[SQUEAKING]

[RUSTLING]

[CLICKING]

JUEJUN HU:

So in the last lecture, we discussed about the electronic structures in amorphous solids. We highlighted some differences here, one being that once you're introducing structure order, you inevitably create localized states, OK? And also, because of the presence of localized states, it means that you now no longer have a well-defined band gap, but instead, you have, essentially, a continuously distributed density of states across different energy energies. OK?

What we will see next in this lecture is how the presence of these localized states will actually modify the transport properties of amorphous solids. OK? So as I mentioned, now, you have two kinds of states. You have extended states outside the mobility gap, localized states within the mobility gap.

So when you're looking at the conduction, both kinds of states can actually contribute to electrical conduction. OK? So starting from the extended states, so for extended states in amorphous solids, the basic formalism describing the conductivity contributed by them are actually quite similar to that in crystalline solids. If you look at the equation here, it's really identical. The conductivity directly scales with mobility and the charge density or the density of the extended states.

What's different, however, is in the expression for mobility here. OK? And this comes from the structure of the amorphous solids. So first thing is that in the amorphous solids, there are actually lots of, essentially, what we call the trapped states. Those are the states that's present in the band gap or in the mobility gap, OK?

So when the electrons that are actually excited into the conduction valence band-- as they are moving along, there are chances that they may actually get trapped into those localized states. Now, once they get trapped into those localized states, obviously, they will stop contributing to the electrical conduction unless from an extended stay perspective, only till when they actually get released thermally back into the conduction band or valence band. Then they will contribute conduction once again.

OK. So to account for the fact that these extended states-- the carriers do not always contribute to electrical conduction, we have to add this additional factor here. 1 minus f trap, OK? So f trap basically gives you the fraction of time when the carrier will be actually trapped in one of those trap states. So this will then decrease the effective mobility, you will see. OK?

So that's one factor. Now, second is that if you look at this expression, mu 0 is what we call the free mobility. So this is assuming, if we ignore all these trapping events, what would be the apparent mobility we will observe for this extended state? I should mention that this mu 0 is also lower compared to the mobility in the crystalline counterpart.

And the reason for that is pretty straightforward because in the amorphous solids, you get all this structure disorder. This structural disorder will contribute to scattering of carriers a lot more compared to in the case of crystalline solids. So as a result, the free mobility is also a lot lower compared to that in the case of crystalline material.

So both factors combined together-- the apparent mobility you will see for the extended states in amorphous materials-- they will end up being orders of magnitude lower compared to the other crystalline solids. So if you look at, for example, in this example, what I'm showing on the right-hand side here, this is the electron drift mobility in amorphous silicon.

If you look at the vertical axis, we are talking about drift mobility of the order of a few or even below 1 centimeters squared volts per second per volt per second. OK? So this is in contrast to the electron mobility in crystalline silicon, which is above 1,000 centimeters squared per volt per second, OK?

So this huge difference means that essentially, the mobility in the amorphous solids tends to be a lot lower. The direct implication is that for mobility, if you are trying to use these materials, for example, for high speed electronic devices, for high speed electronic devices, you need a carrier to be quickly able to move in and out of the active region.

And what this plot tells you is that these amorphous solids probably is a poor material if you're trying to use them for high speed applications. And again, if you look at the actual application people use these devices for-- for example, for display or maybe for solar cell-- none of those applications really require a gigahertz operation. OK? So that's a good reason why people are not using them for those applications.

OK? The other thing. If you look at this plot here, this is basically an Arrhenius plot. Vertical axis is essentially logarithm of mobility. Horizontal axis is the inverse temperature. So you notice that it more or less follows this Arrhenius dependence. And as you go to higher temperature, the apparent mobility actually increases.

And this comes from the fact that as you go to high temperature, the carriers essentially get more energy. It will stay less time being trapped in those localized states. OK? So if you look at the high temperature limit, if you go to infinite temperature, then what happens here is that essentially, the carriers, the, basically, f trap, the fraction of time staying in the trap, will essentially approach 0. And therefore, the mobility you're measuring here will then approach the free mobility, which, as you can tell, is still 3 orders of magnitude lower compared to what you get in a crystalline material. OK?

All right, so for extended-stay conduction, basically, it still follows Arrhenius law, OK? It can be considered as a thermally activated process due to this detrapping process. Now, what about localized states? Now, unlike crystalline states, where the electrons essentially can freely roam across the entire material, in localized states, these electrons essentially only exist in a neighborhood of some defects, basically. OK?

So if you want to have electrical conduction, you need these electrons to move around. So the only way to move around in the case of localized states is that they have to essentially hop from one localized state to another localized state. That's the only way they can actually move across the material, given the spatially confined nature of the wave function. OK?

So the example of this hopping process-- it actually happens even in the case of crystallized semiconductive materials, OK? So for example, if you think about a crystalline material, if you put dopants in there, we mentioned that this is going to create states within the band gap.

And then this will all create, essentially, localized states at each of the dopant atoms, around the dopant atoms, OK? So suppose, for example, what I'm plotting here-- this would be in the case of n type semiconductor with lots of donors. If you go to a really low temperature-- if you're a normal temperature, then because of the nature of these shallow dopants, all of the electrons on the carriers is going to get thermalized.

They essentially release electrons into the conduction band, but if you go to cryogenic temperature, you can freeze out these carriers so that the dopants, or at least most of the dopants-- they will essentially be sitting at the donor atom. Now, this then creates a set of spatially separated localized states.

If you apply electric field, then what happens is that these electrons can then hop from one of these dopant atoms to the next dopant atom and then so on and so forth, and in the process, contribute to electrical conduction. So this process, when from hopping from one atom to the other atom, this is basically a quantum mechanical tunneling process. OK?

Now, in order for tunneling to take place, you need to have wave function overlap for the two neighboring localized states. OK? So more specifically, if you think about, for example, wave function for the electron at this one, because it's localized, what you're going to get-- the wave function is going to look something like this, if you think about the wave function. Psi.

This is the x-axis. It's going to peak right at the dopant atom and then exponentially decay as you move away from the dopant atom. Same thing if you look at its neighbor dopant atom. You also get something like this. OK? So it is the overlap of the wave function that dictates the magnitude or the probability for this tunneling.

So suppose you write the spacing between the two states, let's say, as R. Then mathematically, the wave function overlap will be given by exponential-- this wave function is exponentially decaying, so we can write it as exponential negative alpha R. OK? This will be what the wave function represents.

So now, alpha is a constant we define to essentially gauge the spatial confinement of the localized wave function. In fact, mathematically, you can relate alpha directly to the imaginary part of your wave vector, OK? And that's pretty straightforward, actually. You can figure it out. OK?

OK, then then if you define wave function this way, then the overlap here-- because you have two wave functions, you have to multiply them together. So essentially, it will become negative 2 alpha R. This will be effectively the wave function overlap. And we argue that the probability of tunneling within scales with this factor here. This is just for quantum mechanics, essentially.

All right. So now, if you look at this vector, what it says is pretty clear. Assuming that, because in this case of a doped semiconductor, all the dopant atoms-- they are basically identical. So it means that the alpha is basically the same for all these states.

Therefore, the larger the R, the smaller the hopping probability. And they actually decrease pretty drastically. It decreases exponentially, OK? So physically, what that means is that this kind of hopping will only take place between the nearest neighbors, practically.

Anything further than that, the hopping probability drops exponentially, becomes negligible. OK. Now, this is what's known as fixed-range hopping. Essentially, fixed-range refers to the fact that this kind of hopping conduction only takes place between the two nearest neighbor localized states. OK?

All right, so that's the case for localized states, for example, in a crystalline semiconductor. Now, in a mobile semiconductor, we expect something similar to take place. You get lots of localized states within the mobility gap. And therefore, you can have electrons essentially hop around between those localized states.

Some important differences I want to mention here. First thing is that if you look at what I'm showing here, this is a very, very simplified schematic of the density of states within the mobility gap. There's essentially some density of states near the Fermi level. First thing we argue is that when we look at electrical conduction, we only need to consider localized states near the Fermi level.

The argument for that is also pretty straightforward, similar to that in crystalline materials. If you think about, for example, metal, crystalline metal, when we talk about the electrical conduction, we said that only the states near the Fermi surface actually contribute to electrical conduction because if you look at states much above the Fermi level, they are all empty.

There's no carrier to actually conduct electricity. If you look at states that's well below the Fermi level, then they're all filled. And because an electron is essentially a fermion, essentially, if you have all filled states, you cannot hop one to the other states. You need empty states in order for electrons to hop into.

So that's why all the electrical conduction-- pretty much, they all take place around the Fermi level, where you get plenty of filled states and also empty states. So what we do-- let's label the density of states at the Fermi level with this letter g here. So g is basically a density of states of the localized states at the Fermi level. OK?

OK, so that's the first thing. The hopping conduction only takes place around the Fermi level. OK. Now, second thing I also want to mention here is that if you look at this plot, you immediately realize that this is a bit different from the case of fixed-range hopping. The energy of those states that participate in the variable range hopping is not fixed. It's a distribution around the Fermi level. So it means that this hopping conduction can actually take place between two states with different energies.

So when electrons want to hop from one state to another state with different energies, now, because of energy conservation, it means that it must involve another particle in the process just to fulfill the energy conservation condition. In this case, it's a phonon. So if you are hopping from one state with high energy to a state with low energy, you must emit the phonon to compensate for energy difference. Or alternatively, if you're going from a state with low energy to high energy, it must absorb a phonon in order to be able to actuate that kind of hopping.

So in this case, hopping becomes a two-particle process. So if we still look at the probability of hopping, we are now the probability-- so this is basically hopping probability in the case of fixed-range hopping. In the case of amorphous solids, the probability will now be [INAUDIBLE] to two factors.

The first factor is still the wave function overlap. Same. The second factor is the probability to find the phonon with the right energy to compensate the energy difference. Now, that probability is basically given by a Bose-Einstein distribution. But in this case, Boltzmann distribution is actually a very good approximation, OK? So what we have here-- then we have a-- let me just-- we will have negative kT delta E. OK? So here delta E is the energy difference between the two states that participate in this hopping process. OK?

So next step, we need to maximize P, similar to the case here. For fixed-range hopping, maximizing P is really straightforward. It just means that you need to have the smallest R, nearest neighbors, OK? But in this case, the situation gets a bit more complicated. What we argue here is that this hopping process does not necessarily take place between the nearest neighbors. OK?

Sometimes, if you're willing to travel a little bit further, go to a state that's a little bit further, you may be able to find a state that's actually closer in energy to the starting state. And therefore, the second term actually becomes bigger, which compensate for the decrease of the first term. OK?

My analogy in everyday life is that, for example, if you ever want to refuel your car, and assuming your target is that you want to do this at the lowest cost, you have two options. You go to your nearest gas station and just fill it up, or you also realize that all the gas stations have different prices.

If you're willing to drive maybe another extra half a mile, you may be able to find a gas station that actually has a lower price, which ends up being better. So then there goes this trade-off there. On one hand, you want to be able to search a larger distance range so that you find a gas station with a lower price.

But at the same time, if you drive further, of course, you consume more gas. So eventually, that may actually increase the overall cost. So there's an optimized distance where you want to drive in order to get the lowest overall price. Same idea here. There's actually an optimal hopping distance to actually increase the overall probability of hopping between states.

And this distance, as you'll see later, is a function of temperature. And that's why this hopping mechanism is called Variable Range Hopping, or VRH. So the hopping distance is not fixed. OK? So then what we do-- let's try to solve for this factor here.

So let's try to maximize this function. Let's just put everything together, OK? It's going to be negative 2 alpha R negative kT delta E. So basically, in order to maximize this function, you need to minimize the exponent or the negative of the exponent. So you need to minimize this one.

This is the fact that we want to minimize. OK? We want to make it smallest. So let me just write this as-- I don't know. Let me try to represent it with a letter. Tell me. What's your favorite letter?

AUDIENCE: Beta?

JUEJUN HU: Beta. All right. Sure. Sure. Greek letter. Surprised to learn that your favorite letter is a Greek one. That's OK. [CHUCKLES] Fine. Let's minimize that beta. OK?

AUDIENCE: Alpha.

JUEJUN HU: Alpha? I have omega alpha there. Sorry. No, your favorite is taken. That's why we go for the second favorite, beta. All right. So in order to get the minimum, what we need to do is that we need to essentially take the partial derivative of beta with respect to R and make it equal to 0.

So if you do that, the first term is really straightforward. It's 2 alpha. The second term, we have to essentially look into it a little bit. We need to essentially establish a connection between delta E and R. So let's go back to the definition of delta E. Delta E essentially gives you the energy difference between the two states there.

And if we want to find the states with a given energy difference, this has to do with abundance of the states in the surroundings. The abundance of states relates to the density of states. So density of states-- by definition, what it gives you is the number of states per unit volume per unit energy spacing.

So for example, let's think about-- we have one particle. It won't hop to somewhere that's R distance away from it. If you make a sphere with a radius R, then the volume of the sphere is this one here, this vector, OK? Then you also times the energy spacing delta E.

What this gives you-- density of states times volume times energy spacing-- gives you the number of states you can find within the sphere of radius R and also within the energy spacing of delta E. We argue that we want to set this to unity. We want to at least find one state that satisfies the condition that it's located to the center state within the sphere of distance R, and it's also within energy spacing of delta E.

OK? This guarantees there exists one state that satisfies the condition. So they can hop over. OK? So if you take this condition, this actually relates delta E to R. So now, let's see what delta E is. Delta E now becomes-- this is 3 4 pi R cubed g. OK. Let's move over here.

Now, what we have-- let's see. Let me write this beta term, simply start writing here. This is 2 alpha R plus-- let me just plug that in there-- delta E divided by kT. So you have 3 4 pi kT e. And then this is R to 3. So when you take the derivative with respect to R, now this is a negative.

That's a negative 3 that comes up. So it becomes 9 4 pi kg T and then R negative 4. We let it equal to 0. And we can then solve for R, see what R is. Now, this gets more complicated. R becomes 9 8 pi alpha kg negative 1/4. OK? T is also negative 1/4.

So what we are seeing here-- it basically says as you change temperature, the hopping distance is changing. The higher the temperature, the shorter the hopping distance. OK? This actually makes intuitive sense. The higher temperature means that you have more phonons available in the system.

If you have more phonons available in the system, the importance of the second term actually decreases. It's a lot easier to find a state with energy close to the starting state. So then the system, or these mathematics, would then favor hopping between the nearest neighbors just to minimize beta. OK?

So this is what we call the variable range hopping. Essentially, hopping distance becomes a function of temperature. The lower the temperature, the longer the hopping distance. The system will try to hop to a state that's further away in order to find the phonons, the right phonons. OK?

All right. The last step is then we need to plug it back to the hopping probability. What we argue here is that the conductivity that you actually measured-- obviously, it should be proportional to hopping probability. And if you plug it back, it's actually pretty straightforward to see that eventually, it scales with an exponential-- no. OK?

This is for variable range hopping. This is actually the well-known T to the negative 1/4 law. Some people also call this, essentially, Mott's law. Mott is the scientist who actually first proposed this theoretical formalism. Now, if you compare it with the Arrhenius law that you typically see for thermally activated process for extended states, Arrhenius law basically says that the conduction goes with T negative 1. This is the Arrhenius law, essentially.

So if you try to plot, essentially, the electrical conduction in an amorphous solid or an Arrhenius plot, what we're going to see there is that the temperature dependence is actually less compared to the case of Arrhenius law. OK? Just to give you a-- let's look at-- so this is actually what it's going to be looking like. OK.

This is an Arrhenius plot, typical Arrhenius plot. So if it's extended states, you're going to get, basically, just a straight line. And if it's variable range hopping, you have a curve looking something like this. As I said, the temperature dependence is less so that if you look at the high temperature, at high temperature, you get plenty of, essentially, extended states or plenty of free carriers in the conduction and now valence band.

Now, in that case, extended state conduction always dominates because it's a lot easier to just move the carriers in these extended states rather than having to force them to hop from one localized state to another localized state. OK? However, when you go to low temperature, at low temperature, the number of free carriers essentially decreases exponentially.

So at some point, there are so few extended states with free carrier populated that's available that electrical induction actually becomes very small. In that case, eventually, hopping is going to take over and become the dominant conduction mechanism at cryogenic temperature.

This is very typical for any amorphous semiconductor. High temperature-- it behaves, essentially, linear. As you go to low temperature, Mott's T to the 1/4 law essentially takes over, OK? Yeah. So basically, if you measure the DC conductivity, it's going to be a combination of two terms. This is what it looks like. OK?

So now, to show you that the science is correct, let's actually look at some real data, OK? In fact, by the way, this actually comes from my own PhD thesis. I was doing some conductivity measurement for these amorphous glass systems-- arsenic, selenium, tellurium, copper. OK.

If you put copper into this glass there, turns out the copper actually forms a defect band within the band gap. And then the defect band obviously consists of lots of localized states. So those localized states is then going to promote this hopping conduction. At high temperature, on the other hand, this glass is actually a narrow band gap semiconductor, amorphous semiconductor.

So you get electron electronic conduction. Copper, if you recall-- in the last lecture, we mentioned that this is actually one of the ions that has a very deformable electron cloud as well. So it can also contribute to ionic conduction, OK? But regardless of whether it's ionic conduction or extended state conduction, they all follow Arrhenius law.

So that's why if you look at the high temperature regime on Arrhenius plot here-- this is Arrhenius plot. If you look at this range here, high temperature, you see that they more or less exhibit a linear trend. OK? But there's a very clear deviation as you go to lower temperature. OK?

Now, instead, if you try to fit it with Mott's 1 over 4 law, you see the fitting coefficient. You get 0.99997. That's the moment you believe in science, when you actually look at those data. OK? So this is actually a very good example, where you see that you have almost perfect agreement with the Mott's negative 1/4 law, indicating that indeed, in this material system, there's very strong contribution coming from hopping at low temperatures. OK?

OK? So the same dominance of this hopping at low temperature is quite significant for some other materials as well. For example, if you think about things like amorphous silicon, if you don't passivate it well, there are actually lots of states within the band gap. And as a result, this is then going to lead to a very strong contribution of variable range hopping at low temperature.

And as a result, if you measure the conductivity, for example, for amorphous silicon versus crystalline silicon, at high temperature, obviously, crystalline silicon is going to be much higher because higher mobility, lots of carrier concentration, OK? But as you go to low temperature, it becomes possible that the amorphous silicon actually has higher electrical conductivity compared to the crystalline one because a crystalline semiconductor has very few contribution coming from hopping, unlike amorphous solids. OK?

I'm basically giving you the answer to one of the [? Piazza ?] questions. [CHUCKLES] All right. So just to summarize what we have discussed here about the basic theory of electron conduction, we talked about two kinds of conduction mechanisms. We talked about ionic conduction. We talked about, essentially, electronic transport.

For ionic conduction, everything boils down to this equation here. Conductivity scales with 1 over T times the Boltzmann factor, OK? And we mentioned that the main difference between amorphous system and crystalline system is that when you're trying to hop between those localized states for ions, the barrier height as well as the depth of the barriers-- those are actually statistically varying in amorphous solids.

So as a result, when you actually plot them on an Arrhenius plot, the conductivity does exhibit a slight deviation from Arrhenius behavior. OK? That's the only difference there. For the electronic transport, you need to familiarize yourself with electronic structure, the band structure I'm showing here. OK?

Unlike the case of crystalline solids, you don't have a k, crystal momentum or wave vector, whatever you call it. It's not a good quantum number. So that's why you can only represent the band structure in an amorphous material using density of states. You cannot plot the dispersion diagram or band diagram. OK?

And you also have the presence of the localized states. They're giving rise to, essentially, a band tail in the gap states. And those also contribute to the variable range hopping conduction, which is again absent in the case of a crystalline semiconductor materials, OK? All right? So this is the basic theory chapter.

Next, let me move on to the applications chapter. So for the applications, we are going to discuss amorphous silicon, which is one of the most important and most prevalent amorphous semiconductor systems. OK? And we are going to be talking about how to make macroelectronic devices out of amorphous silicon.

I'm sure all of you have heard about microelectronic devices. In microelectronic devices, we all know that we have the Moore's law. What Moore's law says is that every 18 months, the number of transistors will double on the chip. And then as a result, you can actually get more powerful and more powerful CPUs, making your computer smarter and smarter.

And this is clearly shown in this plot here. Again, this one is a bit outdated. It was still showing 7-nanometer nodes. We know we are talking about 2-nanometer nodes now. So the Moore's law is actually continuing its trajectory in some sense, even till today, with the caveat that you probably know.

Nowadays, when we're talking about 2-nanometer, 7-nanometer nodes, no longer refer to physical length or physical length of any of the structures on chip. Essentially, it's just a brand name. It's just, essentially, a marketing strategy, OK? In fact, if you look at, for example, 2-nanometer, 5-nanometer nodes, the actual length or size of the gate of the transistors in those structures is still of the order of 20 nanometers.

It has stopped shrinking. People are actually going to different kinds of transistor architectures. They're starting from planar transistor. Then they go to FinFET, essentially a vertical thing. And then they go to so-called Gate-All-Around, GAA, essentially. But anyway, they changed the architectures there, but the feature size essentially, more or less, stays [? decadent. ?] OK?

AUDIENCE: [INAUDIBLE]

JUEJUN HU: I saw. That's great. To some extent, there's a lot of innovation, new designs, new architectures, new materials. So there's new opportunities.

AUDIENCE: [INAUDIBLE]

[LAUGHTER]

AUDIENCE: They're lying to you.

JUEJUN HU: Oh, yeah. True Yeah, all of them, all of them. Yeah. You talk to TSMC, Samsung, Intel? Yeah. No. [LAUGHS] There's no extra 2-nanometer transistor there, unfortunately. No. Anyway, but the bottom line for these microelectronics, we know that they are trying to make things smaller. The smaller you get, more devices you can pack there, something that gets more powerful.

Now, macroelectronics-- we are talking about devices that follow completely different scaling laws. We're talking about devices such as displays, such as solar cells. In those cases, you actually need large area devices. And the figure of merit there essentially becomes the overall number of pixels or the cost per area. OK?

Now, if you think about display, for example, when I was a little kid, the most fashionable gadget was a CRT display that's about maybe 8 inches in size. It's smaller than a pad you have, OK? And with a very low pixel count, so everything is very quantized, spatially.

But now, we are talking about essentially huge micro-LED TVs with incredible resolution. OK? So these are what we call the macroelectronics. In this case, the scaling law-- I simply captured it as bigger is better. You want something that's huge. You can produce scalability with high quality.

Well, that's where amorphous silicon comes in, OK? For those macroelectronic devices, you cannot use crystalline silicon out of the very simple reason that if you try to use crystalline silicon-- because single crystalline-- you have to either grow it on a single crystalline substrate, or you essentially have to cut it from a big single crystal boule.

The largest size of wafer people are using nowadays in the industry is 300 millimeters. OK? 12 inches. While it sounds pretty big, it's smaller than your TV. OK? So that's why it doesn't work. OK? And also, for a lot of these macroelectronic devices, the figure of merit is quite different.

For microelectronic devices, you want your computer to be fast. You want your transistors to respond at gigahertz speed. That's why you need single crystalline material with very high mobility. You don't care about your TV operating at gigahertz. Your eye cannot catch up to the high refresh rate, anyway. OK?

So amorphous silicon turns out to be a pretty good material candidate. OK? So if you think about amorphous silicon, what I'm listing here-- these are the main advantage here, why they become attractive for macroelectronics. First one-- they can be deposited over a large area at low temperature in a monolithic manner.

Large area-- obviously, if you can make it a large area, you can essentially scale down the cost per area. You can increase the fabrication throughput. OK? And this can be done essentially using a very mature so-called Plasma-Enhanced Chemical Vapor Deposition, or PECVD process. As I'll show you in a few minutes, people are now able to deposit on enormous glass substrates-- each one of them is several square meters-- in a continuous manner so that you can get extremely high fabrication throughput and that very, very low cost.

Now, low temperature. The deposition temperature of amorphous silicon is also sufficiently low so that when you're actually putting the films on the substrate, you do not disrupt any of the existing devices or structures you already placed on substrate. And that's quite important coming from integration perspective. OK?

Finally, monolithic. Monolithic essentially means that you can directly deposit these materials onto the target substrate versus hybrid approach. Hybrid means that you have to first deposit material on a foreign substrate. And then you can transfer it to the final target substrate.

In lots of cases, monolithic integration is preferred because it simplifies the process, enhances yield, and enhances throughput. OK? And in that regard, because amorphous silicon is amorphous, it can really be deposited on any kind of substrate without having to worry about lattice matching constraints. It's actually advantageous specifically for monolithic integration.

Finally, the last advantage I want to mention here is that in PECVD process, you can not only deposit amorphous silicon. You can also deposit passivation layers in the same process flow. OK? And passivation layers are actually extremely important for semiconductors.

The reason people like silicon is because you get silicon dioxide, which is a perfect passivation layer. If you look back, in the 1960s, people were actually arguing about whether or not they should use germanium in silicon as a preferred material. Germanium does have many advantages with respect to silicon, like higher mobility, that kind of thing.

The problem with germanium is that germanium oxide is not stable. It's actually soluble in water. So it's a terrible passivating material versus silicon dioxide. It's just great. Same thing here. For amorphous silicon, you can deposit the passivation layers, whether silicon dioxide or silicon nitride, in the same chamber where you deposit amorphous silicon without even having to actually break vacuum and remove the substrates. So it's a very convenient process. And you can do that continuously.

All right. Next, doping capacity. You can dope amorphous silicon. While this may sound trivial, it's not. OK? As I will show you in the next slide, for a long time, people have thought amorphous silicon is a useless electronic material because they cannot dope it. OK?

It's limited by a phenomenon called Fermi level pinning, that when you actually dope it, even if you put a lot of dopant in there, you do not shift the position of Fermi level. If you don't change the Fermi level position, you don't change the carrier concentration. You cannot make any, have junction devices. You cannot control the carrier concentration. It's a useless material.

Now, the reason now people are able to dope it is because they were able to eliminate a lot of the defects in the material-- in particular, dangling bonds. OK? So dangling bonds-- these are the unsatisfied chemical bonds with essentially only one single electron. They are the dominant electron defects in amorphous silicon.

So with plasma-enhanced CVD process, there's actually lots of hydrogen getting incorporated during the deposition of PECVD amorphously. And these hydrogen atoms-- they are quite small. They can move around. Hydrogen has one electron, so they can actually combine with a dangling bond to form a two-electron stable structure. And then as a result, this eliminates those electron defects. And now, amorphous silicon becomes amenable to actually doping. So the invention of PECVD amorphous silicon is what really opens up the door for all the electronic applications of amorphous silicon. OK?

Now, finally, silicon. Even amorphous silicon is also compatible with all the CMOS process because it's silicon. So it's quite easy to use a lot of the existing infrastructure as well as technical know-how to develop process for amorphous silicon, leveraging what you already have for microelectronic industry. OK? OK.

All right. So in the end, that's why I put this quote here. "The essence of being human is that one does not seek perfection." That's exactly the case in the case of macroelectronics. You do not need a perfect material. OK? As we'll see there, amorphous silicon still contains lots of defects compared to single crystalline silicon, but it's just adequate for macroelectronic applications. And that's why people use it. All right.

So in this slide, I'm just basically showing you the structure of amorphous silicon. Left-hand side-- this is a unit cell of crystalline silicon. It has a diamond cubic structure. OK? If you look at the rings here, all of the rings in the crystalline silicon is six-membered rings. You can clearly see from here. This is a six-membered ring containing six silicon atoms.

So in amorphous silicon, we have a more random distribution of the ring size. You can get five-membered ring, seven-membered rings, OK? As a result of this statistical nature of the structure, you also get lots of dangling bonds, as I said before. Not all the silicon becomes four-fold coordinated. Some of them have one extra electron hanging around. Those are the key electron defects that we have to address there.

Now, what happens if you have lot of electron defects? Where's the-- OK. So if you have lots of electron defects, we can look at two things here. You can look at the density of states. This is what it looks like. These dangling bonds-- the defect associated with them is linked to this single atom layer.

So spatially, they are very localized. What we have mentioned in last lecture is that if you have this kind of spatially localized defect states, it must have a very large imaginary part of the wave vector. OK? And as a result, it means that these states must be located near the center of the mobility gap. It's very far away from mobility edge.

So they typically locate somewhere in the middle of the mobility gap, OK? So now, if you think about-- you essentially get lots of states right near the middle of the band gap or mobility gap. OK? So what happens if you try to dope it? If you try to dope it-- let's say you put some donors in there, OK?

Normally, these electrons on these donors-- they will essentially thermalize and go to your conduction band. However, because of the presence of all of those states near the middle of the band gap, the electrons will instead try to fill the empty states near the middle of the gap. OK?

So as a result, even if we're putting lots of dopant atoms, all of these electrons are just going to try to fill those mid-gap states. You need to essentially completely saturate all the mid-gap states. Then you can start to show the doping effect. So before you saturate all the states, then what you get is that essentially, you still have lots of empty and lots of filled states for those mid-gap defects.

So the Fermi level, therefore, should also be located within the defect band. So effectively, what I'm saying here is that regardless of the dopant you put in there, if you don't saturate all these mid-gap states, the Fermi level will more or less be pinned near those mid-gap states.

And that's why, when Fermi level position is fixed, you're not changing the carrier concentration. So you no longer get your doping effect. And this is known as Fermi level pinning, OK? So that's what I'm putting here on the slide. The Fermi level essentially gets pinned to the mid-gap state.

Now, you may argue that-- well, simple. We just put lots of dopants in there. At some point, it's going to saturate all the defects. Then you start to get doping effect. It's actually quite difficult. Let's look at this plot here. What I'm showing you on the left-hand side here-- this is basically the conductivity in logarithm scale in the vertical axis as a function of inverse temperature to negative 1/4 power.

So what you're seeing here is that at low temperature, you see that it follows pretty much a straight line, which indicates that you get variable range hopping. OK? Now, from the variable range hopping equation, you can actually infer what is the g here. That gives you the density of states near the Fermi level, which allows you to calculate what is the total number of defects within the mobility gap.

OK? So according to that calculation, in this case, this is actually an amorphous silicon that's deposited using an electron beam evaporation. OK? If you do electron beam evaporation, essentially, you have a silicon. You heat it up at high temperature. They vaporize, condense to a cold substrate.

It's a very high vacuum. So there's no impurity. What you end up getting is a very high purity silicon film only containing silicon. OK? So there's lots of dangling bonds that are not passivated by things like hydrogen. So the calculation tells you that in this pure amorphous silicon film, you get the mid-gap states with a concentration of 10 to the 20th inverse centimeter.

Now, typical semiconductor doping-- you're talking about doping concentration in order of 10 to the 17th, 10 to the 18th. 10 to the 19th is considered high doping. 10 to the 20th-- that's like degenerate doping. It becomes practically metal. OK? So if you want to dope amorphous silicon, you need to put in at least 10 to the 20 carriers in order to then see any kind of a carrier concentration change. So that's not really practical.

OK? So that's why, for a long time, if you don't passivate these dangling bone defects in amorphous silicon, this material is considered quite useless in the electronic industry because you cannot dope it. If you cannot dope it, you cannot make PN junctions. You cannot modulate the carrier concentration conductivity. It's of no use. OK.

So what changes this picture is really the invention of a PECVD process, OK? In a PECVD process, the starting gas precursors are essentially silane, SiH4, typically. OK? And then you use hydrogen as a carrier gas. You then send it into a chamber where you actually get this active plasma. And this plasma is then going to split these precursor molecules into, essentially, radicals.

OK? So you can get radicals, such as SiH3, SiH2, SiH, or even just hydrogen atom itself. Those precursors then condense onto the substrate to eventually form the amorphous silicon film. Now, you can see, in this process here, there's lots of hydrogen around. OK?

First thing is that when you actually decompose the precursor, you still may have hydrogen attached to silicon. Also, because the carrier gas is hydrogen, this environment is really very much hydrogen-rich. So this abundance of hydrogen is what allows the passivation of those dangling node defects. OK. And with a reduced number of mid-gap states, then you'll be able to then effectively dope amorphous silicon together-- electronic devices. OK? All right. So that's the big picture.

Now, on the right-hand side here, I'm showing you a schematic that illustrates how the deposition process actually takes place. OK? So basically, what do you have? On the top surface, what I'm showing here is a few layers of the silicon that's already deposited on the substrate.

On the top layer, on the surface, you get both chemical bonds that are unsaturated, that essentially point upwards. So because there's tons of hydrogen around, normally, most of those chemical bonds would then have, essentially, hydrogen attached to them. So the surface is actually inert. It's passivated completely with hydrogen. OK?

If you have new radicals coming onto the surface-- say SiH3 radical-- they would start by essentially adsorbing to the surface. It's not chemical attachment yet. OK? It's essentially physical adsorption. It will not be able to form the chemical bond with the surface because all the chemical bonds essentially are all saturated by hydrogen. OK?

So what happens is that in some cases, sometimes, some of these SiH3, because there's one unsatisfied chemical bond, can combine with one of the hydrogen on the surface. And once it combines with the hydrogen on the surface, you form this SiH4 gas. It's a gas molecule. So it gets released to a surface.

As you move into the free space you left behind, now, one unsatisfied dangling bond on the surface. The subsequent SiH3 radicals-- they can then diffuse on the surface through, essentially, surface diffusion onto this lattice size and then combine with that to essentially attach a new silicon atom.

OK? So that's how the deposition process proceeds, essentially. So you have this extraction process of hydrogen from the surface by the radicals. And the other radicals then, through surface diffusion, come in, fill in the gap, and then form, essentially, the growth of the film. Does that make sense? You need to essentially remove some of the hydrogen from the surface to form these dangling bonds there so that you can have a continuous attachment of silicon onto those sites.

AUDIENCE: So you're adding more? Was it not already satisfied or stable with hydrogen?

JUEJUN HU: Initially, yes. Initially, it's all covered with hydrogen because there are lots of hydrogen on the surface. But the surface then becomes inert because there's no chemical bond to attach new atoms onto. So that's why you need some of the radicals to extract hydrogen from the surface--

AUDIENCE: Oh.

JUEJUN HU: --to pull it away.

AUDIENCE: Continue to add?

JUEJUN HU: Yes, yeah, because it's a continuous process. You continue to flow gas. So there's always an abundance of supply for this surface adsorbed SiH3. And they will move around. Sometimes, they then remove a hydrogen from surface, go to a gas phase, leave behind the active site where the other can then diffuse onto that, attach to the surface. OK.

So that's how the process goes on. Now, if you look at what I'm plotting down here, it's vertical axis is the defect density, basically dangling bond density in the silicon fuel. You deposit it. It's a function of temperature. There's some intermediate temperature that gives you the lowest defect density.

OK? Now, the reason you have this kind of an intermediate temperature with optimal quality here is because if you go to low temperature, at low temperature, because the surface diffusion is essentially a thermally activated process, following Arrhenius law, at low temperature, the surface diffusion becomes very ineffective.

These adsorbed SiH3 atoms hardly move on the surface. So then this extraction process becomes dominant process. You generate lots of surface dangling bonds. They are not adequately passivated by the subsequent SiH3 atoms. So then this essentially translates to a loss of surface defects, eventually, because of the unpassivated chemical bonds, OK?

Now, if you go to a high temperature, this chemical reaction of SiH3 extraction of a hydrogen from surface and a release to free space is actually an endothermic reaction. Endothermic reaction means it actually absorbs heat. So if you go to high temperature, according to Le Chatelier's principle, the chemical equilibrium gets pushed along to essentially having this extraction there.

So this will then also lead to, essentially, an inadequate passivation of the surface just because of the chemical equilibrium. So that's why there exists an optimal temperature window where you can have a minimal amount of this surface unpassivated chemical bond, OK?

If you look at the temperature, also, you notice that the temperature is of the range of something like 250 degrees Celsius, 300 degrees Celsius. OK? That's also quite important because that temperature is actually adequately low. So it will not disrupt or damage any existing devices you already put on the substrate. OK? That's one advantage of using amorphous silicon here. You can do this low temperature processing. OK.

All right. So that's about the deposition process. Next, in this table here, I'm summarizing the electronic properties of amorphous silicon in comparison to its bulk crystalline counterpart. OK. So what we are seeing here-- mobility. Again, mobility is way lower. This comes from two facts we have mentioned.

One is that the free mobility is a lot lower because of the scattering of the disordered structure. Also, you get trapping effects, trapping and detrapping. So not all the carriers are always contributing to electrical conductivity. So both factors combined together-- you get mobility that's orders of magnitude lower compared to bulk silicon. OK?

Now, this low mobility also means that the carrier diffusion length tends to be a lot smaller in amorphous silicon compared to crystalline silicon. The carrier diffusion length essentially gives you the average distance the carrier will move before they get recombined. OK?

If you have a small mobility, the distance the carrier travels will get a lot smaller. And this accounts for the small carrier freelancing amorphous silicon. Now, what's the physical significance there? So if you're trying to make devices that rely on carrier collection-- for example, solar cells. Solar cells-- it operates like a PN junction.

Light comes in, separates electrons on the host. They then move into the counted electrodes and get collected. So this process of those photoexcited carriers traveling to the context-- this relies on, essentially, carrier movement, diffusion and drift. So if you have a very small carrier diffusion length, it restricts, effectively, the thickness of the solar cell device you can make while still having high efficiency.

What it means is that for amorphous silicon, the thickness of the solar cell probably is of the order of micron, 1 micron. OK? Anything thicker than that, you generate lots of carriers, but they will recombine before they reach your collection electrode. Then you get no current. OK?

Versus crystalline silicon-- because of very large carrier diffusion lengths, you can make, essentially, crystalline silicon solar cells out of bulk wafers that's a few 10s or few 100s microns in thickness. OK? So that's the difference there. OK. Now, what we'll see in next slide is fortunately, amorphous silicon also has stronger light absorption. So this allows you to actually use a thinner film while still getting adequate light absorption. OK?

All right. Now, next one. This is about doped conductivity and undoped conductivity. This is one aspect where amorphous silicon is actually pretty good. So if you look at the actual conductivity, absolute numbers, they tend to be a lot lower compared to the crystalline counterpart, again because of the much lower mobility there.

But what really matters here is the contrast, the conductivity modulation between the doped material and undoped material. You can see that we still have nine orders of magnitude contrast between the dope, undoped states. That's actually really important for the application we're going to talk about here.

For example, for display, people are using this amorphous silicon, essentially, to make thin film Transistors, essentially on/off switch, so they can turn the pixels on and off for display applications. In those cases, the figure of merit there is the contrast ratio, the on/off ratio. OK? And that actually directly relates to this ratio here. OK? So in that regard, amorphous silicon is pretty good for this kind of application. You can make very effective switches out of amorphous silicon. OK?

Last one. Optical band gap. Amorphous silicon has a band gap that's actually much larger than crystalline silicon. The reason for that is because you put hydrogen in there, OK? In commercial-grade amorphous silicon, there's actually lots of hydrogen. Hydrogen is somewhere between 10% to 15% in amorphous silicon film.

And that's why, if you look at this hydrogenated amorphous silicon field, it's customary that people write it in this form here. It's A silicon and then H, where the H represents that this is hydrogenated field with lots of hydrogen passivating defects. OK? So because of the large amount of hydrogen present in the film, it chemically modifies the structure. And therefore, this leads to a much larger band gap because hydrogen is a very light atom. So that's why amorphous silicon has a much larger band gap. OK?

Now, this large band gap, of course, also impacts their optical absorption properties. So on this slide, I'm basically showing you this is basically absorption coefficient in vertical axis. Horizontal axis is the light energy, photon energy, OK? You see that for crystalline silicon, the absorption onset starts at about 1.1 eV, corresponding to its band gap, whereas amorphous silicon has a lot lower loss in this region here.

But as soon as you move into the band gap of amorphous silicon-- as I said, it's about 1.7 eV-- there are two things. One is that you notice that the absorption is not 0, even below 1.7 eV. This comes from the back tail. You get those localized states that extend into the mobility gap or the band gap. So those states can still contribute to absorption.

So that's why the absorption is nonzero even though you're looking at somewhere below the band gap. OK? That's one very important feature for amorphous semiconductors. The absorption does not go to 0 even below the band gap because of the localized state. OK? Second thing is once you go above the band gap, you see that absorption for amorphous silicon actually rises much quickly compared to crystalline silicon. It in fact quickly overtakes crystalline silicon as you go to the visible spectrum.

Now, the reason for that is because if you think about crystalline silicon, you know that crystalline silicon is the indirect band gap semiconductor. In a direct band gap semiconductor, if you want to absorb a photon, it's a three-particle process. You need to have one electron in the valence band. You need to have one empty state in the conduction band. You need to also have a phonon.

The phonon is used to compensate for the crystalline momentum mismatch between the states in the conduction and the valence band because you have k difference between those two states. And that's why the optical absorption is not very efficient in a crystalline semiconductor because you need the phonon to be involved in that process.

OK. Now, what about amorphous silicon? In amorphous solids, we said that crystalline momentum is not a good quantum number. If it's not a good quantum number, you don't have to worry about momentum conservation in optical absorption process. So in this regard, amorphous solids behave somewhat more like a direct band gap semiconductor.

You don't need the phonon participation in the optical absorption process because there's no momentum conservation whatsoever. Does that make sense? Thinking about it?

AUDIENCE: [CHUCKLES] Say it again.

JUEJUN HU: Say it again. OK. In a crystalline solid, in order to have optical absorption-- if you think about crystalline solid material, this is what the band structure looks like. This is your. This will be your k. This is crystalline momentum. This is energy. This is your valence band. Yeah, valence band.

And then your conduction band-- if it's in direct band gap, the conduction band is located-- its minimum does not coincide with the maximum of the valence band. So now, if you want to have optical absorption, you are trying to promote, say, one electron from here to here. There's actually a k mismatch.

So you also need a phonon with a k that corresponds to exactly this amount to compensate for this momentum difference in order to get momentum conservation. OK? So you need essentially one photon, one filled state, one empty state, and also a phonon with that k so that you can promote this hopping here. OK?

Now, this whole concept of crystalline momentum is essentially a manifestation of the translational symmetry in crystalline lattice. OK? That whole thing just simply does not exist in amorphous solids. You can wipe this whole thing completely out. OK? So there's no crystalline momentum. You can essentially promote the carrier directly from valence band to conduction band without having to worry about momentum conservation. OK? So it behaves like a direct gap semiconductor, in that regard, the amorphous solid. You all took 3033, right?

AUDIENCE: And it does-- it--

JUEJUN HU: I can see that it's a while ago.

[LAUGHTER]

I know things exponentially decay. The retention--

AUDIENCE: Particular reason on why it behaves just-- it doesn't need to keep the momentum?

JUEJUN HU: Basically, just because this thing is just ill-defined in the amorphous solids. You don't have long-range structural order.

AUDIENCE: OK, so there's--

JUEJUN HU: OK. So it just doesn't exist, the constraint. You don't have that constraint, essentially. There's additional constraint imposed in the crystalline solid, but it's absent in the case of amorphous solid. OK.

AUDIENCE: So I guess the thing I was thinking about, why I had the blank look on my face, is I was thinking about when we were talking about localized states. And that requires a product for the--

JUEJUN HU: This is extended states. Yeah, this is extended states. We're talking about essentially siting of carriers from, essentially, across mobility edge or mobility gap, yeah, or across the band gap. OK? So yeah. For practical electronic devices, you rarely rely on the conduction for the hopping conduction because hopping conduction's actually fairly inefficient. It's slow.

And it practically is only significant when you go to cryogenic temperature. So for normal device operating conditions, when you're trying to essentially send current through a device, those are all extended states contributing to that. Yeah. Yeah, so these are essentially from extended state to an extended state. OK.

So that's what accounts for this absorption here, absorption above the band gap. Below the band gap, you can have excitation, for example, from a [INAUDIBLE] band tail to the above band tail or from a band tail to extended states. That's what contributes to this absorption here, this tail below the band gap. OK?

Anyway, bottom line. You need to know that amorphous silicon-- once you go above the band gap gap, it's actually a lot more optically absorbing compared to crystalline silicon. You can see from here. So this also can be beneficial because it means that, as I have mentioned already before, while you have to make amorphous silicon cells, solar cells, very, very thin, you can absorb a sufficient amount of sunlight even within that micron-thick film because of a very high absorption coefficient on amorphous silicon.

OK? So that compensates for the drawback in terms of low carrier mobility. OK? All right. Any more questions about this part? All good? All right. So now, next, I will show you, essentially talk a little bit more, about the deposition process. Instead of me talking about it, I will just show you a YouTube video.

This is a fairly old YouTube video, and I'll tell you why.

[VIDEO PLAYBACK]

- Hi, I'm Charlie Gay. I'm the general manager of the Solar Business Group at Applied Materials. About 2 and 1/2 years ago, we had a vision for dramatically lowering the cost of manufacturing thin film solar panels. Today--

JUEJUN HU:

That two years ago is 17 years ago, OK? [CHUCKLES]

- --very site that was just a plot of land. Now, it's a full-scale SunFab production facility that is run by Signet Solar. Let's go take a look.

- The SunFab is an automated blast module production line. The process begins with the front loader robot placing the 5.7-meter-square glass onto a conveyor. SunFab's sophisticated process, equipment, and factory automation software controls the various steps in the manufacturing operation.

[MUSIC PLAYING]

Next, the edges of the glass are rounded by a seamer and the glass washed to remove contaminants.

[MUSIC PLAYING]

The glass then enters a laser scribe, where the front contact layer is ablated to form lines for electrical cell isolation.

[MUSIC PLAYING]

After scribing, the glass is ready for silicon deposition. Because the PECVD 5.7 system is almost two stories high, the glass is transported to the deposition chamber by an elevator.

[MUSIC PLAYING]

The PECVD system is a plasma-enhanced chemical vapor deposition system.

[MUSIC PLAYING]

- We're here at the heart of the SunFab. This PECVD equipment is what's used to deposit the large area uniform semiconductor layers that make a solar panel electrically active. We developed this equipment by adapting tools from the flat panel display industry, where big screen TVs and flat panel monitors are routinely produced at a low cost, high yield, and predictable throughput.

[MUSIC PLAYING]

AUDIENCE: I feel like they're showing us all the--

- After the silicon deposition is complete, the deposit is scribed again before entering the inline sputter-down physical vapor deposition system.

- We're here at the [INAUDIBLE] system. This is the back contact system on the SunFab line. It's designed along the same principles as our equipment that's used in the glass coating industry, where over 200 of these systems have been used in the field for the last 20 years. It's part of what makes the SunFab system so reliable.

[MUSIC PLAYING]

- Following back-contact layer deposition, the glass is scribed again and is then capable of generating electricity.

[MUSIC PLAYING]

- Next, the quality assurance and shunt removal system tests the glass and improves total power output by further isolating the cells.

[MUSIC PLAYING]

The SunFab line is designed to allow our customers the flexibility to make quarter, half, or full-size modules to serve unique market needs. Here you see the glass being scored and cut into the half-size.

[CLACK]

The process of edge deletion then removes the film from the glass edge for greater reliability. The bus line attach tool completes internal cell wiring.

[MUSIC PLAYING]

The glass is then ready for lamination.

[MUSIC PLAYING]

PVB foil is cut to the right size and placed on the glass, followed by a sheet of back glass.

[MUSIC PLAYING]

The laminator evenly spreads out the PVB foil between the front glass and the back glass, creating a uniform bond to secure glass PVE glass module. The module is then subjected to a high pressure and high temperature process within the autoclave, which removes trapped gases and anneals away physical stress for superior lamination. Overall, this lamination process is designed to enable the module to generate maximum power well beyond the typical warranty period.

[MUSIC PLAYING]

The SunFab line is also equipped with accumulators that buffer the line during system maintenance, preserving line productivity.

[MUSIC PLAYING]

Finally, the junction box is attached to the module. The junction box comes with built-in bypass diodes and standardized connectors to reduce install time.

[MUSIC PLAYING]

The solar simulator rates the module for power output and technical characteristics.

[MUSIC PLAYING]

SunFab is covered by an extensive 24-by-7 warranty, enabling faster--

JUEJUN HU:

So basically, glass paneling, solar modules out. Fully automated.

- --reduces operating expenses and increases factory output with the most comprehensive, lowest-cost support solution in the solar industry--

JUEJUN HU:

That's pretty much it.

[MUSIC PLAYING]

- This is really, truly, the beginning of the major industrialization of solar power. The costs are coming down because a 5.7-square-meter module is able to be produced at a very low cost and because the cost to install this large area module out in the field is also very low. There's economies of scale at work here that are unprecedented in the history of solar manufacturing. Thank you for joining us. We look forward to seeing you again soon.

[END PLAYBACK]

JUEJUN HU: What do you think?

AUDIENCE: I think--

JUEJUN HU: Sounds--

AUDIENCE: --have aesthetic complaints. [CHUCKLES]

JUEJUN HU: Oh. I know it's a poor resolution. This is a 17-year-old video. What do you expect?

AUDIENCE: [LAUGHS]

JUEJUN HU: Now, why I decided to choose to do that-- you can no longer buy these systems anymore. [CHUCKLES]

AUDIENCE: No.

JUEJUN HU: It's certainly a technical triumph. If you look at this one here, each of these chambers is this little thing. This is the 5.7-square-meter deposition chamber. In each of the SunFab systems, you have 28. They have seven in each here. And then you have 28 individual chambers to ensure that you can have the potential throughput. So it's really quite remarkable.

In fact, at some point, back in early 2011 or something, I was reading on the news that the UAE-- they tried to build a new technology city, Masdar City. And they purchased several-- not just one, several-- of these production lines. They ended up reselling it before even opening up the package. OK?

Why? Because essentially, the whole business of amorphous silicon solar cell is gone in a few years. OK? Why is that? I guess I will leave that to the next lecture about why that's actually the case.

AUDIENCE: Ugh.

JUEJUN HU: [LAUGHS] That's the hanger. [LAUGHS] Yeah, but well, that's it. OK? Amorphous silicon is still important for many applications. OK? There are a few big applications we're talking about here. The two biggest ones are essentially display and solar cells.

So even though solar cells is gone, I will still talk about it and talk about why it actually eventually ended up dissolving. It's still a very important material for display. OK? Some other smaller market-size applications-- for example, X-ray imaging-- when you go to hospital, you have this actually taking pictures there.

You also need a very large area detector so that you can capture large-area images. And that's only possible with amorphous silicon. OK? You can also have a position-sensitive detector. It's a kind of detector that essentially can tell you where the light is actually coming in the location there. It's also a large area device.

Finally, IR bolometer is basically a kind of IR imager that detects infrared light. The way that the IR bolometer works-- it's actually leveraged on one unique property of amorphous silicon. That has a very large Temperature Coefficient of Resistance, TCR. So when you actually change temperature, the electrical resistance of amorphous silicon actually changes quite dramatically.

Basically, because when you change the temperature, as you go to high temperature, you excite more carriers into the conduction band. And you have, essentially, this extended-stay conduction that contributes to enhanced electrical conductivity. So by measuring the electrical resistance, you can actually know the temperature.

So the way these devices are designed is that you have these suspended pixels. If infrared radiation comes in, it absorbs infrared light, converts it into heat, so then leads to a temperature rise locally, which then changes electrical resistance. So then by measuring electrical resistance, you can then use that to infer the intensity of light incident on the device.

So that's why it's essentially used as night vision devices, basically. OK? So amorphous silicon is still quite important, even though the solar cell industry is basically gone. OK? And as I said, next lecture, we are going to just decipher why the whole amorphous silicon solar cell business just evaporated, OK?