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**PROFESSOR:** Last class, we introduced thin-film technologies. We described some of their generic advantages and disadvantages. I showed that particular book that's going around in the back there, *The Handbook of Photovoltaics Science and Engineering*. That describes several of the technologies that we're discussing today and last class.

So last class we covered general thin films and cad-tel-- cadmium telluride. Today we're going to be talking about amorphous silicon, copper indium gallium diselenide, and the last material system, which is actually more of a stack or a composite of several. Then we'll enter a debate, which will be kind of fun.

So amorphous silicon-- we talked about crystalline silicon. Crystalline silicon is the crystalline form of the element known as silicon, comprising a diamond cubic crystal structure. Amorphous silicon, on the other hand, is a very broad term catching a range of materials that lack long-range order.

Let me be a little bit more specific. Typically, there is some semblance of short-range order in these materials. One can describe the composition of amorphous silicon using, say, for example, a radial distribution function-- the average distance from one atom to the next. And you have these distribution functions describing the material.

It gets a little bit more tricky when you try to define it on a more detailed level, with average number of nearest neighbors, the local configuration, the number of stretched bonds locally. And the reality is that with any amorphous material, you can deposit a range of materials. It isn't just one specific amorphous silicon material that you get every time. Depending on your deposition conditions, depending on the pressure, and the temperature, and the power, during the PCVD-- the plasma-

enhanced chemical vapor deposition-- you obtain a range of amorphous silicon materials.

And within that range, you can find that the mobility of charge carriers can vary by several factors. The mobility, I believe, in amorphous silicon can range easily between 0.001 and 0.1 centimeter squared per volt second. So that's two orders of magnitude easily. And I have heard of amorphous silicon materials that have gone as low as  $10^{-4}$  centimeter squared per volt second, and as high as approaching 1.

So we have a range of material qualities as a result, and also a range of performance. Likewise, there's a range of stress in the film, depending on how you deposit your amorphous silicon. So delamination is of concern as well, depending on how you deposit it.

And the challenges from a material level is getting consistent quality material, high-quality material every single deposition, and overcoming certain degradation modes that are present in amorphous silicon, not present in other material systems-- certainly not present in crystalline silicon. For example, the Staebler-Wronski defect that's still up for some debate as to what precisely is the atomic nature of that defect. But it is known that when one exposes amorphous silicon to sunlight, that the performance will degrade with a relatively quick time constant over the period of minutes and hours, and finally stabilize. So when you report the cell performance of an amorphous silicon cell, it's always very important to emphasize that this is light-degraded or light-stabilized efficiency, as opposed to the efficiency you get when you take it straight out of the deposition chamber, and it hasn't been exposed to high amounts of sunlight yet.

In general, amorphous silicon has low hole mobility. Again, the precise root cause on an atomic scale for the low hole mobility is still up for some debate. There's a professor here at MIT, Jeff Grossman, who has performed a combination of molecular dynamics and density functional theory to obtain amorphous silicon samples in DFT.

And through those samples, he and his colleagues were able to determine that the low hole mobility might be caused by stretched bonds, certain types of stretched bonds, within the amorphous silicon. There are other hypotheses out there as well in the literature. Finally, just getting a uniform film deposition at high speed-- that's really key-- a high speed, uniform deposition of this layer has proved challenging in commercial production so far.

So all of this has combined so that amorphous silicon has received a lot of attention, but hasn't yet, in a massive way, been economically successful. This is a cross-section SCM of an amorphous silicon device, showing the TCO-- the transparent conducting oxide-- on the top. The TCO was deposited onto the glass, which appears at the very top underneath the scale bar.

The amorphous silicon layer right here in the middle is shown. It is in a PIN structure. So we've learned about P-N junctions. The I layer between is an intrinsic layer, meaning lightly doped.

And we'll see the band diagram in the next slide. The silver contact in the back here extracting the charge from the backside. So this is an example of the amorphous silicon technology. Again, another cross-section just for your reference, showing the stack there.

OK, the PIN device architecture-- right here we can see the P plus layer, or the P layer, the N layer, and then the I here in the middle-- the lightly doped, intrinsic layer. Note the band structure or the band diagram, how it's arranged. And interestingly, the layer thicknesses here are on the order of 300 nanometers for the entire stack.

It's rather thin, typically under a micron in thickness. The reason it's very thin is because amorphous silicon absorbs light much, much better than crystalline silicon. For those who have a solid-state physics background and want to know the root cause of that, I'll explain briefly.

For those who don't have the background and can follow, don't worry. Plant a flag.

We'll come right back to it.

So in crystalline silicon, we have crystal symmetry, and hence we have momentum conservation rules when we excite charge carriers, hence the indirect band gap nature of crystalline silicon. When we amorphize our material, we no longer have that crystal symmetry. We no longer have momentum conservation.

We can excite directly from your valence band into your conduction band. So that, in a very quick, hand-wavy way is why amorphous silicon tends to behave like a direct band gap semiconductor, absorbing light extremely well with a very high optical absorption coefficient. Hence, instead of 100 microns, we can get away with 300 nanometers of thickness.

All right, back to our flag. We see here the PIN structure. Everybody should be able to follow along and understand that if light excites a charge carrier here in the middle, the electrons will be swept the right, the holes to the left. And we'll have charge separation occurring.

Sometimes, we can have a stack of materials like shown here, with varying band gaps by, for example, blending germanium into the amorphous silicon. This can modify the band gap of the material. And we can wind up with a stack of layers, or we could simply use two layers of the same material. We wouldn't necessarily be able to absorb more efficiently across the solar spectrum, but we would be able to increase the voltage output of the device. So there's a variety of different amorphous silicon shall we say designs out there in the market.

Here's one example of the triple stack. We have amorphous silicon here at the top, with a large band gap. The band gap is somewhere in the range of 1.7 eV. Yeah, question.

**AUDIENCE:** I just have a question of how that-- so does the [INAUDIBLE] pair have to go to the interface between the [INAUDIBLE] to separate?

**PROFESSOR:** Yeah, yeah, so in this particular case, I believe this is a dual terminal device, which would be rather tricky to perform an operation. What you have to imagine-- this is

right here with very small perturbation. If you imagine it being biased in sunlight, then you can easily see how a larger voltage would result.

Right here, you can imagine a two-terminal device where you extract charge from here and here, or perhaps a four-terminal device-- which is less common because it requires more metal contacts. But that would contact the device here, here, again here, and here. So you'd have the two devices contacted.

If you have a two-terminal device, one can typically think about it as adding the voltages together. Then the current would be limited by the worst performer of those two. And that's why you have this thinner than that one over here, because we know that the light tends to be absorbed preferentially near the front surface.

We're absorbing an equivalent number of photons in this thickness and in that thickness. So the currents tend to be matched. So that's why I would guess, given the geometry of the fact that we have silver in the back and TCO in the front, and no explicit contacts here in the middle, that this is a two-terminal device as opposed to a four.

This stack right here is representative of what is commercialized by Uni Solar, a company in Michigan, where we have an amorphous silicon layer on the top, wide band gap semiconductor-- somewhere in the range of 1.7 to 1.9 eV, depending on the deposition conditions. Again, I mentioned that amorphous silicon is really a range of materials. There is no one amorphous silicon. Depending on the density of atoms inside of the amorphous infrastructure and their local configuration, you can vary the properties quite a bit.

So the band gap can vary, but typically it's in the range of 1.7 to 1.9 eV. Blending in germanium-- germanium being a bigger atom-- tends to reduce the band gap of the material. And you have successively higher concentrations moving toward the back, so the band gap shrinks from front to back.

And you can wind up with a stack like this. And this is an example here of a three-cell stack, where you have the combined quantum efficiency and the individual

quantum efficiencies of each of the sub-cells, showing you how you can really fill up the entire solar spectrum using a combination of these materials. Unfortunately, despite all these efforts, the material is still affected by what's called the Staebler-Wronski effect in honor of the people who initially determined it.

The Staebler-Wronski effect typically manifests itself as a degradation of material performance as a function of time. It's also known that as the layer thickness increases, the predominance of this effect also increases, and its impact also increases. So it manifests itself as a reduction of the fill factor, a reduction of performance, and we see the trade-offs during device design of amorphous silicon. So I would say, the essence of amorphous silicon is that it's a very promising material, has a wide degree of tunability. But the low hole mobility limits its performance to somewhere around 10% for just a single amorphous silicon layer, and in the low teens for the stacks of multiple materials, one on top of another.

And this right here is showing an interesting effect. When you begin heating up your substrate, when you're depositing amorphous silicon, you have amorphous material. If you heat up your substrate to too high of a temperature during the deposition process-- and this is also impacted by the concentration of silane gas to hydrogen ratio during the deposition process-- one can obtain a phase transition from amorphous material into what's called microcrystalline material.

That's shown at the very top. a-Si stands for amorphous silicon,  $\mu$ -Si for microcrystalline silicon. Microcrystalline silicon is right at the phase transition between an amorphous silicon and a crystalline variant polycrystalline variant of silicon. And in some cases, it can actually contain a mixture of both amorphous and crystalline regions.

And so it's very tricky to nail to the position conditions just right. Somebody along the way figured out-- wait a second-- we can actually use this microcrystalline silicon to our advantage, and stack a layer of microcrystalline silicon on the bottom, put a layer of amorphous silicon on the top. And that was called a micromorph technology as a result.

And there are companies that have commercialized micromorph. So the micromorph technology commercialized by Oerlikon and previously by a company in the United States called Applied Materials. And we'll get to that in a couple slides as well.

This right here is a brief slide just addressing the issue of how growth conditions can impact material quality. There are a number of growth parameters, shall we say, that impact whether you obtain an amorphous material with high mobility, with low mobility, a microcrystalline material, nanocrystalline material, and so forth. And if you're interested in more details, these NREL reports from the late 1990s and early 2000s, mid 2000s, are really a treasure trove of information, if you really want to get up to speed quickly on how to grow high-quality amorphous silicon layers.

OK, so these are record amorphous silicon cell efficiencies. This, I believe, was from the Martin Green tables that come out each half year in *Progress in Photovoltaics*. So he and his colleagues produce an article every half of a year in *Progress in Photovoltaics*, describing the record efficiencies of lab size cells-- maybe a centimeter squared-- all the way up to full-size modules.

So we have here amorphous silicon and the blended amorphous silicon germanium, or SiGe for short. People sometimes call silicon germanium SiGe. So we have a variety of different types shown here, and the areas of the devices shown here.

I would caution over-interpretation of the very small area devices. If you're at 0.25 centimeters, you're at a very small linear dimension along the side of the cell, and you can wind up being impacted by edge effects. Sometimes this is the active area of a much larger device, where they've shrunken down the aperture.

But depending on the texturization of the surface, you still get light trapping and, essentially, a larger active area than what is actually being shaded off. So I would caution you against over-interpreting these very small area measurements. At 1 centimeter squared larger, you're typically in a regime where the results are more believable.

The Jse's shown here, Voc's shown here. Note in certain cases, the Voc you would expect from amorphous silicon, if it's a band gap of 1.7 eV, you'd expect a Voc somewhere in the range of maybe 1.4 volts. And sometimes you get much lower than that.

Likewise, the short circuit current is rather low, say, compared to a crystalline silicon device because of that higher band gap-- the inability to capture some of those lower energy photons. And so the record single amorphous silicon device performance somewhere buttressing up against 10%-- not quite. And then if you combine different layers into a stack, for example here, you can move into the low teens for your performance. Flag that-- these numbers here. We're going to get back to this, and use that to understand why some of the technologies didn't make it to commercialization.

This represents the largest scale attempt to commercialize amorphous silicon technology. This was a turnkey line. Let's start from over here.

This is a human being seated at a computer-- two humans. This pod right here-- this machine-- represents one of these little components right here that fits into a much larger assembly line. This is the PCVD reactor, actually. I believe there were seven of them attached to each of these little pods right here.

So this the plasma-enhanced chemical vapor deposition reactors were depositing microcrystalline silicon and amorphous silicon onto sheets of glass that were as large as you could possibly transport. Does anybody just happen to know the number off the top of their head? What is the largest sheet of glass that you can physically transport, say in commercial form, such that you could buy it in bulk without custom design of the Pilkington float glass process?

**AUDIENCE:** It's as big as the cross-sectional area of that.

**PROFESSOR:** It's about, yeah, yeah, definitely. That's a good place to start. It's actually dictated by what can fit on some of the trucks that transport the glass back and forth. You ever seen the glass transport trucks with the sides where they put the panes of glass in?



And they have the chassis of the truck like so, and the glass along the edge.

It's around 3 by 3.3 meters. And so these deposition systems could incorporate huge sheets of glass. And they would leave it up to the customer whether they wanted to quarter them and make reasonable-sized modules, or whether they want the full-size module and have to use cranes to install them, which would reduce the labor content of installation, but would shift the burden onto the automation.

So you see the panes of glass coming along, pre-cleaning, and eventually insertion to these devices. Why so many of those devices? Why so many PCVD reactors like little piglets around a pod here?

Each of these reactors would have a cycle time somewhere on the order of a few 10s of minutes-- so my estimate would be somewhere between 20 and 30 minutes, maybe up to 40. Because the microcrystalline silicon layer just took so long to deposit. But without that microcrystalline layer, it was difficult to reach 10% efficiency.

With just the amorphous silicon layer, the efficiencies were in the range of 6% to 7%. And if you start doing calculations for a 6% or 7% module, you realize very quickly that the cost of the glass, and the encapsulants, and everything else adds up, because your device is so low in efficiency that you need more encapsulant, more gas, more labor, more installation to produce a panel to produce the same amount of power. And as a result, the system cost was very high.

This technology couldn't compete once the Chinese production started really ramping up in the market, and decreasing the cost of traditional crystalline silicon modules. And the SunFab Project, which was Applied Materials name for this amorphous silicon line-- or micromorph line, in reality-- was shut down relatively recently, about a year ago, when it I realized that this was no longer commercially viable in the face of some of the low-cost competition from crystalline silicon. All that could change very quickly, if somehow one of you were to develop a way to, say, double the record efficiency number.

So if someone were to figure out why exactly hole mobility is so low, impairing transport inside of these materials, in principle one could then envision rolling it out into the SunFab line. There's already a turnkey production equipment that's been built by Applied Materials, ready to go. And you're off and running. So that's an opportunity out there.

This lists some of the commercialization attempts. And the bottom line at the end of the day was that 6% modules were too inefficient to be profitable, unless you reach scales of, say, gigawatts. And believe it or not, there was one company out there called OptiSolar, the business plan was literally to scale up to a gigawatt faster than everybody else. And even though it was lower performance, the sheer size and scale of the manufacturing facility would reduce the cost of the amorphous silicon relative to the crystalline silicon competition. Unfortunately, OptiSolar didn't make it, either.

So the companies that are left today producing amorphous silicon include Oerlikon. This is a Swiss company that produces turnkey equipment, and Uni Solar, which is selling the actual modules of amorphous silicon. They have a nice roll to roll deposition process on these stainless steel foils. Very nice factory-- believe it was toured by several members of our current administration. And they're still going.

**AUDIENCE:** Sorry--

**PROFESSOR:** Yeah.

**AUDIENCE:** Is the roll that that person's holding-- what is he holding?

**PROFESSOR:** I usually think, based on the color, that this already has amorphous silicon deposited onto it. But it could be at some intermediate phase. I don't know for that specific roll, but in principle, yes, at the end of the manufacturing line, they'll have a full stack-- the triple amorphous silicon and then the two layers of SiGe beneath it.

**AUDIENCE:** What's-- the base is flexible, so what's the thing that the film is deposited on, do you know?

**PROFESSOR:** So what they incorporate their flexible material into typically, one of their products is roof shingle. That looks very similar to a standard, asphalt-based roof shingle. And it is very nice building integrated technology. I happened to see one back when I was a graduate student, and I was inspired by the building integrated potential there.

So there are attempts to integrate amorphous silicon into regular crystalline silicon technology, as well. Turns out amorphous silicon passivates the surfaces very nicely. And you can create what's called a HIT cell structure, which is a heterojunction with a thin intrinsic layer, using a silicon substrate. Typically what's used is an n-type base. And then the amorphous silicon layers are deposited on either side.

And that device is currently being commercialized by a company called Sanyo in Japan. The patents for the base HIT cell structure expire very soon, if they haven't expired already. And so there is a fair amount of interest-- several companies out there right now attempting to reproduce this process. But it is fairly tricky. And again, a lot of it boils down to managing the interfaces-- making sure the interface between the crystal silicon and amorphous silicon are of high quality.

So we have our HIT cell structure here. Let me hop over to the last thin-film materials so we have adequate time for our debates. The copper indium gallium diselenide, or SIGS for short-- this is a quaternary phase, sometimes comprised of even five elements.

But let's show this is the chalcopyrite structure right here, with copper shown in black, indium or gallium shown in gray-- typically there's some blend between the two-- and the chalcogen-- the selenium or sulfur-- shown in the white right here, typically selenium. So we have here an example of the crystal structure. As I understand the situation, this crystal structure came into being because copper sulfide demonstrated potential as a photovoltaic material early on, say in the late 1970s, early 1980s.

There were attempts to grow high-performance copper sulfide cells. They failed because copper electromigrated. In the presence of an electric field, copper, a very

small ion far to the right on the 3-d series of elements-- so if you look at the transition metals, copper is on the far right, meaning you're adding more and more and more protons to the nucleus as you go from left to right, and you're pulling the outer shell in.

So if you look at atomic radius going from left to right in the periodic table, you'll see that the atoms tend to shrink. So copper, being on the far right-hand side of the 3-d elemental series, has a smaller atomic radius compared to, say, iron, or manganese, or titanium. And as a result, it could move fairly easily throughout the lattice if it is present in a charged state-- if you have, say, copper plus-- and a large electric field distributed across a thin film solar cell device. So copper sulfide devices ended up degrading quickly over time. And it was realized that some heavier elements needed to be included to stabilize the crystal structure.

So in the lab, the reason why SIGS-- this particular material right here-- is so interesting is because in the laboratory, efficiencies on the order of 20% have been achieved. For large area-- you'll have to correct this number right here-- you can increase that to 15% plus-- 15.7% in fact, over large area devices. That's a very recent result coming out of MiaSole, a company in California.

There are dozens of startup companies focused on SIGS development. And it is a very challenging problem to get the stoichiometry right, and to passivate the defects inside the structure, including surfaces. Where many companies fail or fall short is getting the stoichiometry just right over a large area. It's as simple as a manufacturing challenge.

The idealized structure of these thin-film devices-- you have your SIGS layer right here in the middle. In this case, it's shown as CIS or cis, but you can add gallium as well. Typically, gallium is blended in.

Moly-- molybdenum-- back contact on the glass-- the glass in this case is just the support for the structure. Molybdenum here would be non-transparent. It'd be an opaque layer.

The cadmium sulfide on the front side here forms a very nice interface with the SIGS layer underneath, preventing any interface damage or any segregation, say, of gallium to the surface here. And then the zinc oxide layer on the top, which serves as the buffer window layer, depending, is then deposited on the cadmium sulfide layer. And eventually charge is brought away.

This right here is another three-dimensional rendition of the same. What is unique about each of those dozens of startup companies is the process in which they deposit the SIGS layer, typically. So you have companies like MiaSole that are invested in sputtering of SIGS.

You have companies like Nanosolar that are invested in ink-based printing of SIGS. So they print an ink down, and then they sinter the ink to form the layer. And like those two, there are many other companies out there that are depositing SIGS in some way, shape, or form.

The folks at NREL seem to be more in favor of thermal evaporation based process for SIGS. Many of the more successful industrial renditions of SIGS right now-- at least the ones that appear most promising-- are using other deposition methods. So you'll see a variety out there, of deposition methods for SIGS technology.

And one of the things to keep track of, as you watch and monitor all these startup companies, is to bin them by their process, and to begin to discern trends. As we start to see some market leaders evolve in the sector, begin to discern which technologies are the most appropriate, perhaps for large-scale deposition of this material system. Interfaces are critical. Here are some examples of attempts at mapping out-- and quite successful attempts at mapping out the, shall we say, the band diagram of a SIGS-based solar cell. One thing to keep in mind is that, just like amorphous silicon represents a broad class of materials, SIGS also represents a broad class of stoichiometries, meaning the ratio of indium to gallium, the ratio of-- if you include it at all-- sulfur to selenium is critical in determining the properties of both the bulk and the surfaces.

Typically at the surfaces, you will get termination by one atom, one atomic species

or another-- one elemental species or another. And that will determine, to a large degree, the electronic quality of that surface. So for a long time in literature, you had debating world views of what the band diagram of a SIGS device really looked like.

And it turned out a lot of people were right. They just had varying starting materials. So they were comparing apples to oranges.

The thing that keeps people going with SIGS is that in the laboratory, efficiencies, I believe, now up to 21% have been demonstrated. So that is really encouraging. People-- venture capitalists-- will look at this and say, wow, with those high efficiencies, you could really make solar cheap. The amount of, again, glass, encapsulants, labor, and so forth that you have to have for watt peak is lower, because the cell can perform at a higher performance.

But the downside is, there's a gap between-- a substantial gap between-- what is commercially manufacturable today and that record efficiency device. Sometimes the practical matters of commercialization are the ones that impede a technology from getting to market. And I have a modicum of faith that SIGS will make it. But if it fails to reach its true market potential, if it fails to realize its dream of becoming a significant fraction of all solar panels produced, it will most likely be because of these process engineering issues associated with depositing over a large area, coupled to the scientific gap in managing interfaces properly. So that's the story of SIGS in a nutshell.

There are some minor issues, shall we say, associated with cadmium. There are attempts to go to an all zinc oxide or maybe a graded zinc oxysulfide buffering window layer here in the front to get rid of the cadmium. We'll discuss that shortly.

And I would say that's probably the biggest near-term challenge. With the removal of cadmium, you can access more markets. And secondly, SIGS does contain indium, which is not in an infinite supply in Earth's crust. It's debatable how much of an issue that really is. And we'll get to that in our discussions as well, in our debates.

SIGS commercialization-- several startup companies and I would say a lot of

promising research and development going on right now. This particular technology right here-- let's keep this company nameless for now. This company represents some of the difficulties in ramping up large area SIGS.

They deposit it sometimes over large areas, but would achieve inhomogeneous results. And so the ultimate form factor for the devices was to chop them up into areas that are not too dissimilar from an actual crystalline silicon device. So to chop up their layers into individual, discrete cells, and then to connect them-- solder them together, much like a crystalline silicon device would be put together inside a module.

So the dream of having this inline, thin-film process roll to roll was reaching an abrupt wall, shall we say, in the development process because of the lack of large-scale uniformity. So you need to chop them up into smaller units, which would add to the cost, which would decrease the module performance as well, and now you have gaps in between the cells. So it just goes to show the difficulty of bringing a new technology to market. And hopefully, they're doing better now.

Lots of promising news for SIGS, like this particular article-- "The Rise of SIGS, Finally?" question mark. There has always been a lot of promise in the realm of SIGS because of the high performance and high efficiencies reached. The big question is, can you accomplish this at large scale for large area modules? That's been the big challenge so far-- and of course, materials availability.

So let me pause right here. What I'm going to do-- we are going to shift gears. And for the next 20 minutes-- unfortunately, not half an hour, but for the next 20 minutes-- we are going to enter debate mode.

What we're going to do is divide the group into-- this group right here-- into your project teams. And you'll cluster together and work together on this next exercise. So for the very beginning, we're going to have the cadmium telluride debate. That will be debate number one. We'll be discussing the pros and cons of cad-tel.

Keep in mind that First Solar, a gigawatt company, meaning one of the largest

companies in the world, and certainly the largest company in the United States, is going full force producing cadmium telluride modules. The debate question that you'll be faced with is, is it a good investment for the United States? Say, for example, you're in charge of US government research and development funds. Should you be putting your money into cad-tel? Or should you be putting your money into something else?

And we'll have two sides of the debate-- one that will defend cad-tel and say, no, it's a very promising technology. We should be going all in. And the other side that will be adopting the counter argument saying, well, cad-tel has these concerns. Perhaps we should be looking elsewhere to invest. And that's the debate number one-- cad-tel, no cad-tel.

For the folks working on earth-abundant materials, the second debate will be focused on that question. Recently, there's been a lot of interest in developing earth-abundant alternatives to, say, SIGS, because of the indium content, and cad-tel because of the tellurium content. And there's been a huge amount of momentum behind it.

But there are few naysayers out there who say, well, wait a second. We've always come up against shortages of one kind or another, since the days of Malthus's warning about the limits of population growth because of limited food supply. But then we developed fertilizers. And that overcame that limit.

Likewise, in these resource abundance issues, I'm sure we're going to find some new way to extract the metals. We'll find a way around it. We'll discover new deposits and so forth. You hear similar arguments in the peak oil debate, right? And so what I'd like to do is to set up two teams there as well to debate this particular question.

[APPLAUSE]

And we furthermore recognize that several of these issues that might appear black and white, in reality have many shades of gray in PV. This cad-tel debate is one of



them. We'll hear the second debate the next time.

And anything from should we invest in silicon technology or should we develop thin films will have these shades of gray as well. So it's important to recognize that simple fact as you gain maturity, and shades of gray in your own ability to argument one side or another. So thank you, and we'll see us on Thursday.