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PROFESSOR: Why don't we go ahead and get started. What we're going to be talking about today, is what happens after that photon gets absorbed. So we spent a great deal of time in our last lecture talking about light absorption, the interaction between light and the semiconductor. Now we're going to talk about what happens once that light is absorbed.

So we're in the fundamental section. We're right here. Later on, we'll get into the technologies and the cross cutting themes. As we go through the fundamentals, I'm going to attempt to relate those fundamentals to real solar cell technology. So you're not left kind of floating, wondering why it is that we're studying this stuff, but you're really seeing the connection to solar cell devices.

So first if we remind everyone of the broader picture that the conversion efficiency, the ultimate performance of the device, is defined as the output energy versus the input energy. And for most solar cells, this breaks down into the inputs and the outputs. The input being the solar spectrum and the output being the collection of charge. And there are multiple processes that occur here in the middle. Light absorption, we talked about last time. We're going to be talking about charge excitation in charge transport today, mostly charge excitation.

So we're right here. We're going to be marching steadily down toward the right over the next few lectures. And let me remind you, everybody, that the efficiency of the device is the product of each individual efficiency of each different step. So if anything is going wrong here, it will be limiting device performance. And the image you should definitely have in your mind is of that bucket, with each plank representing a different component of the device, perhaps a different physical process or perhaps a different physical component of the device itself. And

whatever is the poorest, is going to be limiting overall performance. Your efficiency is going to be flowing out from that low plank and you will have a low efficiency device.

So the art of making a high efficiency solar cell is really understanding everything that goes into the physical processes, but also the devices. And that's why we break it down like this. We have the physical processes, and finally we get into some of the devices in the architectures of manufacturing methods. So learning objectives today. Oops. That was a little bit of a typo. It's not the solar resource. We're talking about charge excitation today.

We will be talking phenomena logically how this thing called a band gap forms. It's a very important physical concept. We'll lead off the lecture with it, and then very quickly go into applications that you see why it's important, returning back to the fundamentals, how it actually forms, going back and forth until we have a pretty solid understanding. From the background surveys, I understand that about 50% of you understand what a band gap is. So 50% of you may be a little bored, or a little entertained, at my hand wave explanations during the first part of class.

I encourage you to think about the band gap from the perspective of the solar cell device, because this is probably not something you've done before. You've probably understood band gap from the perspective of a semiconductor device as packaged in the dark, perhaps in a little gadget like this. But not something that's exposed to light with the addition of a generation current. Or at least not in detail. So I welcome you to think about that as we go through the explanations in the beginning of class. Then we'll describe how optical absorption in semiconductors represents the transitions of charge in an energy band diagram. In other words, if we imagine a given space of the semiconductor divisive, say a surrounding of a given atom, and we imagine that different orbitals, different electron orbitals will have different energies associated with them. We are going to be talking about how light gets absorbed in transitions electrons between those different energy orbitals.

That's important because then we'll be able to calculate the fraction of photons lost,

not absorbed, by a given semiconductor material. We'll be able to calculate the fraction of incident solar energy that is lost as well, due to a phenomenon called thermalization. And finally, we're going to be able to plot efficiency versus band gap, and denote specific materials on it. In other words, we are going to be doing our first higher level efficiency calculations for a solar cell device by the end of today's lecture.

And the idea is to expose a little bit on the technology side as well, so that you have an appreciation for what's up and coming in the field, what are some of the ways to enhance the performance of solar devices. So band gap. Very, very basic description. If you've never been exposed to band gaps before, the reason it's important is because the band gap is going to define what color, what portion of the solar spectrum that material absorbs light most efficiently.

How a band gap forms is related to the atomic structure. Think of bonds as essentially why stuff is tough. If the mechanical engineers in the room, if you remember linear elasticity, those bonds are what are essentially forming those springs between the atoms that are keeping them, the material, from flying apart. There is also a very interesting property here, that if you have a bound electron, it's usually not moving very far that atom. It's usually in a very localized electronic state close to that atom.

So if you were to apply a resistance meter, an Ohm meter, to your device to measure the resistance across it, and you had just bound electrons, you would measure a very, very low current passing through that material. Because there would be very few free charge carriers to move in that applied field, when you apply the two probes and there's a little battery in here that applies a field across the material, you wouldn't be able to measure much current flow, because there wouldn't be too many free electrons to carry that current.

So the bound electrons essentially enhance the strength of the material. But it doesn't help us from a semiconductor point of view. What we need are excited electrons. And excited electrons are why materials conduct. So let's imagine we

have a bond. For example, in this material right here, these gray lines are really two electrons that are covalently bonded. Essentially two electrons-- one electron from each little black circle representing a carbon atom. And each electron associated with that carbon atom is shared with the other, in a covalent bond. And for the chemists in the room, more precisely, you have sp^3 hybridized orbitals in this diamond cubic crystal structure. For everyone else, these are shared electrons in a covalent bonding configuration.

Now if light comes in with enough energy, it can excite an electron from that covalently bonded state into an excited state, where it can then roam freely throughout the lattice. And that's the nature of charge excitations. So the big question that we have to ask ourselves is, what color of light will this material absorb most effectively? Will those electrons in the covalent bonds absorb light and be excited into a state where they can roam freely around the material, and ultimately conduct electricity?

OK. So the answer to that question is not simple. Understanding how a band gap forms can be an entire semester of quantum physics. But what we're going to do is do it in a three step approach. Simple, very, very simple explanations that hopefully everyone will get. The next most simple explanation, which hopefully 80% of you will get, and then perhaps a more detailed explanation that only a few of you will get. But the idea is to really progress in levels of explanation.

So let me go back one step. Yeah. The band gap energy can be most simply understood as a finite amount of energy needed to excite a highly localized electron into a de-localized excited state in the semiconductor where it can move around the crystal. OK. So this is the description of the band gap, how a band gap forms that you'll see in many chemistry textbooks. And I like it, because it's something that you can really grasp and understand. We have to start with the simple premise that electrons are a type of particle called a fermion.

What is a fermion? Let's refresh our basic physics here. What means a fermion? Spin one half. And it also means-- can two fermions occupy the same state? No,

they can't. Bosons can. But fermions cannot. And so what happens when you put two fermions together in a system? And say we have discretized quantum states. We begin filling up from the bottom up, right? Typically. So the lowest energy states get occupied first. You have, for example, spin up, spin down in your s orbital. And then they begin populating the next electron orbital. Once that's filled, you go to the next one, and the next one.

So if we have one atom in isolation, the easiest example is that hydrogen atom, for those who took quantum mechanics, who actually calculated the energy of the bound electron there in the ground state of the hydrogen atom, around 13.6 eV. So imagine now you take a silicon atom, or carbon atom, or something else, a little bit bigger, more electrons in its structure. So you have the core, the 1s orbital filled. And then you start progressing outward. 2s2p and so forth. And so you begin filling up the orbitals. Let's see atomic separation. So imagine that we have our atoms infinitely separated. So we have just one atom in the middle of an infinite lonely space. One atom. And we would have discrete energy levels corresponding to the different orbitals, the different orbitals around the nucleus.

Now imagine the atom is no longer lonely. It now has a partner. And you bring those two atoms closer and closer and closer together. That's this d getting closer and closer together. What happens? Well, electrons are fermions. They don't like occupying the same electronic state. So first, the first shell that's going to quote, unquote see each other, the first electron shell that will interact is what? Is it the outermost, or the innermost? Outermost. Right? Because they're the closest together.

So you're moving the two atoms closer together, that outermost shell will begin to quote, unquote see the other atom. And those electrons will say, hey, you're occupying my state. And what will happen is they'll begin splitting, in energy level, and that's what you see right here. What this is representing is not just two atoms coming together, but a multitude of atoms coming together. And we have to really imagine, for example, and in most matter, we have something in the order of 10^{22} to 10^{23} atoms per cubic centimeter. So atoms per cubic centimeter.

Fun math, just total aside. If anybody talks about teletransportation, think about the number of atoms in your body. And assign an xyz-coordinate to them, and then calculate the amount of data in terabytes. And then calculate our Ethernet speeds, and try to figure out how long it would take to transmit that data to the other side.

Anyway. So this is to give you an impression of the density of atoms within the cubic centimeter. So you have a lot of atoms coming together, even though the electron wave function can be highly localized, they still interfere with each other. There's still enough atoms coming together that you have this interference. And it's not just two electron states, but many of them that are splitting, that are forming a band of states because no two electrons can occupy the same energy level as these atoms are coming together.

Now, as they become closer and closer and closer, it's not only that outer shell that begins interacting. It's the next most outer shell. This one, here, that begins interacting. And finally another shell, and another shell. And so at some equilibrium distance, the equilibrium distance here defined as the attractive potential between atoms. There's an energy gain by forming that bond. And the repulsive force of the nuclei, their large concentration of positive charge in the nucleus, that if you tried pushing them too close together, they'll repel.

This balance of forces, the attractive potential due to that bond formation, the repulsive force to the nucleus, results in an equilibrium bond distance, d , shown here as this dotted line. And at that equilibrium bond distance, some of the orbitals will be forming bands and other orbitals will still be discrete, namely the core orbitals will still be discrete. The outermost orbitals here will be forming bands. Now an interesting thing happens when it just so occurs, and say, for example, in the system right here, this shell is filled. This shell is filled. This shell is completely filled. And let's imagine that this orbital exists, but it's unpopulated. You ran out of electrons. And you started filling in the orbitals of this atom over here. You had enough for this orbital, that orbital, that orbital, but then you ran out of electrons. You didn't have anything more. And this band of states was empty.

So the band of allowed states exists up there, but it's empty. And this band right here exists, and it's filled. These core states exist, and they're filled as well. So the action is really happening right here. If light comes in, if visible light comes in, it's probably going to excite an electron from this filled band right here to somewhere in this unoccupied band up there.

And this gap, right here, is an interesting thing. There is no stable electron orbital. If you were somehow to take an electron with that given energy, this energy here, from the vacuum and stick it inside of the system here, it would quickly decay into a stable orbital. So this is a prohibited band of states. There is no stable orbital for that electron to exist at that energy. And hence we call it a band gap.

The reason band gaps are interesting, is because different materials have different, or can have different, size band gaps. Some don't have a band gap at all. Most of those that don't have a band gap, because you have a band of states like this one that's partially full. Let's imagine we have three electrons in this band right here. One, two, three. And then we have these other four empty states about it. In fact, you have a partially filled band. And let's imagine, instead of just having seven states within that band, we had a multitude of states within that band. Almost too many to count. And now, with even the slightest of energy, we could excite an electron from this state into that state plus little delta. That would be a metal.

Now if we had a really big band gap, we wouldn't be able to absorb much light. Because you'd need a large amount of energy to excite across that band gap. And that would be an example of, say, glass. Where light would come in. Most of our visible spectrum makes it through the glass, and that's why we see through the other side. And diamonds as well. OK.

So let's review. An atom in isolation has discrete electron energy levels. And on this diagram right here, it's represented with this d , the atomic separation being way out here. We have discrete energy levels. And that we can remember from our basic physics, especially the hydrogen atom. And as atoms move closer together, as in a crystal, where you have a regularly repeating arrangements of atoms, the electron

wave functions begin overlapping, and since electrons are fermions, meaning that the two electrons can't occupy the same state, you have a splitting of those energy levels forming bands. And you can see the splitting as you move from right to left, as you move from further to closer, on these diagrams right here. First starting with the outermost states, the most valence of electron orbitals, and then slowly moving into the core states as well.

And the gap between bands denoting an energy range in which no stable orbital exists is called a band gap. Sometimes you'll see it all written as one word.

Sometimes there will be a space between the band and the gap. Any questions so far? OK.

So now this explanation should be relatively straightforward. What I want you to log into your ram, because we're going into some more detailed explanations, and I want to set a marker, a flag, so we can come back here afterward. And even if you're lost with the subsequent explanations, you still get this one. Right? So remember these three points. If you make a note of them in your notes, and we're going to move on to a few more explanations here.

OK, so another way of looking at this which really builds on the folks who have had a more advanced physics backgrounds, is that the wave function of an electron, inside of a crystal-- if you recall the wave function of an electron in free space, we have what is called the plane wave equation for the electron. It's this regular repeating, nice stable function. Now if we introduce that electron into a crystal, it's almost like an infinitely repeating system of atoms. And so you could envision that you could describe the wave function of that electron as a combination of a plane wave, but perturbed by that locally repeating potential from the atomic nuclei. And let me be more specific about regular repeating potential. What I mean is that you have a series of nuclei here, and if you imagine the electron potential around these nuclei, there is a propensity for the electron to be bound by the atom.

And so as it's moving along, instead of just a free plane wave, now it's almost like driving along a bumpy road, bump, bump, bump. And so the wave function of the

electron can be described as this combination or product of the wave function of a plane wave, envelope function describing the electron localization. So you have this localized function here and the delocalized function describing the plane wave behavior of the electron as it moves through space inside of the crystal.

Now what we have as an easy way to describe this mathematically, is we make an approximation. Instead of describing this potential in detail, the easiest way to do this is to describe this square well potential. We have a so-called Kronig-Penney idealization of the repeating Coulombic potential. It's easier to solve numerically. And then essentially what we do is we solve Schrodinger's equation for two possible solutions. One is for the electron wave function centered on the atoms themselves. So that would be the bound state. And the other is we solve the equation for electron function centered between the atoms. So essentially in the unbound state, right here.

Which do you think will have the higher energy level? In between the states, right? Because if the electron wave function is centered over here, it's further away from the positive charge of the nuclei. You need more energy to put it into that position. It's an unbound state, but it's also at a higher excited energy level. Whereas if it's bound around the atoms themselves, you would have a lower energy state. In this delta of energy levels between the bound and the excited states represents the band gap of the semiconductor in this simple approximation right here.

Now you can take that one step further and say, well, gee, if I could solve that in one dimension in a very simple case, why don't I put a three dimensional structure in place, such as a real crystal, and then solve the Schrodinger equation? And sure you can do that. You can definitely do that. It becomes much more complicated solution numerically, but the general principle stays roughly the same. You can add several more tricks, and bells, and whistles. And of course, I would probably emphasize that the solution could either be done numerically or you could use the symmetry relations of the crystal to develop a very simple expression of the crystal, minimizing the redundant directions inside of the crystal, collapsing it down into the bare essential to describe that crystal structure. And we would have some uniform

energy space that looks, for example, represented by this yellowish surface, where you'd have an isopotential inside of your crystal structure.

So these are different ways of looking at the band gap inside of a semiconductor crystal. If you're really interested, and for the advance reading, I would definitely suggest this book called, Fundamentals of Semiconductors, by Professor Peter Yu, now retired at UC Berkeley. Very nice explanation. Uses an elegant application of group theory to derive the band structure of a semiconductor in detail. So let's hop back to this one, real quick-- actually, yeah?

AUDIENCE: I'm just curious if you could tell us the name of the equation that was at the top of--

PROFESSOR: Sure. Absolutely. So what we're describing here is essentially the e to the ikx , or e to the ikr , essentially describing that periodic potential. And then in essentially an envelope function. So, yeah, that would be the wave function that would be introduced into the Schrodinger equation.

So let's go back to here really quickly, because I don't want to get us lost in the weeds. I want us to focus on the main concepts at hand. Let's, from an engineering point of view-- given this formation of bands inside of real materials, since the atoms are coming together and forming crystals, we can envision a few different scenarios. Let's focus on the this band here, and that band here, and the space in between them, the band gap. And let's assume that we have this band here either completely filled or partially filled, and talk about what happens in three different extreme scenarios.

In one case, when we have the band partially filled, we have what is known as a metal. And the reason this case is interesting is because a very small amount of energy is all that it would take to excite an electron and make it to move around the crystal. As a matter of fact, a metal has what's called electron c , that serves to conduct electricity at room temperature and even at very, very, very low temperatures. Semiconductor, on the other hand. Now semiconductor has a finite band gap, and we'll get to this in a minute.

Let's start with the insulator, because that's a more easy to understand case. If the band gap is very, very, very big, then a large amount of energy is required to excite an electron into an unbound state, so it can move freely across the crystal. And as a result, you're not going to have a very large population of electrons up here. The photo excited carrier population, meaning the population of charge carriers, electrons, that are excited into here from light, is very small. And the thermally excited carrier concentration, just some background thermal energy, kt , Boltzmann's constant times temperature, that energy is also going to be insufficient to drive electrons across this band gap. And as a result, you will have a very, very small population of carriers up here.

And this will be an insulator, because you will have very few charges to transport current. If you apply a potential across an insulator, you will not have very much current flow. And that's the principle of insulating materials around wires. Actually this is in the semiconductor. This is a polymer. But if we had, for example, glass or diamond, that would serve as a nice insulator as well.

Now a semiconductor material is somewhere between a metal and an insulator here. And that the band gap is now shrinking. The band gap is small enough to interact with lights, typically. For example, this little piece of silicon, which I'll show in detail in a minute, towards the end of class. It doesn't look clear, like glass does. It looks opaque. And that's because it's absorbing photons in the visible spectrum.

But it's letting some of the infrared photons go through it. Some of the very low energy photons can go through the material, because those photons have insufficient energy to excite carriers across that band gap. So we have a semiconductor material, defined here as having a band gap. That band gap defines the energy of the light that is most efficiently absorbed. And any photon with energy in excess of the band gap can also be absorbed by that semiconductor. Any questions so far?

AUDIENCE: Are there any natural materials where the spacing of the bands is such that three bands are active, or is it always just two bands which are active?

PROFESSOR: Interesting. So the question is, are there more bands above here that you could excite into? Absolutely. So as you can envision, back here for instance, you could continue drawing more and more and more bands. They're unoccupied, but they exist. And as the atoms come closer and closer together, those begin interacting as well. And so in a few lectures we'll look at a band diagram of a semiconductor, and we'll see all the occupied bands, and all the unoccupied bands. And you can excite into any one of them if you have the right excitation condition. Let's put it that way. Any other questions? Yeah.

AUDIENCE: I'm having trouble seeing the chemist's description along with the physicist's description along with this slide all together. How does, once it's in the crystal structure and it's in its lattices and everything, how does that look in this picture? Where is that in this picture.

PROFESSOR: Sure. So this one here, let me describe the axes, because that might make things a little easier to understand. In the vertical axis here, we have energy. And that's the same axis as we have right here, energy. In this axis right here, we had inter atomic separation. So this was meant to demonstrate what happens when we bring atoms closer and close together. In this description right here, this is an unlabeled axis that could be x real space, for instance. Why do we plot an x in the x -axis? Why do we plot real space?

Well sometimes, when we talk about solar cell devices, we're talking about bringing charge from deep within the device to the front surface where the contact is. And so we want to talk about the flow of charge in real space. So that's oftentimes why you see in these band diagrams for solar cells, you'll see e versus x , versus real space.

Now let me show you what these two levels here represent. This is the top of the filled band and the bottom of the empty band. And those correspond over here. I'm going to use the mouse now, because I'm going to be stretching. Let's imagine that this level on down was filled. And that this level up here is empty. So if I may, these are all filled. All filled. And this one here is empty. Gonna take a little bit. Here we go.

All right. So now this band is going to be filled, because we're really looking at the

equilibrium inter atomic separation in a crystal. We're looking right here this d. That's the spacing right now of those atoms inside of that piece of semiconductor material, inside of that silicon. So what we care about is this right here. And this would be the top of the filled band, and this would be the bottom of the empty band, corresponding to the top of the filled band right here and the bottom of the empty band right there.

So that's how it all fits together. This diagram here can get kind of confusing when you're looking in the abscissa, essentially the x-axis. Because you're thinking in terms of real space. Well, it is real space, but you're bringing atoms together. So it's really meant to be a phenomenological tool to describe how band gaps form. This diagram over here, we're now starting to get into the engineering diagrams that can help explain how solar cells work.

And from here on out, we'll be abandoning that chemists diagram and simply using this one because we assume that we're not applying a significant strain to our semiconductor material to get significant deviations here. We'd have to apply strains of several percent, and probably result in fracture of our semiconductor before we ended up changing that inter-atomic distance. We could also heat it up. It's another way of introducing strain, thermal strain, but not mechanical.

OK. So did that help answer the question? OK. So the second point here, we want to first off describe phenomenological band gap and understand how that works. Secondly, we want to describe optical transitions in the semiconductor and understand how charge carriers, in other words, how electrons on an energy band diagram are moving around.

Why do we call electrons charge carriers once again? Remind me, from this diagram here. Exactly. It's brilliant. I just want to make sure that those two things are synonymous in people's minds, that we're not getting caught up on the language. Thank you.

So again, charge carriers, electrons, being free electrons, unbound electrons, not any electron, not the ones down here, but the ones that are excited. OK, so let's go

back to lecture number two, I think it was, where we talk about the duality of light. It's a wave and a particle. Well it can be thought of, can be described mathematically as waves and particles. We've, in last lecture, when we talked about lights and the interaction with lights with materials, we referred to light mostly as a wave. This was very easy for us to describe interference. It made it convenient to do the homework problems, especially for the graduate students, the last problem. That was a lot of fun

But now we will be talking about life in terms of discrete quanta of energy, because one photon is going to be absorbed by an electron, an excited electron, into another state. So now we think of the photon as having a certain energy, defined by the wavelength of light, and that energy is going to be given to the electron, which will then be excited inside of our semiconductor crystal. So what happens? Well we have our sun. Here we have our semiconductor crystal. Again, I'm representing it in terms of e versus x .

I'm saying that these states here are filled. And these states here are mostly empty. And these are mostly filled. Mostly empty. And this is my band gap right here. I'm plotting e in the ordinate and x real space in the abscissa. And again, x because, ultimately, we'll be looking at the cross section of the solar cell in x , in describing how charge gets extracted from the device. So that's why we're going to be using x on this axis.

Now we have sunlight here, outside of our device. And it's going to be shining light onto the semiconductor crystal. So what happens? Well, we know intuitively that charge should be excited from a bound states to an unbound state, where it can move around the material. But not all light serves this function. If we have a photon that has an energy above the band gap energy, so e photon, meaning the energy of the incident photon is greater than e gap, the energy band gap, then we'll have an excitation of charge. We'll have an electron taken from somewhere here, brought up to a higher excited states, and it might come to settle down at the bottom of that band of states that is allowed. A settling, if you will.

But if our photon energy is less than our band gap, we won't have this process occur. Instead we'll have the light going straight through it. And this is brilliant, because you can begin to understand the behavior of many solids in this way. Let's take a glass, for instance. How many of you have noticed that you never get sunburned when the windows are up? But you get sunburned when you forget to put the windows up, when you're driving around and your arm's sticking out, you get that nice truckers tan. That's because the ultraviolet photons have enough energy in glass to excite electrons across the band gap. So the ultraviolet photons get absorbed by the glass, but the visible photons instead are coming straight through, much like this.

Now glass has a very large band gap. Now silicon, much smaller band gap. And in that case, in the case of silicon, even the visible gets blocked. So silicon would make a really crummy window. But it makes a really great infrared window. So if you're detecting infrared light, and want to block out all the visible, you might consider sticking up a filter made of silicon. And that's regularly done in laboratories.

So you can begin to understand how light interacts with matter, with solids, using this energy band diagram. And ultimately how these optical absorption spectra come into being. So we studied these optical absorption spectra in our last class. We just took them as a given. We didn't question where they came from. Now we're going to be focusing on this so-called turn on energy, or turn on wavelength. Remember wavelength and energy are interchangeable. I've written down below here the energy corresponding to a given wavelength, around 2000 nanometers. We have an energy of around 0.62 eV. At around 200 nanometers, we have an energy of 6.2 eV. Since one is the reciprocal of the other, related by hc , it's only natural that if we change one by an order of magnitude, we're changing the other by an order of magnitude in the opposite direction. So we're wrapping our minds around this interchangeability of wavelength and energy.

That's important, because we'll be referring to them very naturally as a photon either having a certain wavelength or a certain energy. You notice that there are certain turn on energies. So energy is increasing in that direction there. So as we go

from infrared to ultraviolet, the energy of the incoming light is increasing. And if the energy is too low, the semiconductor crystal just won't absorb. The absorptance is 0, or very, very small. It doesn't even appear on the log plot here.

And as we begin increasing the energy, suddenly there's like a turn on. The semiconductor begins to absorb that light, and you begin to have this process occur right here. You begin to go from that red light that went straight through the material, to this blue light example here where we have absorption event. Yeah?

AUDIENCE: This is probably a minor question, but where does the energy go-- that it's released when your electron settles back down?

PROFESSOR: We're going to get to that. We're taking it step by step. That's a really good question. You're one step ahead of me. We're going to be describing the actual shape and character up here, because this is really equally important for the functioning of a solar cell device, over the next few lectures. But that gets really complicated. So for now, we're going to just focus on this turn on energy. And we're going to make some assumptions from here on out that the semiconductor doesn't absorb, and all of a sudden it absorbs, and the absorption goes high. It begins absorbing all of our light, for purposes of our homework assignments.

So again, just to put this all into one big picture, so far we have the case out here where very little light is absorbed by our semiconductor. We have the case of glass, light coming straight through it, visible light rather. Because the incident photon energy is less than the band gap, there is insufficient energy to excite into the conduction band. Now as we transition from a photon energy less than the band gap to photon energy larger than the band gap, we can begin exciting electrons or charges across the band gap, and that's why we get absorption inside of our semiconductor materials. Any questions so far? OK. Good. Everybody's still with me.

We're going to now calculate the fraction of photons lost, not absorbed by a semiconductor material with a given band gap, thickness, and reflectivity. And this gets to Ashley's question right here. So again, we ran through a thickness estimate

in class the last time. And we assumed for a semiconductor, I think it was around 800 nanometers. For gallium, arsenide, and silicon. Or maybe it was a little less, somewhere around 550. What was the thickness necessary to absorb say 90% of the light at a given wavelength? And we, in the back of our minds, have the solar spectrum here as a reference point to begin visualizing the number of photons that occur within each of these delta wavelengths down here. Essentially what portions of the spectrum really matter? Obviously you're not going to optimize your solar cell to absorb light way out here, because there's really not too much of the solar spectrum way out there. You're probably going to optimize it somewhere around the peak of the solar spectrum, somewhere near there.

So we walked through that in the last class. I want to have that in your ram as we move forward. We want to calculate the fraction of incident solar energy lost to this thing called thermalization that Ashley was mentioning before. We have, in this simplified diagram right here, an electron popping up to a higher energy level and then settling down to the bottom of this conduction band, we call it, this band of states that's empty right here, or largely empty. And this settling down to the bottom of what is this mostly empty band of states is a process called thermalization.

And it occurs, well, because there are a series of states the electron can very easily move between them by emitting phonons, or lattice vibrations, or heat. And very quickly that electron will settle down into what is called or referred to as the conduction band minimum, the minimum energy level within the conduction band. And this little arrow shown in red right here has a component in the y-axis, in e space here, which is a finite energy. We can quantify that. That thermalization loss right there is the difference between this energy level and that energy level of the electron. And so that's the thermalization loss.

That is another type of loss of a semiconductor crystal. So we've discussed two so far. We've discussed non-absorption of light. There are certain long wavelengths, low energy light, that go straight to our material and doesn't get absorbed, because the photon energy is less than the band gap. And the second major loss mechanism is when we have too much energy of the incoming photon, we have an excitation of

a bound electron into a very highly unbound state, and then a quick loss of that excess energy due to a process called thermalization. Any questions so far?

AUDIENCE: You said that the thermalization can result in heat being released or phonons--

PROFESSOR: Mh-hmm. Yeah. So not the prime energy that we extract from the solar cell of electricity. In principle, if you could develop some clever way of extracting heat, perhaps by slapping on a thermoelectric device in the back of your solar cell, then you could extract that energy as well. So there's a potential to recover that heat. It's not total loss, but from a mechanical engineering point of view, if you think about the thermodynamic efficiency of a Carnot engine, where your t high is this, and your t low is your ambient temperature, that Δ really doesn't look that good. Yeah. It's really tiny. So you have to think of a more clever mechanism, perhaps through a thermoelectric device, or some other mechanism to extract that extra thermalization loss.

I wanted to-- so what we're doing is we're taking the simplest picture, and then adding layers of complexity. And you'll hear me stumbling over my language, as I sanitize it in my head, to remove all of the complex techno lingo, and reduce it to its essence. And so right now I'm going to add one more layer of complexity, and ultimately build up to the point where I can feel conversant again. We have incoming light, not exciting the electron all the way up to there from the top of the valence band, but typically somewhere within the valence band. Not really at the valence band maximum or the maximum energy level within the valence band, these being the filled states.

So this is a more realistic representation of charge excitation. We have an electron being excited up. And this little h plus that's right here, who did the reading and know what that h plus represents? A hole. So what is a hole? It's just what it sounds like. It's the absence of an electron. There used to be electron here. Now it's up there. It left behind a hole. An easy way to think about a hole is if you're in a big traffic jam, bumper to bumper, something bad happened up ahead, and backed up the traffic. Now imagine just removing one car from that highway. You've created a

hole.

So the car that used to be behind that hole moves forward. And the car that used to be behind that one moves forward. And the car that used to be behind that one moves forward. So three cars moved forward. And the hole moved backward three places. Right. So you can either describe the dynamics of the system as n number of cars moving forward or one hole moving backwards n places. It's much simpler from an accountability point of view to be talking about one quasi particle, a hole, rather than talking about n cars moving forward, n electrons moving.

So when we talk about this hole right here, thermalization is going to drive this electron to the lowest energy level within the conduction band. And it's also going to drive the electrons above the hole, essentially to fall down into the hole. In other words, the hole is going to move up to the top of the valence band. Yes. Question.

AUDIENCE: Why isn't the hole originally created at the top of the band?

PROFESSOR: Well, it really depends on what's called the matrix element of the absorption process. In other words, what electrons have the largest capture cross section for that incident photon. And it is a probability distribution function. So you will get some electrons further down from the top of the valence band absorbing light, as well as some of the electrons right there at the tippy top of the valence band absorbing light. So I'm representing, say for example, a typical case, where you have an electron that's not right at the top of the valence band, and certainly not deep in the core level, but nearish enough to the top of the valence band absorbing that light being excited across.

So in reality, this is meant to be an arbitrary scale here, but more representative of a whole process. And to think about this in a more realistic sense, what you would do is you think, OK, I've this incoming photon, and there's a certain probability distribution function that represents the probability of absorptance by different electrons in my system. Which one is going to absorb the light, let's roll the dice. Do a Monte Carlo. OK. That one absorbed it this time. That one got excited up. OK. Another photon with identical energy coming in. Which electron absorbs it? That

one.

So that's the way I would say it really works. This is a simple representation on the lecture slide. So we have the hole going up, and the electron going down. Both particles are relaxing. Right. So the electron is moving to its lowest energy state and the hole is also moving to its lowest energy state. So if you want to think about the electron as a bowling ball, and the hole as a balloon, you're welcome to. Whatever mechanism helps you think through this process, use that as a crutch right now as we move forward. Always remember that in the system, these are electrons essentially moving down, and filling up that hole, and the hole is moving in the opposite direction, much like the vacancy in a traffic jam.

So again, thermalization losses can be described by both electrons and holes in our system, by both the rattling around of an electron in the conduction band and the settling of electrons here in the valence band as well, or the rising of that hole toward the valence band maximum and the settling of that electron toward the conduction band minimum. So a natural question is, how fast is this process? Can it be reversed? If we're losing all this energy due to thermalization, can somehow we halt it and stop it from happening?

There are people trying. It is a valiant fight. This plot right here represents what's called the density of states. We're going to get to that in another lecture here, but I'm going to expose you to the rough concept here. Y-axis is energy. So again, we have our valence band maximum and our conduction band minimum up there. X-axis here is representing time. So we're going from the excitation event, which occurs right at t equals zero. Zero plus represents what this is on the positive side, moving time forward from the excitation event, so instantaneously after the excitation event.

We had to the equilibrium population of holes and of electrons inside of our semiconductor system. There weren't absolutely zero electrons in the conduction band, because of heat. There was enough thermal energy in our system to excite some of those electrons across. And that's why we had that small population of

electrons there and holes down here, the holes they left behind. Now we had a photon coming in, high energy photon, that excited these electrons down here up there into the valence band. Up into here, in the valence band. And over time, this excited population will decay down to the conduction band minimum and valence band maximum, the electrons and the holes respectively.

And over time, when I say over time, I'm referring to something in the range of one picosecond, 10^{-12} seconds. That's like that, but faster. So we have a quick decay of these photoexcited carriers, and so extraction of that energy is going to be nearly impossible, unless we do something very clever with our crystal to prevent that decay from happening. Somehow we suppress the phonons from being emitted at that frequency, at least, or at that energy.

So there are a lot of people, clever people, working on this problem and trying to prevent the decay. The next challenge, of course, is extracting those so-called hot carriers, the excited carriers, from your device and keeping that energy when they're going into the metal. That's a whole another can of worms. So we have the time scales of thermalization, and this is why, at least from the perspective of your homework, we're going to treat thermalization losses as inevitable. As Harvard and MIT students, I would urge you to never consider anything is inevitable. If we understand the physics well enough, we can probably engineer a solution. But for now, let's consider this a reality, a loss mechanism.

So if we start putting things together, if we put non absorption, which we talked about last lecture, we actually ran some calculations, back of the envelope, and we calculated the thickness necessary to absorb 90% of the photons at a given wavelength. We also know how to calculate reflectance off of a front surface. And so we get this third point right here. We actually got it last class. And the fourth point right here, we intuitively understand now that if the photon comes in with more energy than the band gap, that excess energy is going to be lost due to thermalization.

So now if we have the solar spectrum, and we know the band gap of a

semiconductor, we should be able to do a very cursory plot of the efficiency versus band gap, versus energy. So again, we have thermalization losses. The band gap is too small. And non absorption losses, if the band gap is too large.

And let's just do an absurd thought experiment. If we say, OK, I'm really, really scared of thermalization losses, so I'm going to make the biggest band gap material I possibly can, I'm going to have a very low efficiency in my cell, because I'm not absorbing any light. The solar cell will be transparent. If I'm scared of non-absorption losses, I say, OK, I'm going to make my band gap really, really, really tiny. I'm going to be losing a heck of a lot of energy due to thermalization, due to this loss mechanism right up here. And so there has to be some happy optimum, somewhere between the two, where we have the maximum potential efficiency of a solar cell device, given our solar spectrum.

We're going to walk through that right now. So approximating non-absorption losses, very first step. What we're going to do, for our non-absorption losses, is run a very quick approximation that any photon with photon energy corresponding to the band gap energy is going to be absorbed. So if our photon has a larger energy than the band gap, it will be absorbed. If it has an energy less than the band gap, it will not be absorbed. And that's what this plot right here is representing.

We have wavelength right here, longer wavelength, lower energy. Smaller wavelength, larger energy. And at some point, we have the turn on of absorption of our device, because we have band gap at that energy. And the y-axis here, I've plotted EQE, which is External Quantum Efficiency. I've coined the term over here on the left-hand side. It's the efficiency at which free charge carriers are generated by an incident photon on the device. So one way to think about it is if I have a EQE of 100%, that means that for each photon that I throw at my solar cell device, I'm generating and collecting one free carrier from that device. One electron hole pair, if you will, from that device.

So that's plotted right here. That makes intuitive sense. This is an approximation though. And I wanted to take it one step further, again, planting the flag right here.

Because we're going to come back to this, we're going to use this. But I wanted to go one level deeper into the trees, for everyone else who wants some more advanced concepts. This is the reality of how quantum efficiency looks. Yes, we have a turn on, depending on the material that's involved. We have silicon, gallium arsenide, copper indium gallium diselenide, amorphous silicon, dye sensitized solar cells, organic solar cells, a variety of different materials right here.

And their different turn on wavelengths right here. So we have wavelengths, different energies. Some turn on at lower energies, others at higher energies. So this represents, more or less, the band gap turn on energy, more or less. It also has to do with the thickness, how it absorbs light.

At the shorter wavelengths though, instead of just having a QE of one, going all the way out to x-ray territory, we have a turn off at some point. Why is that? Why in a real device would we-- Yeah. We have glass absorbing, on the front side, that's one real big reason. Do we have another idea? Yep. Glass absorption is one real big one. There are other dead layers inside of a solar cell device in the near surface region that also absorb the light in some architecture.

So it's not a perfect QE spectrum that looks like that. But why don't we care? For the purposes of just engineering approximation, why aren't we bothered by these photons that we're losing down there?

AUDIENCE: Because the percentage of the solar spectrum that falls in that region is small.

PROFESSOR: Absolutely. So what we're doing is an engineering approximation right here to get to a very first cursory efficiency calculation, neglecting things at the extremes. Two short wavelengths, because there's just not a whole lot of solar flux down there. And too long wavelengths, because again, not a whole lot of solar flux right there. So we're going to be using this approximation in our homeworks and that will get us somewhat close.

If we really want it to be true, instead of using a box function like this, an absorption box function, we would use an absorption spectrum that looks something more like

that. We've used a two absorption spectrum. And then convolute that with the thickness of the device to calculate what fraction of photons at each energy is absorbed inside of my device. And that would give you a plot that looks something more like this. Instead of this box plot up here, it might give you plot that looks something more like this. So you'd have instead of just a sharp turn on, if you had a one micron thick silicon wafer, and we calculated last class that we need somewhere around 10 microns or 100 microns to absorb light well, if we reduce the thickness of the wafer to 1/10 or 1/100 of what's necessary to absorb light well, we don't see that sharp turn on at the band gap. We see rather a gradual turn on of our silicon as we move to shorter and shorter wavelengths that are absorbed more and more efficiently by the device.

So again, just wrapping our head around the basic concept that we're going to use for the purposes of our calculation, but, again, some of the more fine structure, some of the more advanced concepts that come into play when we're doing more detailed calculations.

Approximating thermalization losses now. We want to calculate the amount of energy lost of incident sunlight lost due to thermalization, due to heat. And we're going to say here that if the photon energy is greater than the band gap, than the photon energy is approximately the band gap plus thermalization. Another way to put it would be the thermalization is approximately the photon energy minus the band gap energy. I kind of wanted to hide all this down here. Forget this exists right now. Let's focus on that top part.

So that's the easy way of thinking about it. We're going to be thinking about this in terms of just any photon coming into our device with a larger energy than the band gap is going to generate one electron hole pair and lose some energy due to thermalization. The reality is that for very high energy photons, say for example photons with three times the band gap energy or more, you could have electron-electron interactions. So if you excite one electron to very highly excited state, it can bounce around and in the process excite another electron across the band gap. That's the case when x-rays are incident on a piece of silicon. For instance, if you

have a 10 kilo-electron volt, so a 10,000 eV x-ray incident on a piece of silicon, you will generate approximately 3,000 electron hole pairs with that one x-ray. Because that one x-ray is going to take an electron and excite it to very highly excited state, and that's going to excite further electrons across the band gap as that excited carrier decays, as it loses its energy and settles at the conduction band minimum.

So we have what's called multiple exciton generation. Sometimes we've heard it as multiple free carrier generation. In semiconductors, it's a hot topic, because folks would like to take the ultraviolet portion of the spectrum, the high energy, short wavelength, portion of the solar spectrum, and use it to excite multiple carriers. One photon exciting multiple carriers across the band gap.

And so there's some work, or was some work, it was a hot topic for a while. It's kind of decayed a bit. It comes in waves. It cycles, kind of like a plane wave. There is an interest, a general interest in the field, of how do you capture these higher energy photons and convert them in some usable way, instead of just having thermalization loss, instead of just having heat. And then for really high energy photons, gosh, you can really get into some neat physics. I've given you a link and cross section here. This is the electron cross section, or actually really what it is is an atomic cross section, because of the electrons in the material versus photon energy going through 10 eV out to 10 to eV 11. A very high photon energy.

We're transiting from the visible spectrum over here deep into the infrared, and then going into the x-ray, and finally to the gamma ray regime. There you can have a number of interesting phenomena. You can even have an electron hole, or electron-positron pair generation with gigaelectron-volt incident radiation or above. We're not gonna even talk about this regime, because the total amount of solar flux in that regime is really tiny compared to visible. But it's a lot of interesting, fascinating physics. So I put it on here anyway just to keep our approximation in focus.

So again, I'm kind of mixing the forest in the trees here to give you a sense of the complexity. But also to give you the tools necessary to do simple calculations. We're going to combine this simple approximation right here of the non-absorption losses.

We're going to say that any photon with energy less than the band gap doesn't get absorbed by our crystal. It's gone to us. And we're going to make the approximation that any photon with energy above the band gap will have that excess energy loss due to thermalization.

And we put those two things together. And one very convenient way of representing this is shown in a paper in 1980. Let me walk you through it. So this curve right here, this outermost curve, represents the solar spectrum, energy versus number of photons. So we have essentially a photon density. This is number of photons per centimeter squared, per second. So photon flux, if you will. And over here we have the energy of those photons.

And so what this is meant to represent is the cumulative solar spectrum, going from a high energy here all the way down to the lowest energy. So we're essentially adding the different components, cumulation plot. And if we have a photon energy in excess of the band gap energy, as would be the case, say, for example three eV photon, and let's say the band gap is 1.35 eV, represented by this straight line right here, this energy is going to be lost. And so by drawing this cumulation plot, we're plotting the area here, the energy area that is lost to us due to thermalization.

We could also say that if the photons have an energy less than the band gap, that is going to be lost to us as well. And what we're left with is a little box that represents the total usable photons, the usable photons that we can extract device. This particular plot is a little bit complicated, because it contains two curves. One is this one right here. The other one is this one right here. This second curve represents another realistic loss mechanism that we didn't talk about yet. And that is why the extractable work, represented as w , is going to be less than the band gap energy of our solar cell device. So if the band gap is 1.35 eV, the total usable work would be 0.9 eV, we'll get to that in a lecture or two. And that's why the white box here is going to be smaller than this horizontal line box over there.

But it gives you a very first approximation, a very easy way to describe the different losses that can occur in a solar cell, and quickly visualize them here, thermalization.

Over here, non-absorption. And plot them out very nicely as the total area and representative area fractions. And that's why you can see here that the total usable solar energy is going to be somewhere around 30%. This band gap right here, around 1.35 eV is actually pretty near optimal for the solar spectrum. You can imagine if we increase the band gap energy, we would be doing something like this. So we would draw another box right around here. This would be the new band gap, instead of 1.35, that would be out here. If we increase the band gap further, we might have something that looks like that. And the area of this little rectangle would be much smaller than the area of this rectangle.

Likewise, if we said, OK, we're going to shrink our band gap energy to avoid non-absorption loss, we're going to have an excess of thermalization loss. We'll have a very narrow rectangle, right, like this, and all of this would be loss. The solar spectrum, obviously, does not change. This line right here this is fixed, it's constant. You folks kind of see it? Beginning to grasp it?

This is a convenient way of representing the total usable portion of the solar spectrum from a given semiconductor material. You can begin seeing the trade offs between different material systems. You can say, what happens if I change my band gap? How would that change the fraction of photons, or fraction of photon energy not absorbed? Or fraction of photon energy lost due to thermalization. And you can also see what happens if you-- what would be an easy way to extract more potential for the sun? Instead of just using one semiconductor material, you? More than one. More than one. Right.

So now you're drawing different boxes that represent the different materials. And if you stack them right, you're able to capture more of this total area, more of the total solar spectrum. So this is a really cool plot. A lot of good work back in the 1970s, 1980s. If you recall from lecture number one, this was the first wave of real hardcore solar science, after the initial Bell Labs invention. When we had the OPEC oil crises, and there was a large rush of funding into solar research. So you had a lot of good work coming out from those days.

This next plot that I'm going to show you represents the area of this box relative to the solar spectrum, the percentage of light that is usable, the balance between non-absorption thermalization losses as a function of band gap energy. So if the band gap is too small, again, we're losing a lot of energy due to thermalization. If the band gap's too large, a lot of energy we're losing to non-absorption. And somewhere in the middle is our happy medium. These little symbols here represent different materials. Cadmium sulfide, cadmium telluride, gallium arsenide, indium phosphide, silicon, germanium, and so forth, and calculated efficiencies.

So I'm going to go into one advanced concept, the multi-junction devices. And we just talked about this box here representing the usable energy from the solar spectrum. Now if we go to an absurd case of 36 band gaps. If we imagine 36 materials with graded band gaps, starting from large band gap at the top to small band gap at the back, you can envision almost approximating the entire curve. And you can estimate what the upper efficiency limit would be with many band gaps inside of your material.

So for one band gap, somewhere around 37, we'll have an entire lecture dedicated to calculating that number. For two band gaps somewhere around 50. For three band gaps, 56. For 36 band gaps around 72. So you can begin seeing how the efficiency of solar energy conversion changes as you change or add materials, you move materials to your system.

So how do you practically do that in a real device? Well one method is to put one material on top of another, much like it's demonstrated right there. You have E versus x . So I have my E versus x , and I have multiple materials. Another way to do it would be to use optics to split our light into different colors. So if we have polychromatic or multi-colored light coming into our system, we somehow have a set of optics put up that reflect one color, or one band of the solar spectrum, while letting the other portion of the solar spectrum through it. And we have different solar cells with different band gaps, each matched to the incident light. Each matched to the particular color of light.

Notice this paper, 1982, this concept was out. So again, during that first wave of real photovoltaics innovation in the late 1970s and early 1980s. And this was coming right out of Lincoln Laboratory. This is about 35 minutes north of here. And this group at the time, the group number continues to exist and is in operation at Lincoln Labs. So most of the people have moved on obviously, but several of the ideas continue to this day.

There was a more recent incarnation in 2009 of a spectral splitter, a very similar concept as you can see, optics to concentrate the light, a dichroic mirror, meaning it reflects certain wavelengths, let another portion of the spectrum pass, and solar cell devices down below absorbing efficiently in that region of the spectrum and avoiding thermalization losses, and avoiding non-absorption losses. This was a \$50 million DARPA project, in fact, involving University of Delaware and several other companies. And they published the results in 2009. It was one of their wrap up papers that described the results of the project.

So concepts. To this day, this spectral splitter it's not in commercial production. What is in commercial production are the multi-junction devices, where you stack one on top of another. And we'll actually be having the benefit of using some of them in class. Boeing spectral lab was kind enough to donate a set of them for our class purposes. Yes, question.

AUDIENCE: This is also basically what plants do by having multiple different pigment molecules in leaves, right? That would absorb the different wavelengths?

PROFESSOR: Well, it's not exactly separating light by optics in that case. So the question was--

AUDIENCE: No, I mean multi-junction.

PROFESSOR: Oh, the multi-junction idea. Yes, if you consider that there is a reaction process occurring in series. The important distinguishing feature of the multi-junction device is that the same current is flowing through the entire device. So each sub cell has to be current matched to the others, because the cumulative current output is a harmonic mean of each one. So in other words, you're limited by the worst resistor

in series, if you will. So it's very tricky to engineer properly these multi-junction devices. You have to be thinking about the current output for each sub cell and match the currents. That means you match the geometry, the thickness, but also the resistivity of each layer and so forth.

So similar to a plant, but not quite. There are some special characteristics of the inorganic system. So we have a small demonstration. I'd like to welcome Joe up to the front as well. We have a small demonstration of a few of the concepts that we've covered today in class. We're going to be exciting silicon with light, and we're going to be monitoring the current output using this little resistance measurement device right here. So actually I think it's set to a current readout. Yes, current readout. So it's in microamps right now, probably going to milliamps. Is that right? OK, so milliamp current readout.

Let me explain to you what we have right here. We have a bare piece of silicon, and two electric leads on either side. So a bare piece of silicon, no device. Just a piece of silicon. And we have electrical leads coming out of either side. We have a very low resistance contact on either end. For those who are curious, we used a mixture of indium and gallium, soldering iron, scratch the surface, penetrated the native surface oxide, and put the electrical leads on either side. And we have this connected in series here to our current readout device.

So now what we're going to do is we're going to illuminate this. And again, bare silicon leads on either side, and we're going to be passing the current through the current measurement system. Before we turn it on, we're going to ask people, how many people expect there to be current driving through the system? We have light incident on the material. We're exciting charges. Based on today's lecture, there should be free charges moving around that material now. How many expect a current to flow? A few. But a lot of people shaking their heads. Why do you think a current won't flow? There's no electric field. There's no potential.

Why don't we give it a shot, and why don't we see. If we turn this on right now, what do we see? We see zero. Right. Can some of the folks right here in the front see?

Says zero. All right, so what this is telling us again, you're welcome to come up after class and take a closer look. What this is telling us here is that yes, what we talked about in class is important today. Yes, it's all very important and it's the foundation of calculating ultimate solar cell efficiency, how the material absorbs the light, how charge is excited.

But we need something else too. Once the charge is excited, somehow we have to give it an incentive to leave the material. We have to have a field. In this case, we're going to be using an applied field, a couple of batteries. So total voltage around three volts, applied across that small material. But in a solar cell device, we're going to have a built in electric field that we'll engineer into the device. And we'll talk about that over next lecture.

So just for purposes of sanity, we have our batteries now connected in series, and is now applying a potential across those two leads. And now if we turn on the light, what do we expect? We expect to see some current going through. And voila, we have a current running through it. So now, what is the nature of that current? If we move the light closer, we see the number go up. What is the nature of that current? That current is photo excited. That current is exciting electrons from the valence band, from bound states, into the conduction band, it's unbound states, where they can move freely across the material. And now, because we have that potential applied across the material, there's an incentive for them to drift in one direction. The net flow of electrons is in one direction. We have a drift current in our material, in our semiconductor, and hence we have the flow of charge that is readable by this current meter right here.

So without the light, we have no current. With the light, we have current flowing through the material. But current and light-- actually light is not the only thing necessary to create that output current. We also need the potential. So next class we'll be talking about the potential and how that's created inside of a solar cell device. I've included a few slides extra for people to see through. I'm going to explain once again the experiment. We just had light coming in. It was in the visible. We were able to excite carriers, but no current was observe because we didn't have

a potential. When we applied the battery, or the potential across, now when we shone light of the sample, we had a current flowing through.

And we even have a current, a very small one, flowing through when we have the battery applied without the light on. And you need microamp detection I think to really see it. Yeah. Just from the battery. These are a very small population of excited carriers, either thermally or donated to the electron conduction band. Any questions before we close for the day? Yes.

AUDIENCE: Yeah, so I guess-- I'm the devices person in here, so also the notion of the direct band gap, versus an indirect band gap, are we going to discuss that? Or is that something that's not relevant?

PROFESSOR: We will definitely discuss direct and indirect band gaps. So this goes back to describing the notion of a direct and an indirect band gap is fundamental for describing the reason why these curves have the shape they do. For example, this one right here, if you plotted as α -- if you plot it in a certain way, you'll be able to see a very characteristic shape, indicative of direct transition into a direct band gap. The reason we aren't launching into several of those terms right now is because several of your colleagues, more than half, don't have a semiconductor physics background. And the beauty of this approach is that you will be able to understand most things about a solar cell without really diving deep into the semiconductor physics until it's necessary. And hopefully we keep everybody with us. So for those who have a strong semiconductor physics background, I bid you, I urge you to have patience, because we will get to the interesting stuff. But we're working on that fundamental background right now. Thanks.