[SQUEAKING]

[RUSTLING]

[CLICKING]

JUEJUN HU: OK. So we'll get started. So as I said in the last lecture, we are going to be discussing about devices, microelectronic devices made out of amorphous silicon. OK. Specifically, we are going to focus on two classes of devices, display and solar cells.

All right. Display. So for display, what we want to do essentially is that we want to be able to control an array of pixels so that we can actually control the spatial dependent light emission pattern.

So the first question we want to address here is what is the architecture that we can use to actually realize such a pixel level address array. The conventional way of doing a display-- the earliest days of doing such a display architecture is to use an architecture called direct drive. So your direct drive, each pixel is essentially driven using a pair of electrodes so that if you have, say, n number of pixels, you need essentially 2n number of contacts so that you can realize individual addressing of each of the pixels. OK.

One example of this kind of direct drive of a display is if you think about the early days of the liquid crystal display calculators. Right. They use, essentially, this kind of a seven bars to represent numbers. In that case, each of these bars is actually individually controlled by a pair of contacts.

Now you can easily see what's the challenge with this kind of scheme here. It's really not scalable. If you are going to go with, hundreds, thousands, millions of pixels on a display, you obviously cannot afford having that large number of electrical contacts. OK.

So that's why, to realize this kind of large scale 2D array of pixels, people use two sorts of architectures here, essentially called passive matrix and active matrix. OK. Both cases use a crossbar architecture. So this is actually quite similar to the obtain memory we talked about, the phase change memory, the 3D cross point memory we discussed about when we talked about phase change memory devices. OK.

Essentially, you have electrical wires that goes in two orthogonal directions, horizontal and vertical directions. And then you can think of them as this wire goes in two different planes. OK. And then at the cross point between each horizontal and vertical wire, you have one pixel essentially sitting in between here. OK. So at each cross point, there's essentially one pixel. You can then light up each of the pixel by applying a bias across a pair of corresponding horizontal and vertical wires there. So this is the basic architecture for both passive and active matrix displays. Now the difference between passive and active matrix displays is that, for a passive matrix, there's no individual switch that's co-located with each of the pixels here. So for example, let's say if you want to light up say this pixel, what you want to do is you want to apply a bias essentially across these two wires here. It's going to light it up. OK.

Now suppose if you want to light up another pixel, let's say maybe this one, if you want to light up this one, then what you have to do is you essentially apply bias across here and here. But now you see the problem. In addition to lighting up these two target pixels, you also light up this pixel and this pixel.

It's also, essentially, you also apply bias across that two. So what this means is that if you don't have an individual control located within each pixel, then the best you can do with this kind of passive matrix display is to do a row by row scanning. So what you would do, you essentially, for example, apply bias across one of the horizontal lines. These are actually called scan lines.

OK. Then depending on which pixel you want to light up in that row, you then correspondingly apply the bias on the vertical lines. The vertical lines, these are actually what are called the data lines.

So now, for example, display these two pixels. They light up. Then you move on. You turn off this one, this scan line. You move on to the next scan line, apply bias, and then you display the next line. So you do this kind line by line scan. That's why it's called scan line. Data line, essentially, gives you the actual data or the actual display pattern.

So the advantage of this kind of scheme here is that you can significantly simplify the electrical contact structure. If you have an m by n pixel array, you only need m plus n number of contacts. So this is vastly simplified compared to a direct drive display.

Downside for this kind of passive matrix display, obviously, it it's slow because you can only display patterns line by line. And that's why, if you look at state of the art displays people use, most of the time, you'll be looking at an active matrix display. OK.

So active matrix display is also a crossbar structure. But the main difference here is that, within each pixel, you actually integrate a transistor, a thin film transistor, TFT. OK. So TFT.

A thin film transistor is basically an electrical switch. You can use it to essentially control a pixel being on or off. So therefore, you will be able to individually control all the pixels here without having to worry about the crosstalk, as you see here in the kind of passive matrix arrays. OK.

Now the TFTs. This has to be made out of a semiconductor. And because most displays, they're actually made on glass substrates. So as we have mentioned in the previous lectures, you will not be able to grow single crystalline silicon on amorphous glass substrate. So that's why you have to look into amorphous or polycrystalline materials. And that's where actually amorphous silicon comes in. They are the material that's being used to make the thin film transistors.

So that is the basic structure of the display arrays. Now, in this next slide here, I'm showing you, essentially, the specific architecture within each individual pixel. So for active matrix display, there are, in general, two main variants there, active matrix liquid crystal display or AMLCD, or Active Matrix Organic Light Emitting Diode, AMOLED.

So if you look at the layer structure for liquid crystal display pixel, what you have backlight. Backlight essentially is a large area light source. It's constantly on. It's always emitting light. OK. White light, basically. OK. Broadband white light.

It goes through a linear polarizer, which cuts immediately 50% of the light. It's only when you actually-- usually, the light source is not polarized. So when it goes through this polarizer, you lose 50% of linear polarized light. We'll explain why we actually need to do that. OK.

Then it goes through a TFT backplane. So this is, essentially, on the glass substrate where you have the thin film transistors made of amorphous silicon or polysilicon, as we'll talk about later. And then the light continues to transmit through and then go through a liquid crystal layer.

So you probably have already learned about liquid crystal materials. Right. This is the kind of material where they are actually intrinsically optically chiral. So when I say they are chiral, essentially means that they have this unique property that the polarization of light as a propagating liquid crystal, the polarization plane actually rotates as it propagates. And you can actually electrically control the chirality of the liquid crystal so that you can control the extent of this polarization plane rotation.

OK. So for example, suppose that you don't apply any electrical bias. Then you have, essentially, say 0 degree by rotation. If you apply bias, you can have 90 degree rotation.

So then if there is no electric bias, then the polarization plane will not change. It will just go through all the top structures and then directly go to the top polarizer. The top polarizer is set up in an orientation that's 90 degrees with respect to the bottom polarizer.

So if you don't have any light polarization, then all the light coming from bottom polarizer is going to get blocked by the top right polarizer. So it's not going to go through. It's stuck. So the pixel is not lighting up.

On the other hand, if you apply a bias, you rotate the liquid crystal molecules so that you actually turn the polarization plane of light by 90 degrees. Then that will align with polarization plane of the polarizer. Then you get light transmission through. So the pixel will light up in that case.

So that's how you actually use, essentially, this kind of electric bias across the liquid crystal to control light transmission. You can think of liquid crystal essentially as a tunable filter that allows you to control light on or off.

So then the next part is that you have color filter. For color displays, we need to essentially make up all the visible color using three primary colors-- red, green, blue. So the way to do it in liquid crystal display is to have three kind of color filters which, again, cuts off a lot of transmitted light because when you have a red light filter, you essentially throw away all the green and blue light. Same thing for the other two colors. So again, you're losing lots of light in this process here.

Finally, then you go through the color glass. You go through a polarizer and then it comes out. Right.

So what we're seeing here, AMLCD is basically a tunable light filter. It allows this voltage gated selective transmission of light. And that's how you actually see a color pattern.

All right. Now what we have also seen here is that this kind of architecture actually wastes a lot of light from the polarizers, from the color filters. You really have to throw away a lot of useful light. And also the backlight source, this light is always on. Right. It always stays on.

So that means that there is also a constant power supply you have to supply to the light source, regardless of whether or not a pixel is light up or it's dark. A more energy efficient alternative to this kind of AMLCD is so-called Active Matrix Organic Light Emitting Diode, AMOLED. This is also maybe a more advanced, more recent generation of displays that we're seeing also in high displays right now, especially in small consumer electronic devices like smartphones.

For AMOLED, what you would do, you actually directly have this organic light emitting diodes. You can process them so that they directly emit the different colors. So for example, if you want to get three colors, you have one LED that emits a red, one emit a green, one emit blue.

If you use them, you apply bias. You send current through them. They are going to light up. When you don't use them, you just simply don't send the current through them. They are going to be dark. OK.

So you see that in this regard, AMOLED can be more energy efficient compared to AMLCD. Number one, you don't have that many light loss mechanisms. Number two, you don't have a backlight source that's always on. You only turn on LED when you actually need the display pixel to light up.

Now you may also notice here there's still a polarizer on top. You may wonder why you need a polarizer. Again, this is actually a circular polarizer but same thing. If a circular polarizer, you throw away 50% of light. You have two circular polarizations.

One is left-handed circular polarization. One is right-handed circular polarization. So if you have such a polarizer, again you throw away 50% of light. You may wonder why you need polarizer there.

Now, the reason you need this polarizer here in this case is actually because it's customary that behind this TFT backplane, there's usually a metal mirror metal reflector. The reason you want a metal reflector there is that because in OLED, the light emission is isotropic. So 50% of light emitted is actually downwards.

If you have a metal mirror, you essentially reclaim that 50% of emitted light. But now what happens-- suppose you don't have the polarizer-- is that if you are trying to use your display, especially in a bright ambient environment, then the ambient light is going to go through a screen.

It's all transparent. It's going to go all the way to the reflector, [INAUDIBLE] reflector, and then comes back. So this gives rise to a very bright background due to the ambient light.

OK. You don't have a dark screen. And this will severely decrease the contrast of the display pattern you actually see. So that's why they add this circular polarizer there.

And the idea is that if you have any ambient light that comes in after it goes through a polarizer-- let's say polarizer is, say, left-hand circularly polarized. OK. So then the light is going to go through a metal mirror where it gets reflected by the metal mirror. Its handedness actually gets flipped. So from left hand polarized, it becomes a right hand circularly polarized.

So when it comes up, this reflect light is going to get blocked by this circular polarizer so you don't see, essentially, this kind of reflected light. And that's why, if you look at the typical display screen, despite the presence of this reflector there, the screen typically looks dark. That's because a lot of the ambient light is actually getting blocked.

The only reflected light you are seeing here is actually direct reflection on the top surface, the glass cover. The glass cover will reflect a little bit. That's the only reflection you see. That's why the screen appears mostly dark OK.

OK, so in both cases, you always have this TFT backplane there. This is the backplane where you have an array of these thin-film transistors. Each transistor controls one pixel. This is how you control on/off switching of all the pixel arrays here. And as I said, these things are made of amorphous silicon, or low-temperature polysilicon, or LPPS. We're going to discuss about these materials in a little bit.

Now before I go to that, I just want to quickly mention about the advantage and disadvantage of these two kinds of architectures here. So if you look at the AMLCD, you can see that it has a more complex layer structure. It's thicker. And as I said, it tends to be a less energy efficient compared to AMOLED. But AMLCD is a relatively mature technology. It's been very well-established. It's also relatively low cost. So that's why it's still used in a lot of more low-end display applications. For more high-end electronic devices, people now tend to use OLED instead of AMLCDs.

OK. So now, let's take a look at-- this is actually what the display looks like. What I'm showing you here, this is actually a little optical micrograph of one of the older generations of iPhone displays, something like iPhone 1 or iPhone 2, where they use AMLCD. If you look under an optical microscope, you clearly see the pixels here. These are actually three-color pixels. You see some black shadow right here. These are actually the thin-film transistors.

Now amorphous silicon is actually absorbing in the visible spectrum. That's why people can make solar cells out of them. So that's why they are opaque. And you can see that. It blocks some of the light there. So you will not be able to see the individual pixels in more recent generations of displays because they have what's called a retina display. "Retina display" essentially means that the human eye will not be able to resolve individual pixels. So you won't be able to see individual colors.

However, there's actually a very simple trick that allows you to see the individual color pixels. So what I have here is a pipette. This is water. Let me try to put some small water droplets on top. It's not easy, but OK. I'm going to pass my phone around. You can try that using your phone as well. But if you look at the water droplets, because of small meniscus, they serve essentially like a lens. You can clearly see the magnified pixels. Three colors. Are you able to see it?

Good. All right. But now if you look into what actually goes into this little transistor there, this is a cross-sectional structure of what it looks like. So you basically have a substrate. This will be some kind of display glass, typically made out of a sodium-free glasses that were actually prepared using a downdraw method. If you recall what the downdraw method is, this is a technique people developed so that you can actually prepare large flat glass sheets without surface contamination. The surface is not in contact with any kind of other materials. It's basically suspended in air. So those are what's designed for mainly stringent requirements of the display industry.

On top, you have a gate, which basically is metal. Essentially some kind of an electrical conductor, some kind of electrical contact. Then you have a gate material, gate dielectric. The gate dielectric typically is silicon nitride that's deposited using PECVD in the same process as amorphous silicon. And then on top, you have your actual amorphous silicon material. And you have two electrodes here. These are the source and drains.

So essentially, the current flow through a source and drain is where you want to switch on and off by this kind of thing going through this. So it's a field effect transistor, basically. So the way it operates is that you can control the electrical conductance or the magnitude of the current between the source and drain by controlling the voltage you apply on the gate.

So the way it works is if you think about-- so this is the bottom gate. This is the gate. This is a dielectric material. You have your source and drain here. And then this is your semiconductor material. So let's say plus, this is minus. So if you apply a bias onto the gate, let's say if you apply, say, a positive bias, now this layer of gate dielectric, this is actually electrically insulating material.

So what you have here, amorphous silicon is electrically conductive, gate is electrically conductive, separated by an insulating layer. What you have here is basically a parallel plate capacitor. So if you apply a positive bias here, you are going to accumulate a lot of positive charges on the gate. At the same time, it means that you're going to accumulate a lot of negative charges at the interface between amorphous silicon and the gate dielectric. So eventually, you will be able to form essentially what they call an n-channel, a thin layer where you have lots of electrons accumulated near the interface.

So you're starting amorphous silicon, if it's undoped. Then, as we have mentioned, if it's undoped, it has very low electrical conductivity. Now, effectively, through this field effect, you are able to essentially dope electrostatically the surface layer with a lot of n-type electrons. So now this becomes a conductive channel, and you can now pass current through between the source and drain electrodes. So this device will now be in an on state. So simply put, by changing the bias on the gate, you can change the electrical conductance between the source and drain. And therefore, you can essentially switch this device on and off by simply changing the bias you apply on the gate. OK.

All right. Now on the right-hand side plot here, I'm basically showing you what the I-V curve looks like. So vertical axis is the current, horizontal axis is voltage. Now we are referring to the voltage and the current between the source and drain. I have plotted a few different curves there that correspond to different gate biases, of different gate voltages. You can clearly see the curve actually goes into two different regimes.

Initially, you have what's called a linear regime where the current essentially scales linearly with the applied bias. Now that's easy to understand. Initially, you have low bias. You have a conductive channel that's present. If you apply higher bias, you have more current flowing through the conductive channel, the n-channel. And therefore, you get just more current, basically. So higher bias, more current. So that's what happens in the linear stage.

Now beyond the linear stage, you see the curves start to plateau. This is called the saturation regime. In the saturation regime, what happens is that you essentially apply a very large source-drain voltage. So what happens if you increase the source-drain voltage? So if you increase source-drain voltage, basically you put more charges here and here. This is positively charged.

So it means the electrons in the n-channel is going to get attracted to this side. Same thing this side. This is negatively charged. So it means the electrons are going to get repelled away from this electrode. So as you increase the source-drain voltage, what's going to happen is that the shape of this n-channel is going to change. It's going to become asymmetric. You're going to have more electrons accumulating on this side and less electrons accumulating on that side. So this n-channel will look more like this.

Eventually, if you continue to increase the bias between the source and drain, you're going to have a phenomenon of so-called pinch-off. Pinch-off means you have such a high bias such that the n-channel becomes disconnected from the negative contact here. Again, because of electrostatic repulsion. Because of the large negative bias. So it pushes all the electrons away from this electrode there. So then you only have the n-channel that's not connected to one of the electrodes.

Now this is what leads to the current saturation. Once you have a pinch-off, if you continue to increase the bias, you're not going to increase the current going through between the source and drain. Because as you increase the bias, this region, the disconnection region, the separation is going to become bigger, which essentially restricts the more current you can pass through there. So that's why you see that in the saturation regime, as you increase the source and drain voltage, the current flowing through is actually not increasing. It pretty much plateaus. That's exactly because of this kind of pinch-off mechanism there. Yes?

STUDENT: Why does it plateau and not drop to zero?

JUEJUN HU: Well, basically because this is not going to-- when we say pinch-off, this is a schematic. You will actually have a decreased density of negative charges. It doesn't go to zero. There is still current that can actually pass through this small gap there.

And also what you also notice here is that in this regime, this actually can be a very nice switch because you can actually control the current by changing the gate voltage. You can imagine that if you apply a larger gate voltage, you put more positive charges here, you can attract more negative charges on the other side.

So the higher the gate voltage, the higher the current going through is going to be, the higher the current is going to be between the source and drain. Essentially a higher gate voltage can effectively impede or inhibit the formation of this kind of pinch-off phenomenon. So you can essentially operate these devices in this regime here as a very effective switch using the gate to control the current and voltage between the source and gate.

So that's the basics about this kind of thin film transistor there. Now what I want to do, there are actually two main material systems that people-- there are two main materials that people use to construct these kind of thin film transistors, are amorphous silicon and what's called a low-temperature polysilicon.

Before I go to that, I do want to highlight one difference, why people want to use one technology over the other. So there's one important difference between an AMLCD and AMOLED that we have not talked about yet. So if you think about a liquid crystal display, liquid crystals are an electrically-insulating material. The way you rotate a liquid crystal molecule is you apply a bias across the liquid crystal. The electric field essentially changes the polarization and the orientation of liquid crystal molecules. That's how you change your chirality.

Now it's basically a capacitive device. So when I say "capacitive," it means that we only apply a bias. There's no current flowing through when it's actually in a steady state. Now this is different from the case of an AMOLED. For OLED, it's a light-emitting diode. Similar to any kind of light emitting diode, you need to have current flowing through a device in order to have electrons and holes will recombine and emit light. So it's a current-driven device. So LCD display, this is a voltage-driven device. That's a current-driven device.

Now this difference is actually quite important because as I will talk about the Low Temperature Polysilicon, LTPS, you can afford much higher driving current compared to TFTs made of amorphous silicon. So that's why for AMLCD, most of the time, people are happy with amorphous silicon TFT. But for AMOLED, people tend to use LTPS rather than amorphous silicon because they actually need the current to flow through their devices, not just the bias.

So now let's come back and talk a little bit about the difference between these two material systems there. So these two are the dominant technologies for essentially display thin-film transistors. There's another kind of a class of material called oxide TFTs, which mostly are made of a material called IGZO, Indium Gallium Zinc Oxide, which is basically a semiconductor primarily based on zinc oxide. Indium and gallium are added, essentially, as chemical modifiers. So you can think of it as like doped zinc oxide to some extent. It has many properties similar to amorphous silicon and polycrystalline silicon. But in terms of market share, this is still a lot smaller compared to LTPS or amorphous silicon. Those are the dominant technologies.

So for amorphous silicon, LTPS is basically a polycrystalline silicon. Now to prepare LTPS, you have to first deposit amorphous silicon. That's the way to do it. You start by depositing amorphous silicon. You then crystallize it to get LTPS. You have a couple of different ways to do a crystallization. You can either just do a blanket annealing of the amorphous silicon thin film. You just put it into a furnace, heat it up to 600 degrees Celsius. It's going to crystallize.

It's actually not usually preferred, that kind of technique, because-- for a couple of reasons. One is mostly because-- number one, 600 degrees Celsius, this temperature is higher than the softening temperature of most glass substrates, like sodalite. So it means that if you want to use this process here to prevent any kind of mechanical deformation of the glass substrate, you have to use a specialized glass with high softening point just to prevent that, which, of course, adds to the overall cost.

And also, if you do this kind of a high-temperature annealing, there will be concerns about other kinds of-- different kind of components that's already existing on the substrate that may be getting damaged because of high temperature. So for example, if you're trying to do a flexible display with lots of polymer components, you will not be able to use this kind of high-temperature annealing across the board to crystallize the material.

So another way to do this kind of crystallization is to use, essentially, lasers. Excimer Laser Annealing, ELA. So this typically uses a short wavelength excimer laser. These are lasers with wavelengths of typically 305 nanometers, so in the UV regime. And then you essentially focus laser to a spot, heat it up to high temperature to induce local crystallization.

The reason this kind of excimer laser annealing is preferred also is because you have a lot more control in terms of the kinetics of crystallization process. In fact, one popular way of doing this kind of laser annealing is a process called sequential laser solidification. This is also called SLS.

Now, the way a sequential laser solidification works is you start out by essentially focusing laser spot into a small region. In many cases, people also make essentially a little shadow mask so that you can essentially tightly confine the laser spot only to the that region. Within the desired regime, you can start by inducing nucleation. And then once you have a nuclei, you then start to laterally translate the laser spot into different regimes.

Now you can imagine that if you do a furnace annealing, what's going to happen is that nucleation is going to be completely statistical. It's going to be random. You have essentially nuclei popping up all over the place, across the entire volume of the amorphous silicon material. You have no control over the crystal nucleation or growth.

In the case of sequential laser solidification, on the other hand, you basically start out by nucleating in one region. You then induce the growth by translating the laser laterally along one particular direction. So in the process, in this forming new nuclei, what's going to happen is that you are going to preferentially grow the existing nuclei.

So then what you end up having is that you have this kind of directional lone crystalline grains that are almost single crystalline. You have very few crystalline grain boundaries because essentially, you are building upon existing crystal nuclei rather than trying to form new ones. And that's actually beneficial because the resulting material-- obviously, because of larger grains, you have a lot less defects. You have here-- for higher current, you have essentially less carrier recombination. You also have higher mobility. You have all the nice electronic properties because of this kind of a directional growth approach induced by lasers. Yes?

STUDENT: And so-- I mean, it says that the processing temperature of this process is very high. So is it-- I mean, I guess-- but it's only in a very small spot.

JUEJUN HU: Exactly. That's the idea. Yeah. In fact, in the next slide, I'm going to show you one example. You can even use this kind of laser annealing even for flexible displays where you have lots of polymers around it. As long as you design your structure so the laser spot-- the heat generation is thermally insulated from the surrounding environment, just a few tens of microns away from the laser spot, the temperature can go down to below 100 Celsius, which is well affordable. So that's another advantage of this kind of laser annealing approach is that it's localized. You don't have to worry about cooking everything on the substrate.

Now, in terms of the properties, you can see that the biggest difference is the mobility. Amorphous silicon, as I mentioned, you get lots of trapped states. You also get lots of scattering just from disordered structure for carriers. So it tends to have quite low mobility. LTPS is actually better. It's still not comparable to single crystalline silicon. Single crystalline silicon mobility, we're talking about above 1,000. So it's still low [INAUDIBLE] silicon, but it's quite disatant.

So that's why you can actually-- LTPS TFTs, they can be used as a current driver, while amorphous silicon TFTs, people typically only use them as voltage drivers. Another advantage of using LTPS is that you can directly integrate ICs, Integrated Circuits, on LTPS. For amorphous silicon, because of its very low mobility, people tend to make only TFTs out of them.

They don't make ICs out of amorphous silicon. But you still need ICs to essentially program all the TFTs to get the desired display pattern. So the way they do it is they do a hybrid integration. They have ICs fabricated separately. They then attach ICs into the displays that's made with amorphous silicon TFT backplane. And in lots of cases, those ICs actually attach to the edge of the display panel. So if you look at amorphous silicon, some of the TFT display panels, the edge is usually dark, because the edge is here reserved and a lot of spaces are occupied by ICs.

So there's essentially a little edge where it's not lighting up. The edge is a lot narrower, or can be a lot narrower in the case of LTPS, because ICs can be directly integrated within the polycrystalline material as well. So that's one additional advantage. And also LTPS, because of the much better properties, you can also get higher resolution of the pixels. So again, PPI, this is Pixel Per Inch, so you can get high resolution pixels with LTPS. The amorphous silicon is also a bit more difficult to reach.

Now the biggest downside for LTPS, you can imagine that with all the additional processing, it gets more expensive. And that's why amorphous silicon is still the dominant technology, especially when you're looking at LCD displays. LTPS is really used more for high-end displays, like these kinds of devices.

All right. But even if you want to make LTPS, you always start from amorphous silicon. You still have to start with essentially a PECVD deposited amorphous silicon and then go through the process there. So amorphous silicon is everywhere in this regard in display industry.

As I promised you, in this slide, I'm going to show you one example where you can actually use this kind of laser annealing process to actually fabricate a flexible display in this case. So what I'm showing you on the left-hand side here, this is basically the process of fabricating a flexible display. You start out by essentially fabricating the display structures on two separate glass substrates. You then bond them together so that your display basically gets sandwiched between these two rigid glass substrates. You then delaminate the rigid glass substrates from the display and then transfer it onto your final flexible substrate.

Now they use this kind of process here. You notice that the display devices are actually sandwiched right in the middle of the stack. This is mostly out of mechanical considerations. You may recall that when we were talking about essentially this kind of flexible glass substrates, we said that when you actually bend the glass plate, you have the so-called neutral plane. Right in the middle, you actually get zero strain and stress, despite the fact that you have a mechanical deformation. Same idea.

By placing these devices aligned with the neutral plane, you can minimize any kind of mechanical strain exerted on your fragile devices despite the geometric deformation. So that's the idea. Now to get LTPS, people use laser annealing. And this is actually-- I quoted from this paper here. They did some simulations looking into-- you can locally heat up this amorphous silicon to a very high temperature, above 2,000 degrees Celsius. But just moving a few tens of microns away from the devices, you can actually quickly cool down to low temperature, below 100 degrees Celsius.

So this kind of a highly localized heating characteristic is what enables laser annealing to process this kind of flexible displays with polymer components that cannot withstand high temperature. Questions? Make sense?

STUDENT: Based on the image on the left, is the--

JUEJUN HU: Left is also zoomed in plot looking at locally where you have a focused laser spot hitting the amorphous silicone.

STUDENT: OK. So it only goes-- the depth only goes to the [INAUDIBLE].

JUEJUN HU: Well, there's always a little bit of thermal diffusion. But the idea is that you design the layers and also you design the pulse so that you limit this kind of thermal diffusion to the surrounding regions. And this is the zoomed out region. This is actually where the focus spot is. But then, as soon as you move away from that, the temperature quickly kind of cools down.

All right. Any more questions about displays before we move on to solar cells? All right. Good. So what we're seeing here is that in the display industry, as I said, amorphous silicon is still a dominant material. It's everywhere. People use it to make TFTs or use it to-- as a source material to create low-temperature polysilicon to make TFTs. So it's still a very useful material. Now we're going to switch gears a little bit and talk about solar cells. Solar cells is one industry where there used to be lots of interest in amorphous silicon. Not anymore.

We're going to see why. So let's start by-- this slide just to give you a basic architecture of solar cells. You probably have seen it in 3033 or other classes. Solar cells are probably one of the most simple kind of semiconductor devices, basically a p-n junction. If light comes in, you are going to generate electron-hole pairs.

Because of the presence of the building electric field in the p-n junction, these electrons and holes are going to get spatially separated. Electron goes one direction, hole goes the opposite direction. They are going to get collected by the electrodes. And then that's how you can have current flow in the external circuit to drive load. That's how solar cells work. If you look at I-V curve here, we are operating in this fourth quadrant here.

If you have light, essentially this is basically a photocurrent. Photocurrent leads to, essentially, a lateral shift-- vertical shift of the curve here. This corresponds to a short circuit current. This corresponds to the open circuit voltage. I assume you learned a bit of that in 3033 or whatever. If not, go back to review the text in those classes.

So it's basically just a p-n junction. Really simple. Now where does amorphous silicon fit in? So if you look back in about 15 years, in early 2000s, maybe early 2010s, there used to be lots of interest in thin film amorphous silicon solar cells. There were lots of startups trying to look into this. I think pretty much all of them failed.

At the time, the premise was that you can deposit amorphous silicon over a large area with high-throughput CVD process. Remember the applied materials [INAUDIBLE] fab? You can deposit this on six-square meter glass substrates. So you can presumably we process these cells at low cost.

An additional benefit of amorphous silicon compared to crystalline silicon is that you have a much higher absorption coefficient. Now this goes back to when we were talking about essentially amorphous silicon. Oh, sorry, crystalline silicon being an indirect bandgap semiconductor. So in order to have light absorption, you need a phonon-assisted process, which is pretty inefficient.

So typically, in crystalline silicon solar cells, the typical wafer thickness is at least a few tens of microns, maybe 100 microns order of magnitude. So that's actually quite a lot of material. Versus in the case of amorphous silicon, because it's amorphous, you no longer have-- essentially, you're constrained coming from the momentum crystalline momentum conservation. It behaves more like direct bandgap semiconductor. So you can actually absorb pretty much all the sunlight within just a couple of microns. So you can save a lot of the semiconductor silicon material compared to crystalline silicon. So that's another factor that contributes to reduced costs.

So that's basically the assumption people are making when they are exploring amorphous silicon as a solar cell material, that you can achieve lower cost compared to crystalline silicon. I put a question mark there. I'm not going to talk about whether or not that's correct. Now there are also some additional benefits of amorphous silicon. So for example, one very interesting concept people are exploring here is the so-called monolithic silicon tandem structures.

So a tandem cell essentially means that you're stacking semiconductor of different bandgaps together. If you look from top to bottom, like sunlight coming from the top, the top cell is the one that has the largest bandgap, so it absorbs essentially the blue part of the spectrum and generates photons, generates current with very high voltage. The remaining red photons that continue to go through, because it's transparent to this wide bandgap semiconductor, it gets absorbed in a semiconductor with smaller band gap get underneath, which, again, generates some additional generally low voltage, but additional current. You can continue by stacking multiple of these cells with different bandgaps so that you collect different part of the spectrum of sunlight without losing any of the other energy there.

Conventionally, when people are making this kind of tandem structure, you have to essentially grow semiconductors epitaxially using different compositions, typically in III-V semiconductor systems, which gets quite complicated. But in the case of silicon, recall that amorphous silicon actually has a larger band gap compared to crystalline silicon because of the presence of hydrogen.

In hydrogenated amorphous silicon, you get lots of hydrogen, which increases the band gap to about 1.7 EV. So by controlling the hydrogen content, you can basically tune the bandgap of the amorphous silicone. So in principle, this gives you a method to realize a monolithic tandem structure by just putting amorphous silicon on top of crystalline silicon. And by changing the hydrogen content, you can actually get several different bandgaps so that you can have essentially just one second material, but you also get this kind of graded band gap, and therefore create a tandem structure. So this is quite a unique capability that other materials will be difficult to actually realize.

Now let's come back to why amorphous silicone is not gaining popularity. One of the first big barriers there is the so-called Staebler-Wronski effect, also known as the Light-Induced Degradation, LID. So this effect was discovered, obviously, by Staebler and Wronski back in 1977, almost 50 years ago. What I'm quoting here, this figure at the bottom left corner, is the original graph from the paper there where they discovered this light-induced degradation effect.

So what I'm plotting on this plot here? Vertical axis is basically electrical conductivity. Horizontal axis is the light intensity. So essentially, these curves are showing the photoconductivity in amorphous silicon. If you send light into amorphous silicon, you generate electron-hole pairs. You have more carriers. You have essentially a higher conductivity. That's photoconductivity.

Now what they have noticed is that initially, if you just freshly prepare amorphous silicon, hydrogenated amorphous silicon, you get decent photoconductivity. But after extended exposure to light, the photoconductivity drops by orders of magnitude. So this is known as a light-induced degradation. Essentially what happens is that light radiation can generate defects in amorphous silicon, which leads to a degradation of the material quality, which is what compromises the photoconductivity.

What happens in the case of photoconductivity is that these defects essentially serve as recombination centers. So your photogenerated electrons and holes, they will recombine. They get expedited by these defects. And therefore, you effectively have less amount of electrons and holes available in the defective material. And that's why the conductivity will drop.

Now if you go to solar cell, the mechanism is very similar. Because these generated defects increase carrier recombination, it means that lots of these carriers will not reach your collection electrodes to contribute to external current because of the recombination. So then, effectively, the efficiency of solar cells will also drop.

So this is actually quite a significant effect. In a typical amorphous silicon panel, if you look at efficiency when it's freshly prepared versus when it's actually saturated with this kind of light induced degradation, the efficiency can drop from anywhere from 10% to 15%, in some extreme cases even up to 30%. So it's quite a significant job of efficiency there.

Now why's that the case? It goes back to a dangling bond. We mentioned that dangling bonds is the main defects that essentially lead to essentially these midgap states that compromise the electronic properties of a circuit. You need to pacify them with hydrogen so that you can actually dope amorphous silicon and therefore use it as a semiconductor material.

Now what happens during-light induced degradation is that light actually releases dangling bonds. So how does light releases dangling bonds? There are a couple of different mechanisms people have proposed. One of them-- this is called a bond-switching model.

So what bond-switching model says is that-- say this is your amorphous silicon. Silicon-silicon bonds. Now you can absorb this light. The light comes in, you generate electron-hole pairs. These electron-hole pairs, they're going to recombine. When they recombine, sometimes they can pass energy to this silicon-silicon bond.

In the case of crystalline silicon, all the silicon-silicon bonds are identical from each other. They are all the same. However, in amorphous silicon, there are always some silicon-silicon bonds that are weaker compared to others, just because they are further apart, or maybe they are strained, or whatever. So there are some weaker silicon-silicon bonds. Now these weaker silicon-silicon bonds can be severed by this additional energy coming from electron-hole recombination. So now what we end up with is essentially these two unpaired electrons.

Now over time, these two electrons can again recombine and form a chemical bond again. In that case, no defect is going to get generated. However, in amorphous silicon, you get lots of hydrogen. So the hydrogen can also be released by light because the light coming and cutting the silicon-hydrogen bond. So then this hydrogen sometimes-- opportunistically, they can essentially diffuse next to one silicon and form a chemical bond with one of the silicon atoms.

Now you are left behind with one unpaired electron that can no longer restore a chemical bond. So this is a dangling bond. That's what's called the bond-switching model. Essentially you're switching the silicon-silicon bond to Si-H bond, leaving behind the dangling bond. The other model is called the hydrogen collision model.

In the hydrogen collision model, you have Si-H bond. Same thing. The photon energy generating electron-hole pair can pass energy to silicon-hydrogen bonds. You can actually break this silicon-hydrogen bond. And this process can happen in lots of different locations in the actual material. You release this kind of hydrogen atom, which is highly mobile, becomes very small.

So then, again, opportunistically this hydrogen can bump into each other and form this hydrogen complex, H2 complex. Now keep in mind this is not hydrogen gas. This is actually two atoms attached to each other. But still within the matrix of an armophous circuit. So this is not really H2 gas molecules. But in any case, this also leaves behind, essentially, an unpaired electron or silicon dangling bond.

So bottom line, this always involves essentially a light-induced breakage of chemical bonds and therefore a generation of dangling bonds in an amorphous circuit. And these dangling bonds are the defect that leads to a degradation of the electronic properties of amorphous silicon. All right. Now you can also take a look at more specifically the kinetics of this kind of light-induced degradation.

So on this plot here, I'm showing you the measured kinetics of the process, which this is a pretty crowded plot. Let's just look at-- forget about the inset. Let's look at these curves here. So the vertical axis is the number of dangling bond defects in log scale. Horizontal axis is the illumination time, also in log scale. You see that these curves-- essentially, they are all straight. They're all straight lines. They correspond to different light intensities.

Now a straight line in this kind of double logarithm plot essentially means that you have a power dependence between the two parameters there. And the exponent in the power dependence is given by the slope of this curve here. So if you look at the slope, it actually corresponds to one third. So basically what it says is that the dangling bond generation scales with time to the one third power.

Now if you look at the inset, vertical axis is still the number of dangling bond defects in log scale. Horizontal axis is the light density in log scale. You also have a straight line here. The straight line has a slope of about 0.6, according to this experiment here. Now the horizontal axis, light intensity, light intensity basically gives you the generation rate of carriers. Generation rate of this-- essentially the electron-hole pairs.

So that's what we write as G. G, essentially, is our light intensity. If you do some kinetic modeling, if you go ahead and read the paper, what they did is they-- based on these different models here, you can perform a detailed balance study by writing different kinetic equations. And then from that, you can write the rate constants.

Then that allows you to provide several equations that involves the parameters such as external light generation rate. Generating rate for this kind of-- for example, dangling bonds. So if you go ahead and solve those kind of coupled differential equations about the rate equations, you're going to end up with the conclusion that the defect generation should scale with generation rate to the two thirds power and time to the one third power.

You notice that actually agrees pretty well with the experiment. With time, it's one third. With rate, it's 0.6. The model predicted 0.67, which is pretty good agreement. So you generate more defects with higher light flux and also with a extended exposure, which makes sense.

Now next thing I also want to mention here is that you can also partially reverse this kind of light Staebler-Wronski effect by essentially annealing. So what I'm showing on this plot here, this is actually measured efficiency of a solar panel. If you just put it out in the sun, then what's going to happen is that efficiency is going to drop within the first few hours of light exposure.

But if you knew it, you can essentially remove some of these dangling defects by annealing there. Essentially induce diffusion of the hydrogen atoms in the matrix so that they can combine with the dangling bonds during the annealing process, which annihilates some of the dangling bond defects. You see partial recovery of the efficiency. You notice it never really goes back to original efficiency there.

But if you put it out in the sun again, you'll get the grades. You [INAUDIBLE] again, again it partially recovers, but then it will degrade furthermore. Until, at some point, eventually it's going to reach a steady state. This stabilized efficiency is what people should be reporting for the efficiency of amorphous silicon.

Because for solar cells for solar panels, you typically call them for a lifetime of 25 to 30 years. So this first few hours really doesn't count. What really you should be reporting is the stabilized efficiency for amorphous silicon cells. So this is already one big challenge for amorphous silicon here. You see that there's a significant efficiency drop just coming from this light-induced degradation effect there.

Now let's take a look at what efficiency looks like for state-of-the-art amorphous silicon cell after stabilization. Yeah, I apologize. The phones are really small. I know you can't read it. That's really not my fault. That's because people have so much interest in new solar cell materials and stuff. That's why it gets really crowded as you go to this regime here. But I don't think you can really see it.

Let's see if I can zoom in. Oh, OK. I cannot. All right. Now I can read it on my screen. I have a very high pixel density. It's a retina display, so I can actually see it. I apologize this is not sufficient optical quality. But this is basically a summary of all the state-of-the-art. So the world record solar cell efficiency.

Let's try to find amorphous silicon. Amorphous silicon should be here. [INAUDIBLE] You can see it. You can sort of read it. It's this big green open circle there. Now you notice it says, amorphous hydrogenated silicon stabilized. So it should only report stabilized efficiency. Now let's look at this big, green, open circle here. It's right here. 14%. Remember that number.

Now what about crystalline silicon? For single-crystal silicon, you have two-- these are the square symbols here, concentrator, nonconcentrator. You should look at the nonconcentrator because concentrator actually increases the effective light flux, which increases the electron density. It actually increases the open circuit voltage by increasing the quasi-Fermi level separation. 3033. Go back and review that. But the idea is that you should look at nonconcentrator silicon solar cells for fair comparison. So that's a field square. Field square is right here, 26.1%.

So what is in there? Crystalline silicon cells have an efficiency that's almost twice that of amorphous silicon. Now is that really a problem? We'll see. Now before I get to why amorphous silicon is losing ground, let's first take a look at this plot here that shows essentially the global PV production by technology.

You see most of it-- so you have three different kinds of technology here. Monosilicon, this is basically single crystalline silicon. Multisilicon is essentially polycrystalline silicon, but they have a large grain sizes. So with large grain sizes, you have reduced the amount of crystalline boundary defects. So you have essentially better quality there right. Thin film. This is all type of thin-film technologies, including amorphous silicon. So now you can see, as I said, in early 2000s, 2010s, thin films indeed gained lots of traction. But then now today, it's pretty much just single-crystal silicon.

Now let's also further zoom in. Look at this very small green bar here for thin films, because there are actually different competing thin-film technologies. There are three dominant thin-film technologies, cadmium telluride, Amorphous silicon, CIGS, copper indium gallium selenide.

This is where we are. I actually tried to zoom in and look at the plot. It's basically one pixel. I don't know if it's even real for amorphous silicon. Cadmium telluride is practically the only thin film technology that actually survives. So sad? Now let's wonder why it is so sad.

STUDENT: [INAUDIBLE]. I don't like to see anyone fail.

JUEJUN HU: Well, you see that this is their high days when you actually get lots of amorphous silicon layers. But then it quickly drops out over the past 10 years. So why is that? Now keep in mind, why did people look at amorphous silicon in the first place? The argument was that they can have a lower cost compared to crystalline silicon for the solar panels. Because you can do large area deposition, high throughput fabrication. You also need less semiconductor material. Is that true?

So what am I plotting in this plot here? This is actually the manufacturing cost. Sorry, not manufacturing cost, but the price. The module price, the sale price for modules. I don't have a number beyond 2014, but the trend is pretty similar. If you look at the curves here, this one is thin-film silicon, amorphous silicon. These are actually crystalline silicon by different suppliers.

Now what you see here is that indeed amorphous silicon solar panels are cheaper than the crystalline counterpart. Now keep in mind this is already normalized with respect to efficiency. You may argue that they have low efficiency. But what we're showing here, this is dollars per Watt. So when you're doing this kind of dollar per Watt calculation, this is basically dollar per Watt calculation, what you have? The numerator is your efficiency in percent.

Now on top, this will be your module cost. This would be the cost of your module. So you can argue that amorphous silicon has a lower cost. But it's really already taken into account in this expression here. So indeed, the assumption was at least partially correct, that the modules are cheaper for amorphous silicon. So then why did they fail? Yes.

STUDENT: Is [INAUDIBLE] you have to cover--

JUEJUN HU: Very close. Very, very, very close. Well, there's more than that, but you are going in the right direction, because there are other additional costs. A solar system requires not just the module itself. So what I'm showing you here, this is basically the total price for the systems, not just the solar module, not the solar panels. You see there are actually two components. This orange bar corresponds to the actual solar modules, the panels.

This blue bar is what's called a balance of systems, which is everything else outside the panel. You see that back in like early 2000s, the dominant price comes from the modules. Modules are the expensive ones. But over the years, modules get really cheap. But the problem is that this blue bar, the balance of the system, did not scale. So what are these balance of systems?

Now for that, we have to look at essentially the whole system. So if you look at the whole solar system here, you essentially start out with cells. These are the individual wafers or individual substrates. You have to string them together in series or parallel to form a module so that you can have sufficient current or voltage output. The module can be further integrated. It can be tied together to form an array. And then in the end, you also need to put them together to form a system.

To get the system, you get multiple different kinds of components there. You need to have this kind of charge controller. You need an operating point controller so that you ensure that you're always operating at the right voltage and right current to maximize efficiency. You also need to have an inverter, because the current coming from solar cells are DC. But all the grids use AC. So you need an inverter to essentially convert DC into AC and vice versa. DC to AC, basically.

And then you also have all the additional hardwares. So these are all captured by the essentially so-called balance of systems. So in this plot here, I'm looking at the hardware components for balance of system. You can see there that lots of different things besides the modules. You have even mechanical mounting frames. You have all the cabling, you have junction boxes, you have all this power grid infrastructure. You have switch boxes.

So there are lots of things you have to invest in order for solar cells to be useful to generate electricity. And this is only the hardware. There's also what's called a soft cost that goes into balance of systems. So what are the soft costs? As you said, you need to acquire land. You need to also essentially pay for people, staff time, personnel to actually install the solar cells. You need maintenance.

Also, all the companies, they need to have profit. Otherwise, they cannot survive. They need to pay sales tax. So all of those things, they all go into the balance of systems as soft cost. Now you see what the problem is. Because if you look at the real dollar per one number, what you should really be gauging here is the system level cost. So you should also put in the numerator here the cost coming from a balance of systems. And now you see the problem. With low efficiency, the relative cost coming from balance of systems essentially increases.

And I want to argue that that's actually a pretty universal trend, not just for rooftop solar system. In the previous slide, I showed you [INAUDIBLE] for rooftop solar systems, and the dominant cost comes from balance of systems. It's actually the same whether it's residential, or rooftop, or it's commercial solar cell systems, like for parking lots and stuff, or utility scale, which these are big power plants in the desert in Arizona or whatever.

So in all cases, what I'm showing in this plot here-- again, this is pretty crowded. But if you look at the different cost breakup there, the yellow part is actually the actual module of the panel. You then have inverters, the balance of system hardware, other hardware, outside inverter. You get labor. You get other kind of soft costs. But all of these things essentially are the balanced of system in general.

So you can clearly see that this module cost has decreased a lot. In all three cases, the module cost is really not the dominant component for the overall system cost. In fact, sometimes you go to the solar conference and you hear people saying that cells are for free. They even say that, because it's such a small fraction there. The real opportunity for cost saving comes from balance of systems.

Now one way to more efficiently decrease the balance of system cost is by increasing efficiency, which makes a lot of sense. For the same solar panel, the installation cost is basically fixed. It scales the area of solar cells. The land acquisition scales the area of solar cells. So a lot of those costs are actually fixed. The scale is essentially the area.

So if you have a high efficiency, you can essentially still amortize all those costs. And then therefore, you will be able to achieve a much lower overall dollar per watt number. So that's why efficiency is actually important. It's not just that you produce more electricity. It's that effectively, you are saving your cost there for your system.

And that's also why people spend lots of-- essentially invest lots of money looking into new solar cell systems that potentially can give them even higher efficiency than silicon. Like recent years, a lot of people are looking into perovskite silicon tandem cells. Because if you put perovskite on silicon-- and if you go back to the plot, you can probably see that perovskite-silicon tandem. Let's see. Perovskite silicon tandem. Where is it? Where is the perovskite-silicon tandem? Right here. So this is a perovskite-silicon, this open yellow triangle here. 34.6.

I mean, this is lab results. It's not like production, largescale models. But you can already see the potential there. You can increase more than 8% of efficiency compared to just silicon by putting perovskite on top of silicon. So that's why it's showing lots of interest. It's not just because of perovskite cells itself. It's actually because the potential of integrating perovskite with silicon. In this case, silicon basically comes for free, practically.

So they are really looking for adding a few percent of efficiency. That's why, because of the cost-saving aspect there. And that's also partially why a lot of the other solar cell technologies with low efficiency, they never really take off, like organic PV, basically because of the same reason. Yeah. It's very difficult to match with other kind of technologies Even though you have the premise that some solar cell technology that can be very low cost, but if you don't have decent efficiency, you cannot win.

Now does that mean that amorphous silicon is completely eliminated from the picture of solar cells, or from the solar cell industry? I mean, not quite exactly. They still have some unique applications there. So one example here, for example, what I'm showing you here, this is actually a silicon heterojunction solar cell. So normally in a typical silicon solar cell, you have a homojunction made of silicon, p-type silicon n type silicon, both made of crystalline silicon.

In a heterojunction cell, one of the doped regions is actually amorphous silicon. Now the reason they like to use it is because amorphous silicon actually has a larger band gap. So if you put the junction, for example, on the surface here, where one of the junction material is amorphous silicon because the larger band gap essentially creates a barrier towards carrier diffusion to the surface.

And this is actually useful because surface is where you get lots of-- typically, you get lots of defects because of, essentially, the unsatisfied chemical bonds. Those can cause carrier recombination. So by having a wide bandgap material on the surface, you can push away carriers from the surface and therefore mitigate this kind of surface recombination.

On top of that, because amorphous silicon, you get lots of hydrogen due to the PECVD process, those hydrogens can also diffuse to the amorphous silicon-silicon interface. And then for passivate the surface with those kind of hydrogen atoms. So that's an additional benefit there. So amorphous silicon is still getting used in the solar industry, but only for these more specialized, niche applications, not using them as the solar absorber itself directly.

All right. I think that's pretty much all we have for this lecture here. We have basically talked about amorphous silicon here. We mentioned about hydrogen dangling bonds. Dangling bonds are really important kind of defects there. In order to get amorphous silicon to be useful, you really need to passivate this kind of dangling bond, OK?

If you don't passivate dangling bonds, one example is this Staebler-Wronski effect. If you release new dangling bond defects, you're going to get to lead to a degradation of the solar cell efficiency. We have mentioned that amorphous silicon-- now active matrix displays based on TFTs, this is probably the dominant industry where lots of amorphous silicon is still getting used. Solar cells, we have seen why it's losing favor against crystalline silicon. Again, because of the combination of light-induced degradation as well as the lower efficiency compared to crystalline silicon. Any more questions about--

STUDENT: Yeah. When you annea, and then you get back some of your efficiency, and you said that there was a stabilization point?

JUEJUN HU: Yeah.

STUDENT: After how many annealings? I feel like a limited number of annealing before you just--

JUEJUN HU: Yeah. When I say "stabilization," I don't mean, actually, annealing. Essentially, it's like if you don't do annealing, you just expose it to sunlight, eventually it's going to stabilize. That's what I mean. Yeah.

Annealing, as I said, can help to partially recover some efficiency because annealing essentially allows the hydrogen to diffuse around. As they diffuse around, they find, essentially, some of the dangling bonds recombine with dangling bonds to passivate it. But people don't do it practically. They just essentially let it stabilize.

STUDENT: OK. So these stabilizations are independent of the annealing.

JUEJUN HU: Independent of the annealing process, yeah.

STUDENT: Right at the start of this section on solar cells, you mentioned the layered structures of crystalline and amorphous silicon.

JUEJUN HU: This one? In the last slide or what?

STUDENT: Yeah. I mean, also in the front. It seemed similar, like, where the wider bandgap kind allows for the filtering effect where you can have a higher voltage.

JUEJUN HU: Oh, yeah. The tandem?

STUDENT: Yeah.

JUEJUN HU: The tandem thing, yeah.

STUDENT: Yeah. So why does that just not work, or why is that not in use?

JUEJUN HU: It's complicated. In fact, in order to get the tandem cell to work properly, you need to essentially make separate junctions. You also need to have tunneling junctions to ensure that the current actually flows through, and then you build up the bias. You essentially need to have cells working theories.

It's actually a quite complicated process. It's not nearly as simple as just deposit the different layers. You have gradient bandgap. It's going to work magically. You need to essentially make separate solar cells essentially, one solar cell on top of each other, each with complete structures of p-n junctions so that they are essentially strung together in series to add up the voltage. It's nontrivial in the end. So it's a nice concept--

STUDENT: Like, the efficiency gains are not actually worth it?

JUEJUN HU: Yeah. It's a nice concept, but people do not really do it in the end. Yeah.