed in with the metalorganic precursor that you're putting in, and the byproducts obviously need to be managed. So that's MOCVD in a nutshell. Yes?

AUDIENCE: And pure quality is much better with MOCVD than it is for sputtering, right?

PROFESSOR: It depends on a lot of factors. So the reason the purity of MOCVD is generally better than sputtering is because the mass flow controllers necessary to control the gas flow specific for particular types of gases. Now, in sputtering, because of the versatility of the sputtering chamber, you could take this target out and put-- maybe Ashley comes along into your sputtering chamber, and she puts in another target of another metal. And now you're depositing two different metals in the same sputtering chamber. You're going to get cross contamination.

There are things you can do to minimize cross contamination. You can have a chimney around your target to prevent flakes from coming down. You could sandblast the sidewall coating and so forth to prevent stuff, gunk, from building up around the side, but you're still going to get a lot of cross contamination here. And furthermore, the purity of your film is dictated by the purity of your re-target.

And if you go online and look at [INAUDIBLE] or CERAC or some of the big metal selling firms, which are essentially from where the target manufacturers are purchasing their precursors and they compact them and make their targets, the target purity, or the metal purity, is only on the order of maybe 2/9 to 6/9 pure, typically within that range. So from an MOCVD point of view, you could do a distillation process and increase the purity of your precursor gas and avoid that.

So I think two big reasons why MOCVD can produce higher purity films in the sputtered system, one is the quality of the target, and the other, I think, bigger

parameter, at least in our growth system, is cross contamination. And whenever you deposit, say, an EML-- they have a sputtering system there from AJA, or over at Harvard CNS, there's another AJA sputtering system there-- you're going to get cross contamination. Just look to the log book and see what people have tried to deposit. It gets kind of scary.

PECVD, Plasma Enhanced Chemical Vapor Deposition-- so similar to the previous variety right here, but instead of saying, OK, we're going to put the burden of the design, the scientific design, onto this interface right here and on to the chemist, who has to design this molecule that reaches a surface and breaks up in just the right way in an orderly fashion, leaving behind the metal and letting the other gases go away, what we're going to do here instead is to shift the burden of separation onto the plasma. So the centers around the physicists.

We can flow in gases. We can break them up inside of a plasma, atomize them or, at least, create radicalized versions of them and then allow them to hit on to the substrate-- very simple in theory. In practice, what happens inside that plasma, depending on the temperature, depending on the frequency and other factors, you'll get different types-- and the pressure, especially the pressure-- you'll get different types of molecules forming in the plasma. They may be charged, and they'll be accelerated toward your substrate and eventually grow and form a thin film. But depending on what species you have up there that is being deposited on your surface, you'll get different types of thin films growing-- different quality material.

And so, again, this shifts the burden back to the spectroscopist to measure what is exactly the composition of that plasma. What is the active molecule that's being accelerated and deposited on the surface? And usually it's some probability distribution function of varied species.

The plasma is created by this radio frequency. Let's put it this way; usually you have a plasma frequency of around 13.56 megahertz. Does anybody know why this 13.56 keeps on coming up over and over again? Yeah?

AUDIENCE: [INAUDIBLE] energy to the ionized hydrogen, right?

PROFESSOR: Well, if we're thinking about eV, that would certainly be the energy necessary to remove the electron from the hydrogen atom, but this is another reason. Yeah?

AUDIENCE: It's a special band that's dedicated for these crazy noise-emitting medical and industrial purposes.

PROFESSOR: Exactly, so this is falling within the radio frequency regime, which would affect communications. And if everybody was allowed to run rough shod around, creating these very high intensity emission sources of radio frequency waves, we would very likely have interruptions to our police communications or maybe even our radios or cell phones. And so, at some point, they had to say, look, we have to assign definite bands within the radio frequency space and allocate them to specific purposes.

In one band, they allocated to all the scientists and medical personnel and said, you have to operate your equipment in these specific bands, and we'll give you a few of them, because we know that one frequency doesn't work for all the things you're trying to do. But for medical equipment, for scientific equipment, and I believe even some home electronics, like microwaves, there are specific bands dedicated to them. And that's why we have this 13.56 number popping up over and over again.

The reality is that if you change the frequency, you'll change the nature of your plasma. You may change the deposition rates and the quality of your film as well. And so there are people who get special permits and have these radio frequency shielded rooms, where they do experiments outside-- or excursions outside-- of the 13.56 megahertz range.

So this is PCB-- excellent conformal surface coverage again. Because you're biasing your substrate, you're able to conform. The electric field is usually always perpendicular to the surface, and so the angle of entry of those atoms or molecules, the ionized species, entering the surface is going to be normal to that surface. And you can get good coverage around rough textured surfaces.

The deposition is very sensitive to temperature, pressure, power, carrier gases. Power of the-- here, as well, shown. And the byproducts, as well, need to be

managed because sometimes you're sucking out-- in this particular case, you could be pulling out silane, as shown right there, and we talked about all of the risks involved a silane in our last class.

So, as you could guess, each of those different deposition techniques is used or is favored for specific material systems. And we shouldn't forget, as we talk about all these fancy vacuum equipment that look nice and cool as you walk through the labs, and you see these big stainless steel chambers, we shouldn't forget about the simpler, lower cost, lower thermal budget, lower capital equipment cost techniques-- the solution-based deposition methods. And these involve printing. They involve a electrodeposition, spin casting, colloidal synthesis, layer-by-layer deposition-- developed here at MIT-- and other technologies as well.

I want to point out two technologies, in general, the first of which is still under some development printing. Obviously, we have inkjet printers. That's pretty straightforward. But printing fractional solar cells is something being commercialized by only a handful of companies, Nanosolar being one of them. And I would say there aren't any authoritative textbooks that will describe for you their technology, because it's largely under wraps. They're a startup company, and it's not publicly available.

Electrodeposition, on the other hand, is fairly well known. You're, again, applying a voltage difference between two electrodes, one of which will be your substrate, and depositing a species contained within your electrolytic solution onto that substrate, growing your layers. Because you're growing it at room temperature, these films, I would say, tend to have rough surfaces. That could be a downside of electrodeposition. They might have some pinholes as well. But you do get fairly large grained materials. It can be a very gentle growth process, and, of course, the advantage is lower temperature.

So you have a variety of different growth techniques. Let's talk about the general issues involved with thin films in general, and then we'll dive into the specific materials. So taking the same tact as we've taken the full class, going from

fundamentals toward the technologies. Yes?

AUDIENCE: I'm just curious; do you know of any companies that actually use electrodeposition?

PROFESSOR: I know of some companies. Let me think which I can talk publicly about. So IBM, they presented at the Electrochemical Society meeting last Monday here in Boston. They're an example of a company that is developing electrochemical deposition processes for material systems, including copper zinc tin sulfide and copper indium gallium diselenide. We'll talk about the latter in a few slides, but that's one example of a company.

So general issues in thin films-- thin film compounds are typically, not always, but typically, binary, ternary, quaternary, or multinary semiconductors. Meaning you don't have just one element comprising the semiconductor species. You might have several, and they form a crystal structure with repeating structure but alternating atoms typically.

And so, if you have multiple atoms in one compound, a couple of issues could arise and need to be controlled to grow good films. The first involves phase stability. What is shown right here in multinary parameter space, this is the chemical potential zinc, copper, and tin in a so-called zinc copper tin sulfide material system. This red fin right here is showing you the parameter space within which this compound is stable.

If your stoichiometry takes an excursion from that red fin, you could wind up in a bi-phase regime. Meaning you have CZTS and something else, a copper tin sulphide, a zinc sulfide, or some other species that happens to be nearby in phase space. One way to think about this is it's just you have a homogeneous material. If you exceed a solubility limit in one direction or another, you'll have precipitation of a secondary phase.

So you have to make sure that in a gross perspective, on a percents basis, you're in the right regime of stoichiometry. Stoichiometry being the ratio of different elements in your system. So it's like cooking; you need the right set of ingredients to make the right material.

Now, that has to do with-- large excursions from stoichiometry can result in phase decomposition. Small excursions from stoichiometry, a much more subtle effect can occur. Let's imagine for a moment that we have two species comprising a binary material. One species has three valence electrons. The other species has five valence electrons.

Now, because of a small error in stoichiometry, maybe something in the order of a few tens or hundreds of parts per million in stoichiometry, we didn't get the ratio just right. We were off by a little bit. Now we have one of our compounds in excess and the other one in deficiency.

If we have a different number of electrons surrounding the atoms, we could wind up with an excess free carrier density. In other words, you could self-dope your material if you're unlucky, in other words, if the material system has a propensity for this. And you can change the free carrier concentration, and because the free carrier concentration is changing, you might even change your mobility. So there are some effects that can occur as a result of small excursions from stoichiometry.

As a result of the self-doping, you're shifting the Fermi energy inside your semiconductor. And as a result of shifting the Fermi energy, it might lead to a cascade series of events. There could be other defects that form as a result of the Fermi energy change. You could have other so-called antisite defects. Atoms could switch positions inside of your lattice, and as a result of that, have very low minority carrier lifetime in certain materials.

So nailing the stoichiometry both from a very large sense, to avoid phase decomposition, instead of having a dalmatian film, you have phase pure film, and from a local perspective, once you get on to this phase space where you can grow your film well, you want to make sure that your stoichiometry is controlled to avoid self-doping and to prevent certain types of intrinsic point defects from forming that might lower minority carrier lifetime or change carrier concentration, change other properties of your film. For those who are working on these sorts of materials, I'm happy to talk ad nauseam about these topics, maybe after class, since this is a

more detailed subject.

Another topic of interest in thin films is grain size. At some point, grains don't matter anymore. The grain size, typically if you exceed the thickness of your film by about a factor five. In other words, the grain diameter's about five times wider than the thickness of your film, grain size is not as much of an issue. But if you do have very small grains, they can impact performance, because carriers will interact with those grain boundaries. And depending how recombination active they are or where the grain boundary is pinning the Fermi energy, the density of state at that, at the grain boundary, will dictate the effect on device performance.

So these are some very rough plots in crystalline silicon for thin film devices and for some thicker ones as well. So performance is a function the grain size. And I show crystalline silicon because the data is really well developed for it, but you see similar types of plots for organic materials, for some inorganic thin film materials, like CIGS and so forth. And this convolutes a few different parameters. You have to take into account that the recombination activity of the grain boundary is also a factor.

The next topic, general topic of interest, another tool that we'll want to have in our material science toolkit as we start designing these materials, we have to think about the interfaces between the different materials. Especially in thin films, interfaces are so important because we don't much bulk anymore. So the device could really be affected or device performance really reduced if we don't pay proper attention to our interfaces.

What are these plots over here? These plots are used to grow some very high efficiency materials, for example, by MOCVD or molecular-beam epitaxy. And what is represented on the horizontal axis is lattice constant. Lattice constant refers to the equilibrium spacing of atoms inside of your material. So this regular repeating unit cell that defines a crystal has a certain lattice constant, a certain distance-- physical distance-- shown here in angstroms.

The energy of the gap is shown on the vertical axis. And if we want to select two or three of these materials to stack on top of one another to absorb well at different

portions of the solar spectrum, we'll be choosing, for example, one band gap at around 1.9 eV, another band gap of 1 eV, or maybe if we want three materials, we'll go even higher at the top end and lower at the low end. So we'll stack different materials on top of each other to absorb preferentially in different regions of the solar spectrum and hence exceed the Shockley-Queisser efficiency limit, because now we're absorbing well in two or three different colors as opposed to just one.

And the energy gap here is important because you want maybe one material at 1 eV, one material at about 1.9 eV. But you also want to make sure that they can grow on top of each other, that you're not going to get a mismatch of that interface, that the lattice constants aren't so different that you wind up with these dangling bonds at the interface, where you have an atom coming down and nothing on the other side for it to bond to. And so you need to make sure that the materials that you grow are matched in lattice constant but varying in band gap, if you're trying to grow a multi-junction device, if you're trying to grow a very high efficiency solar cell device. And so the growth or matching of materials one on top of another is important, especially for the multi-junctions, also for some of the single junction materials if you really want to minimize the interface recombination.

So let's look at this growth system up here, the one that is typically used in high efficiency solar cell materials. We have germanium right here, gallium arsenide, and indium gallium phosphide, which is essentially a mixture between gallium phosphide up here and indium phosphide down here. You can alloy the two together and get an indium gallium phosphide mixture and stack these three materials on top of one another-- germanium, gallium, arsenide, and indium gallium phosphide.

They have three different band gaps. They absorb in three different regions of the solar spectrum. But they have a very similar lattice constant, and so the interfaces will be very well maintained. That's an example of using a chart like this to design your solar cell materials.

Next topic is material abundances. If we're trying to engineer all of these other parameters that we've been talking about-- the lattice constant, the band gap, the

grain size that also is a function of how the material grows, the ability to self-dope. We have all of these material issues that we have first and foremost in our minds. We go to the periodic table. We find some compounds that work. We're really happy about it.

But then, all of a sudden, life comes along and slaps us the face and says, well, we don't have enough of this material to really scale to get all the way to the terawatt cell [INAUDIBLE]. Oh, I wish I had known about this before when I first got started. So we're presenting to you upfront the state-of-the-art of what is known about material abundances.

And these last two studies right here, APS Energy Critical Elements and the DOE Critical Material Strategy, both of them represent a synthesis of the information, essentially the equivalent to the IPCC reports in climate change, but the best synthesis that we have right now about the abundances of different elements out there. There are as well a variety of different papers that have been published in the subject over the last couple of decades or even earlier.

So what we have to keep in mind is that our stardust out there is not in infinite supply. Every element we have on the planet that we know of came from fusion reactions in stars, and there was a probability distribution function of the appearance of those elements as a function of z on the planet as a result biased toward the lighter elements. And some of the heavier elements are in lesser supply, that we know of, on the Earth's crust.

Not to say that the deposits don't exist. Not to say that these studies right here are the authoritative end-all and be-all. We might discover next year or next month for tomorrow huge deposit of a particular element at a specific spot, let's say, under the Arctic. But from what we know right now, that's the stardust that we have to work with. These are our abundances. So if you'd like to design around it, I'd advise looking into those reports as well.

And finally, radiation hardness, getting back to Ashley's question, gee, what are the most radiation hard species? This is the efficiency of solar cell performance

normalized at the very start of a test, and this is the equivalent radiation damage. You could also think about this as the amount of momentum or energy depending transferred to the atoms inside of your semiconductor that would result in lattice damage that would result in a decrease of minority carrier lifetime or mobility, which ultimately would impact cell performance and efficiency.

We can see that different material systems have different degrees of radiation hardness. Some maintain their high efficiency until very high radiation dose, and others degrade much quicker. And look at this. This is a dose in orbit per year, right around there. And you can already begin to see that some of our most common compounds are not doing too well out there-- not doing too well in outer space. So we have the radiation hardness to take into account if we're putting these solar panels out there into outer space.

This is one older study I would definitely encourage you to look. There may be some newer studies. As the solar cell efficiency improves, they become more sensitive because you begin decreasing your efficiency with smaller variations in the minority carrier diffusion length. So those charts make look a different as time goes by.

AUDIENCE: Is the effect of the radiation cumulative? So for example, gallium arsenide or any of these would just continue to degrade as they're out in space?

PROFESSOR: So is effective radiation dose cumulative? I am not the expert on this particular topic. But from what I know about radiation exposure of detectors at synchrotrons, which is a little similar, not quite the same, the mechanisms involved with this essentially involve atomic displacements within the lattice. You have atoms physically being displaced from their equilibrium positions as they interact with this incoming radiation. And the probability that it occurs is a function of time, will increase per unit volume, and hence it can be thought of as accumulative exposure effect.

The first order impact would be on minority carrier diffusion length, impacting both lifetime and mobility. And to the effect that you have a relationship between

exposure time-lattice displacement, lattice displacement-minority carrier diffusion length, minority carrier diffusion length and efficiency, you might be able to model this effect. That would be my uninformed answer. Again, you might want to look this up yourself. Question?

AUDIENCE: Do you know why the cadmium telluride improves?

PROFESSOR: Oh, why does it improve with efficiency? I don't know specifically about why that is for this particular case, but do know that some materials are what are called defect tolerant. Some are more naturally able to withstand antisite defects or a certain concentration of damage, internal surfaces, voids, grain boundaries. Cad-tel, cadmium telluride, is fairly defect tolerant. It's one of nature's gifts to humanity in that regard.

The degree to which a material can be defect tolerant depends partly on the carrier density. If you have very high carrier density, you tend to screen defects. Another reason why they could be defect tolerant-- all of these compounds are somewhere between an ionic and a covalent semiconductor. In a covalent semiconductor, those materials tend to be very defect intolerant because there's the conduction band and valence band as a function of position, tend to be very flat. The material tends to be fairly homogeneous throughout the electron densities, fairly well distributed in a covalently bonded material.

In an ionic material, you tend to have charge localization. So energy as a function of position might look like this on an atomic scale as you go from one atom to the next atom on your lattice, to the next one, to the next one, to the next one, and that reflects the localization of charge in your material. Those materials can be more defect intolerant, because conduction can happen more from a hopping mechanism than from a band conduction mechanism, and this is really a gradient between, and most materials, they tend to be partially ionic partially covalent going down the list here.

And there's a bit of a shift between cadmium sulfide in zinc sulfide in terms of the ionicity covalence. So cad-tel would be with the chalcogen two lower than sulfur on

the periodic table. I would imagine it would be at this transition as well, but I'd have to look that up. Gives a place to get started and read more about it.

And then reliability and degradation-- this is important. This is a crystalline silicon module being loaded into environmental testing chamber. Inside of that chamber, the module is going to be put through hell and back. The temperature is going to be raised. The humidity is going to be pumped in.

Sometimes ultraviolet light is even put in there in some of the more modern advanced ones. And then the temperature can drop down to temperatures as low as minus 40 degrees C, depending on what the environmental chamber is designed to do, exactly how it's designed to stress or test your module. And the idea is to promote an accelerated degradation of the module on purpose to test what its failure modes will be, and we'll see these we go take a tour of Fraunhofer CSE in a couple weeks.

This is a crystalline silicon module being loaded in. If you were to put a thin film material-- and crystalline silicon are materials very, very thick, and we said at the native oxide was very tenacious. It was only a few tens or maybe hundreds of angstroms thick, and the junction depth was about on the order of a micron. If you have water attacking the surface of you silicon wafer, water vapor, really not too much of an issue, and silicon's is fairly inert anyway.

But now if you take a fairly reactive material, a thin film material that might react with air or might react with water, and it's so thin that the these rusting modes, or reaction modes, the weathering modes, can really impact a large fraction of the thickness of your device. Now you've become a lot more sensitive to accelerated degradation. Now you've become a lot more sensitive to the elements, and this includes both oxygen and water.

So if the ambient is able to penetrate through the encapsulate and get to the active absorber material, you may have accelerated degradation of module performance as a result. And so there also some unique failure modes within thin film modules. If you have two different species comprising your compound, one of them might be

prone to move in electric field. For example, copper is notorious for zipping along in electric field, in electromigrating. And so that's a failure mode that doesn't exist in large thick crystalline silicon modules but could exist in thin films.

And so because of all of this, and because of the growing realization that the way we test crystalline silicon modules and drive them to failure is not the same that we might be able to achieve failure in a thin film module. There are newer testing protocols, such as IEC 61853, that have been introduced in an attempt to do test appropriately thin film modules for their respective failure modes.

And this is, I would say, still work in progress. So much so, that we have a group project focused in part on this. It's still a work in progress to try to figure out how do we appropriately test these thin film modules toward the point where they can fail. Any questions so far on these topics? Because these are general issues that will affect all thin film materials, I wanted to make sure that we were comfortable with these general topics before we dove in any detail into the technologies themselves? Yes?

AUDIENCE: A question about lattice matching-- is it important to lattice match the semiconductor to the contact as well? Or is that not as important

PROFESSOR: So the question was is it important to lattice match the semiconductor to the contact? So let me emphasize that in many semiconductor contact combinations you would have a highly doped semiconductor right before the contact, a very localized region of highly doped semiconductor that would create a tunneling junction. In that case, the density of states at the interface doesn't matter because you have a tunneling junction. You're able to tunnel straight from the semiconductor into the contact.

The lattice matching would matter, though, if you didn't have a tunneling junction. If you had a regular Schottky ohmic contact, then you might have to worry about the density of interface states, which would be regulated by the number of dangling bonds, and then you might want every single atom pairing up with a neighbor on the other side. So lattice matching would be important for the contacts there.

All right, fun stuff-- wow, we've had a good dose of material science of the day. Thin film cost structure-- I just wanted to highlight one quick thing. This material right here, that's not the absorber material. The absorber material is a really tiny fraction of the material. This comprises the other materials within the module as well. So the encapsulates, the glass, and so forth, just keep that in mind as a kind of asterisks. So it's typical thin film cost structure. It evolves with time. This is a few years old, this slide, but it gives you a sense, a feeling.

In terms of global production, this is a year-old data now from 2010. During this past year-- so this was 2009 data shown in 2010. The 2010 market was very harsh for the thin film producers, many of which tend to be in the United States and in Europe. In 2010, prices dropped quite a bit, and that favored the low-cost Chinese solar cell manufacturers, many of which were invested in crystalline silicon technology.

So by no detriment to the technology itself, market dynamics worldwide, due to other factors, tended to favor crystalline silicon in the past year. And the market share of thin films contracted a bit so it's now about 90% crystalline silicon, 10% thin films worldwide in 2010. But the break down between the different thin film technologies, we had the so-called cadmium telluride, CIGS, so that's Copper Indium Gallium Diselenide, and amorphous silicon. And the dynamic between 2009-2010 was that the amorphous silicon shrank a bit. CIGS grew, and cad-tel continued growing, but more marginally because it was already big to begin with. So you could think of this red portion growing at the expense of the green, if you want to translate this into 2010 numbers.

So what is CIGS, cad-tel, amorphous silicon-- what are those materials? Well, we'll get into that. I think the best thing to do is to leave this for next class. I'll briefly go over cad-tel just because it is so important. It is the biggest-- the single biggest US solar cell manufacturer is producing cadmium telluride solar cells, or cad-tel for short. And to make just a description of what your solar panel would look like in cross section, this is your glass on the backside here.

This ITO Indium Tin Oxide. It is a what? A transparent conducting oxide, very good. So the ITO is a transparent conducting oxide. Your light, your sunlight, is coming in through here. So this is electrically conductive layer, but it's transparent, so it's allowing the sunlight through.

Tin oxide, we'll get to that in a second. Cadmium sulfide and cadmium telluride-- so the cadmium telluride layer is a layer that's absorbing most of the sunlight and producing electron hole pairs. The cadmium sulfide is providing the hetero junction separating charge at the hetero junction between the cad-tel and the cad-sulfide.

This tin oxide is generally an intrinsic layer. It's assisting here with the ITO on the front contact, and then you have your back contact that extracts charge from the back. There are a couple more tricks to creating a good cad-tel device that involve chlorine treatment and passivation of defects. That's where some of the activation comes in.

This is another view of the cad-tel device in cross section, another example. This transparent conducting oxide, in this case, is fluorine doped tin oxide, another TCO material. But very similar structure here, the cad-tel being the p-type material, and cad-sulfide the n-type material.

The thicknesses of these different layers you can see. The cad-tel is only a few microns thick, and the cad-sulfide this is even thinner. It's a very thin layer just serving to separate the charge.

The band diagram of a cad-tel solar cell is shown right here. We have the cad-tel here and the cad-sulfide right here. So you can see the junction. Notice, because of the thickness of this layer, the band bending at these interfaces extends quite an appreciable percentage of the total thickness of your device.

Whereas in crystalline silicon, we have the band bending right near the junction region, so right within a few hundreds of nanometers, maybe a micron away from the junction, and the device is 100 microns thick. So we had 100 microns approximately of this flat band condition, at least in the dark. Here we have bending

extending an appreciable percentage of the total thickness of our device, just by virtue of the fact that we have such a thin film.

And the characteristics, the deposition technology of cad-tel, as I said, it's nature's gift to humankind. If you put cadmium and tellurium in together in a pot and start heating it up, what evaporates is cad-tel. It congruently evaporates. So you could use a process called close space sublimation, where you essentially sublime your cad-tel, and you deposit it onto your substrate.

If you try to do this with most other compounds in the periodic table, you'll get either one element or the other element evaporating first. They'll create an overpressure. They'll evaporate off, and you won't get your compound depositing, but you'll get one element depositing on your substrate preferentially. cad-tel, again, nature's gift to humankind. The two come off together and form a cad-tel layer and so that congruent evaporation makes it very nice from a deposition point of view-- very low cost, high throughput deposition process for solar benefits from.

Environmental concerns-- cadmium has raised quite a bunch of concerns amongst folks in environmental groups because it's a known carcinogen. It is responsible in Japan for, I believe it was called the itai-itai ban, which means "the ouch-ouch disease." It was a disease that was acquired by folks exposed to cadmium during manufacturing. And as a result, cad-tel solar panels are not allowed to be installed in Japan. So First Solar cannot sell its cad-tel products in Japan.

There are very tightly regulated emissions laws in the EU and the United States, especially in the EU, where cradle-to-grave recycling of cad-tel solar panels are necessary. So you'll see a lot of cad-tel solar panels in large field installations or in commercial buildings where it's very easy to collect them all after their 20- or 25-year life span and bring them back to the factory, as opposed to having them distributed amongst hundreds of thousands of smaller systems deposited on rooftops.

The arguments in favor of having cadmium inside of solar panels is the following. It's better to tie up cadmium inside of a relatively inert compound, cad-tel, then to

have it go off and cause problems on its own. If you heat it up, the cad-tel would evaporate congruently. Typically cadmium is so-called "negligible" amounts are released during fires, and they put it in between quotes because these are studies, very good studies, and I trust the work coming out of the [INAUDIBLE] group very much.

His critics would argue that, well, the studies were paid for, in part, by First Solar, so how do you trust studies like that? I would counter and say, this is a pretty good group. Out of all the people to life cycle analysis, he's within the top tier. So it's some question as to that. People do question were the temperatures used in these studies representative of what you would actually get in the hot zone of a fire and so forth.

There's a public fear and perception issue. It's a big deal. And the folks would argue that much less cadmium is released per kilowatt hour than, say, in a battery, where we would use a nickel cadmium battery, for instance. And safe production methods now-- fully automated, and recycling is guaranteed by law. So have arguments in favor and against.

I'm going to stop right here, and I'm going to pull aside the teams during the last 15 minutes of class. I emailed to you. If those of you had checked your email before last night at 5 o'clock, should have received an email saying you're on a particular project team. Find your partners, cluster together. Joe and I are going to come around to spend a few minutes with each of you just to make sure that our first steps are clear and that we have a forward path and we gain some momentum. So self-assemble and don't leave the room before the chance to come talk to you.