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AUDIENCE: Yeah. So you have basically two semiconductors to start with-- one n and one t-- one p-type and-- p-type. So for example, on the left-hand side, you have a p-type. Right-hand side, you have an n-type. And since you have a high concentration of electrons on this side, the electrons will basically jump to this side.

And you have a higher concentration of holes on the p-type. Holes will basically jump to the other side. So you will end up with this space charge that [INAUDIBLE] talked about last week. And this is basically the characteristic of [INAUDIBLE]. And I just throw them there. And I see these [INAUDIBLE]. So you have a neutral [INAUDIBLE].

So [INAUDIBLE] you have your [INAUDIBLE]. And then you have the contact [INAUDIBLE] which basically [INAUDIBLE]. OK? So you impose [INAUDIBLE] or something to this junction to get rid of all the drivers or close the circuit to generate [INAUDIBLE] power. I just talked about the open circuit voltage.

So this is the first thing that basically happens when you [INAUDIBLE]. This space just [INAUDIBLE]. For [INAUDIBLE], and this basically also includes [INAUDIBLE], both in voltage [INAUDIBLE]. So you have the space charge region that's right here. And then basically, for example, the [INAUDIBLE] concentration.

And so for the electron, this is p-type and n-type electron [INAUDIBLE] concentration. And so you're basically saying you have neutral [INAUDIBLE]. You have a field generator to do [INAUDIBLE]. So in case you have-- for example, a photon comes in. And we'll talk about this later at some point.

When a photon comes in, in general, it's [INAUDIBLE] exciton. So they're still very close to each other. These excitons are just generally-- they have to use [INAUDIBLE] space [INAUDIBLE], but it's separate. So for this case, for example, we have [INAUDIBLE].

So basically, the electron will basically track through an electron's force in this direction. So we're having to [INAUDIBLE] to basically get separate from the [INAUDIBLE]. And it jumps on the other side. And you end up with just a positive charge here.

And due to the neutral region from here, first, you have the diffusion of the electron [INAUDIBLE] two-way contacts in here. So further, so this is the carrier concentration. And then you can also draw the charge in there. So [INAUDIBLE] charge here, positive charge here.

And the new field looks like [INAUDIBLE]. So if you have-- this generator decided to [INAUDIBLE] about this, or more accurately, it's called a [INAUDIBLE]. And I think this was also-- when he talked about the [INAUDIBLE] last week, he said something that-- this is important [INAUDIBLE] talk about the buyback.

The buyback was just the spatial expansion of distribution [INAUDIBLE]. So he basically said this [INAUDIBLE]. So just say up to a certain point it basically drops down to a certain level [INAUDIBLE], especially [INAUDIBLE]. Up to this point, the exciton-- when it comes, it will start feeding the space charge region, and will start to separate the electron [INAUDIBLE].

And then I wanted to talk about-- so in the [INAUDIBLE] case, when we actually have a photon coming up to [INAUDIBLE] electron, [INAUDIBLE]. So when we joined [INAUDIBLE] environment since the [INAUDIBLE] have to be the same.

So [INAUDIBLE] somehow. So this would be the [INAUDIBLE]. So that's [INAUDIBLE]. And see, what happens is most of the times, an electron is basically excited [INAUDIBLE]. But at the same time, first, you have the [INAUDIBLE] state.

And then when the particle goes through the state [INAUDIBLE], et cetera, that's [INAUDIBLE]. And this basically changes the [INAUDIBLE]. So what you end up with is the [INAUDIBLE] will actually increase this to [INAUDIBLE]. And when we remove the electron here to end up with a hole here-- so we're basically keeping this model here. So we end up with some type of region just [INAUDIBLE].

This is basically the whole circuit board. So the difference between these two [INAUDIBLE] is due to the exchange of [INAUDIBLE]. This is basically [INAUDIBLE]. So the idea is, obviously, you could, basically, go all the way. So it's maximum open circuit. And just [INAUDIBLE].

AUDIENCE: So the electron goes through the conduction band [INAUDIBLE], right? Is it because that's easier?

AUDIENCE: Yeah. What was the question?

AUDIENCE: So the [INAUDIBLE] band [INAUDIBLE]? Yeah.

AUDIENCE: That's a good question. I was thinking about that, too-- whether it's actually a step like this that goes-- and then it goes down.

AUDIENCE: Yeah.

GANG CHEN: Very good question. I think I can provide an answer.

AUDIENCE: You want to answer?

GANG CHEN: Well, it's a distributor. So at this point, you should not look at the spatial. So it's a locally-- it could be anywhere along that curve-- the induction curve. So I think that's a good place. I think back to the same point that I [INAUDIBLE].

AUDIENCE: [INAUDIBLE]

GANG CHEN: So yeah, that's where we stopped. The last lecture is about the, apparently, [INAUDIBLE] junction diode. It's a Schottky barrier. You can think about-- on the left there's a Schottky barrier. On the right is the induction.

And when you look at the current voltage characteristics, it looks very similar except that the coefficient-- because remember, the [INAUDIBLE] for [INAUDIBLE]. And saturation [INAUDIBLE] quality-- this is a metal semiconductor junction-- a Schottky junction.

And in the case of a metal semiconductor Schottky barrier, the saturation current [INAUDIBLE] the barrier module. And in the case of the [INAUDIBLE] junction, the saturation current include the band gap and include the [INAUDIBLE] of hole. From the t side is the [INAUDIBLE] hole that carries the current. On the inside is the electron. So if you see an electron on the inside, you can see the problem inside. And then we have this one-- recombination time.

This is, say, when you create an electron hole pair, you excite the electron from valence to conduction in the conduction band. How long they can be separated-- and after a certain amount of time, they will recombine and give off either photon, as it were, laser or light emitting-- that, you want-- or give off the general forms.

So this is the recombination time for hole electron. You can see that the difference, really, in this saturation [INAUDIBLE] current can sometimes [INAUDIBLE] mathematics. But I want to emphasize another fundamental difference. Yes?

AUDIENCE: Sorry. I would have thought intuitively that the longer the recombination time, the more current you would have.

GANG CHEN: The longer the recombination time-- yes, let's see. Recombination is also related to longer recombination. Well, longer recombination-- smaller [INAUDIBLE] current. But I see your point, where if the longer recombination-- essentially, recombination happens in this region. OK?

So I think in that case, what happens is the diffusion supply is also limited-- your current flow. So this is where I want to emphasize. The important difference between these two formulas is the Schottky barrier. When electrons go from here to here, it's electron. It's still electron.

The way I draw it-- here is the electron. And the metal side is the electron. Whole problem. Now, if you look at the t junction, on the inside is electrons. And then p-type's the hole. So if electrons go [INAUDIBLE] here, electron goes from here to here, go through this space charge region, there's no more electron.

You have two p-type [INAUDIBLE]. So what happens? And you have to have current continuity. The charge has to be supplied, right? So what happens is that the hole will recombine with this electron. OK? So the hole recombines with the electron. That means you have to supply both from this side.

So you draw a hole from this side, recombine with whatever electron comes to this side. And this is where the recombination really happens. It's not only the space charge. It's slightly just offset the space charge. So it's a minority carrier device.

That's a really fundamental difference between a majority carrier device and a minority carrier device. Minority carrier device-- recombination is crucial. And later on, I'm going to talk about solar cells. All people are trying to refine solar silicon. It's trying to increase this recombination. OK?

So that's your problem. This is the point. That's really important to appreciate the minority carrier [INAUDIBLE]. OK? And of course, I mentioned-- so this is what I drew on the card. You can see electron diffusion is on this side.

So the hole diffuses with the-- once it comes to this side, there's no more electrons, right? So the electrons will recombine with holes. So there's less electron flux forward. So there is more. So if I look at electron carbon, the decrease in this recombination regime, and then I look at the hole current-- on this side, the hole difference in this region.

That's where the supply recombines with electrons. So the electron goes through this [INAUDIBLE] region recombination. This is as approximation. So the concept-- and then after space charge, they recombine with the hole. So the electrons diminish. Now at this side, it's just overflow. So that's how we go from an electron to a hole.

So the PN junction theory-- Shockley-- let's see. The PN junction with the-- let's see. It's three people who got work with [INAUDIBLE]. One is Shockley, and the other is Bardeen. And the third is Brattain. And I think it was Shockley and Brattain who did the invention. And Bardeen was the manager at [INAUDIBLE] building.

And then if you look at the history, Bardeen was one of the guys that [INAUDIBLE]. Superconductivity-- also [INAUDIBLE]. Right? So he was very-- the history of the [INAUDIBLE] invention-- Bardeen had the [INAUDIBLE] field. This was so important, he had to do something [INAUDIBLE] theory, OK?

But this is really a very ingenious theory. Think about how electrons on this side and those on the other side-- by the end, the your current has to be continued. The summation of the electron current, the hole current-- that's constant, right?

And in the last lecture, I also said if you look at the energy flow and when electrons right here-- yes, I would like to know what happens [INAUDIBLE] because [INAUDIBLE].

It's a matter of-- there's no hope. Again, there's no hope. So typically, contact, people want [INAUDIBLE] contact. So what happens is that when-- so the whole motion is really majority of electron motion in [INAUDIBLE] region.

So when [INAUDIBLE] move this way-- so to move from here to here, that means this electron goes out to the metal. So that's what happens. And they have [INAUDIBLE] potential-- electrochemical potential. That's what the [INAUDIBLE] junction is-- sort of like [INAUDIBLE] barrier, but [INAUDIBLE] at those sites.

And if you think about the counter effect, counter [INAUDIBLE] is the kinetic energy part, which is a 2 KG of the charge average [INAUDIBLE] minus [INAUDIBLE] minus ef-- the chemical energy. And you look at this-- [INAUDIBLE] minus ef is growing.

Here, on the other side, [INAUDIBLE] minus ef is here. And the space charge region is growing larger and larger. So electrons carry more heat. Per charge, it's carrying more heat.

It's carrying heat out of this space charge region. That's why the space charge region is actually [INAUDIBLE]. And then immediately outside space charge region, recombination happens. Recombination dumps the heat just immediately outside the space charge region. It will flow back when the space charge region heats up.

The physics is it's not the junction-- the space charge that really heats up. The heat is actually generated outside the space charge here in this recombination. This is where heat is generated. That's a fact that most people probably don't know.

So to finish what I was talking last lecture, the [INAUDIBLE] more research. This is the basic physics. And so we're talking about the Richardson formula, thermionic emission. So there are people doing, for example, in the-- this is the conduction band.

If you don't have the Fermi level around this place, the energy electron below the Fermi level is actually carrying negative energy, and the electron above carries positive energy. So my idea is if I do a Schottky barrier or potential barrier, and I just scatter this part of the electron, that's called the energy field term, or it depends on if you have an interface. You also call it thermionic emission.

So some people call this thermionic emission [INAUDIBLE] thermoelectric [INAUDIBLE] thermionic effect. The so-called solid state thermionic. But say essentially, it's cutting out the low energy electron, or sometimes it carries latent heat because the electron below the [INAUDIBLE]. And if I [INAUDIBLE] states, most [INAUDIBLE] states need sharp feature. The sharp feature helps increase the thermoelectric effect.

So the way I view is, in this region, I cut it off by transport. I cut out the transport electrons. I still have the electron, but they are scattered. They don't move. So then the middle ones up here, and I can [INAUDIBLE]. So that's the way I say, OK, it's all really coming back to the idea, if you can create the sharp features in these states, [INAUDIBLE] a lot of electrons there, and you can potentially improve the electron power factor [INAUDIBLE] sigma.

But see, the key is you don't want that. You only want to scatter this part. You won't affect this part [INAUDIBLE]. That's [INAUDIBLE] lot of states. I think that this idea [INAUDIBLE] fully convincing yet to me.

And I made a few slides on this. That's all my own [INAUDIBLE]. I published a paper before. There's no experiment, and maybe some of you will be interested. But basically, an issue I'm wrestling-- what is the evaporation?

I said that the molecule coming out of the liquid surface, that's like an evaporation. That's equivalent to thermionic emission. Let's say, how about I have a vacuum here.

I got a liquid here, and the [INAUDIBLE] of liquid drop into the vacuum side area and suddenly expand. Is that corresponding to evaporation? And I have a solid state case, where I'm comparing these two examples. And these two example are-- why is the thermionic barrier, as everybody have described before, with electron [INAUDIBLE] this way. The low energy electron in this region, [INAUDIBLE] surrounding [INAUDIBLE].

The other case-- I consider [INAUDIBLE] physics-- is what about I flow electron this way and suddenly drop a [INAUDIBLE]? And that means to me it's more like I take a droplet and put it in vacuum and suddenly evaporate. And this one is more like I have a water surface and the water molecule coming out of the surface like [INAUDIBLE] water.

So that's a solid state analogy that we're trying to make. So what I did is I did some energy balance analysis, which is essentially a recursive formula [INAUDIBLE]. And you can do-- you can assume the two sides has different temperature on both sides and different type of potential.

The real way to do this is [INAUDIBLE]. Very complicated how to do it. And so you solve this, actually, problem-- even when I try to [INAUDIBLE] a very, very detailed, very hard computation. [INAUDIBLE] you can do your derivation. No [INAUDIBLE] statistics, energy balance, current balance at the interface.

And what I found is that this is the electron temperature on this side. The electron temperatures one and two just right at the interface. It turns out that when I go down a step, there is an amplification factor.

This is the potential high [INAUDIBLE], and this is the mean free path. So normally, this is very small because the mean free path time [INAUDIBLE] just a temperature drop within [INAUDIBLE]. That's a very beautiful inversion.

But what I thought interesting is if I have this structure, suddenly, an electron expand-- actually reach this temperature-- or create a large temperature drop. There's an amplification factor. I can amplify how much electron temperature drop at the interface. So that's what I call potential amplified.

On the other hand, if I put this structure, same analysis. Didn't have that amplification. So I follow up. I said this [INAUDIBLE] statistic. I could have Fermi [INAUDIBLE] statistics and solve some equations. And this is the equation.

This is the electron temperature at the interface. And you can see you can actually drive thermally-- with a temperature gradient, you can drive electron and proton out of equilibrium. And this is the electron temperature jump at the interface.

But if you do the reverse structure, there's no discontinuity at the interface. So this way, since it can help the efficiency of cooling. But so far, I have not-- like I said, this is just a theory. No experiments.

Now I'll move on. That's just an example. Sometimes it's interesting to think whether you can have new ideas in this field. Now, coming back-- now we talk about the theory-- the photovoltaic cells. And this is the PN junction I just showed, and the saturation current. Sometimes, people [INAUDIBLE] current [INAUDIBLE] detector current.

And now, we have a photon comes in-- generates electron hole pairs. So if the photon energy is larger than the bandgap, the bandgap is always the same. Everywhere, bandgap is the same. So if the photon energy is larger than bandgap, you generate-- lift the one electron from the valence band to the conduction band.

And this could happen anywhere in the device. That depends on how vertical [INAUDIBLE]. We'll talk about that later. So what I'm doing-- OK. My photon happened to be absorbed within the space charge region, then the electron-hole pair is generated within the space charge region [INAUDIBLE].

Now, what happens after this generation? Of course, they were-- they have a tendency to recombine. And if you do recombine, your photocell is [INAUDIBLE]. You don't want them to be combined. We want to separate them.

And now, if this PN junction [INAUDIBLE] the space charge region, there's one [INAUDIBLE] because electron-- now there is an electric field inside. So the electron wants to go lower energy this way. The higher energy as a whole, positive is a higher energy. Electron [INAUDIBLE] higher energy. So hole go this way [INAUDIBLE]. OK?

It just go down the potential field. Now, this is the potential [INAUDIBLE] hole. This is potential field for the electrons, going down here. That's natural.

And this natural tendency. So now, you've got more electron on this side than, say-- normally at equilibrium, there's no voltage. Now you accumulate more electron on this side, accumulate more hole so you generate a voltage.

And once you generate voltage, this voltage will drive your diode. Just like on this side, if you got a voltage difference, you have a diode current. So now, if I have light comes in, this is the current-- the electron-hole current generated due to absorption of photon.

And now, once I do the voltage, this is the current-- moves forward and balance it. Now I'm going to have voltage. I drive the diode, and this is where I have an electron-hole pair generation-- the counter going this way. And of course, in a solar cell, I want to go this way. I don't want-- I want this less than this.

So that's-- if you understand that, that's a solar cell. And so this one, I want a [INAUDIBLE] short circuit current. For the short circuit, the voltage difference is 0. You shorted this. There is no resistance, then this has to equal this.

No voltage drop. That's the short current-- short circuit. Short circuit voltage [INAUDIBLE] for 0. That's your current. jl is your short circuit current.

Now, I'm going to, with that-- starting from there, the rest is simple. It's math. I can see what's my open circuit voltage. And my open circuit voltage is just the same. There's 0 current.

So if I set this side equal 0, I find out what's the open circuit voltage. That's the open circuit voltage. And you can further simplify because we know [INAUDIBLE] to dark current. Look at-- this is called dark current or saturation current.

And then [INAUDIBLE] high open circuit voltage. What do you do? Smaller is better. [INAUDIBLE] smaller is better. You look at it-- smaller js, higher open circuit voltage. So it's js-- how recombination time is longer, js smaller.

So I don't want the recombination. I want the long lifetime for the electron. Basically, I want long lifetime so I can stretch it out. And you put again the js [INAUDIBLE] related to [INAUDIBLE] diffusivity recombination time, and I'll write it down out here.

Basically, you substitute in [INAUDIBLE] approximate [INAUDIBLE]. That's what you get. That's just electronics [INAUDIBLE] on this. Now, of course, open circuit is useless, because there's no power output. In real operation, we always have a load.

We have current flowing. So when we have a current flowing, [INAUDIBLE] power. And so before I do that, I want to show you, if you draw this current voltage-- so this is your short circuit voltage for 0-- short circuit current negative.

When current is 0, open circuit voltage. So it's more likely you're shifting [INAUDIBLE] down. If you don't have a light illumination, it's a diode equation, right? That's a diode equation. [INAUDIBLE] to the negative [INAUDIBLE].

And of course, you can look at this. The power output is the voltage times current. So somewhere, your voltage [INAUDIBLE]. That's [INAUDIBLE]. It depends on which one you operate in. You'll have maximum, and that's how you optimize. You change your load resistance so that you can control the current and the voltage by changing external load resistance.

So that's a little magic. We do that for thermoelectrics, you do that for solar cells. All the same. You need to optimize. So some people just design their circuit to optimize. And the [INAUDIBLE] this way just reverse it just for convenience. So that would be another way to [INAUDIBLE]. That's the [INAUDIBLE] actually [INAUDIBLE].

Now, we can [INAUDIBLE] maximum power. When the power output is maximized, this is the current times voltage. That's the power. So you just take a derivative of your voltage and say when it's maximized.

When you take derivative, physically, what I do is I'm changing my external load to find out where is the optimal voltage so that power is maximized. So that if you take this derivative, you'll find out where the optimal current, where is optimal voltage.

And again, see, this is just a mathematic detail-- not important. But very often in the terminology, people say, what's your fill factor? What is that? So this is the rectangular-- this is where you optimize-- you run your optimum current voltage point. So that's the actual maximum power you have.

And if you draw another rectangle, where you draw the-- this set up, the [INAUDIBLE] short circuit current and open circuit voltage, you draw another rectangle. This ratio of this extra power divided by the outer rectangle, that's your fill factor. And you want to fill as much as you can-- you can see-- to get the maximum power.

Now let's do the source [INAUDIBLE]. Source, this is the electron-hole generation. So I have the deletion coming in. Only electrons-- the photons with energy larger than bandgap can generate electron-hole pairs. And also let's suppose this is blackbody. Let's treat the sun as a blackbody.

So the solar radiation comes from the sun, and this is the fraction of solar radiation actually-- so you have to look at the distance, the fraction of solar radiation. Because the blackbody of the sun is 5,800 Kelvin. It's not a-- it's close object-- 5,800 Kelvin [INAUDIBLE].

It's very far. It's diluted. So that's this fraction in relation for the effect. But it's not the radiation intensity, it's the number of photons, because each photon generated one pair of electron-hole.

So I'm looking at the energy-- because this is the energy. That's the energy per photon. So divide that. That's-- lots of photons coming. It's not a flux of energy. It's a flux of photon coming from a solar cell.

And this is the reflectivity. I assume that the [INAUDIBLE] cell is absorbed and generate electron-hole pair. That's, of course, an idealization. You [INAUDIBLE] different losses. This is just best case.

And of course, the maximum best is no reflection for that one. So this is source term. And the good thing is that the source term depends on only the temperature if you idealize. It depends only on the temperature of the source.

And when I calculate efficiency, this is the energy of the photon coming towards the cell and this is the power. So of course, I want to maximize the efficiency. Everybody wants maximum efficiency. And then the question is, what's the maximum? How much is in there?

Second law. First, the solar cell is limited by the second law column. You can always say [INAUDIBLE]. The maximum efficiency you can get [INAUDIBLE] between the sun and the Earth. So T [INAUDIBLE] is 300 Kelvin. T hat is the 5,800.

So that's [INAUDIBLE] efficient. That's an upper limit [INAUDIBLE] upper limit. You can't get anything beyond that. Yes?

AUDIENCE: So I'm just curious about-- so the way that the picture you have on that slide-- so it's actually instead on the p-type [INAUDIBLE]. And then don't we want it to hit the space charge region ideally?

GANG CHEN: So the photon can be absorbed along the [INAUDIBLE] absorption. So some of them penetrate.

Before the [INAUDIBLE] here in the space charge region. They have-- less probability goes on the other side. Electrons [INAUDIBLE] there are some diffusion happening here. Just to take a more [INAUDIBLE] chance of getting there is less. So that's why we want it that way and not [INAUDIBLE].

AUDIENCE: You see how that is [INAUDIBLE]?

GANG CHEN: Uh-huh.

AUDIENCE: So--

GANG CHEN: So you want to have a longer potential field to drive the-- actually [INAUDIBLE] field [INAUDIBLE].

AUDIENCE: No, I'm talking about this is a picture right here [INAUDIBLE] the really thin and flat [INAUDIBLE].

GANG CHEN: Really thin PN-- of course, the good thing is your electrode is very close. You can get to the electron, but your photon may not get through. So this is another [INAUDIBLE].

That's your backup. Your solar cells [INAUDIBLE] better. [INAUDIBLE] absorbed. Two, you want to get the charge to the electron before they recombine. One is thinner, the other one's thicker. This is essentially the thing people are trying to solve.

But the question we want to ask is, what's the maximum possible? What's the maximum possible efficiency? And this one [INAUDIBLE] is two solar cells. The first [INAUDIBLE] by Shockley-- the Shockley-Queisser limit.

And then that's the Shockley-Queisser limit I will discuss next. And of course, the real diode is hard to get what's maximum, because the saturation current depends on the field material recombination time, resistivity and electron-hole. It's hard to get your maximum.

And the ingenuity of Shockley [INAUDIBLE] very, very smart guy. And [INAUDIBLE]. So this is what Shockley [INAUDIBLE]. So if you think about a PN junction, put it on the other side-- open circuit.

Of course, the solar radiation will create electron-holes continuously. Every photon will generate electron-hole pairs. If there is no recombination, no defects will combine. What happens?

You can't have an [INAUDIBLE] recombination process-- spontaneous recombination. [INAUDIBLE]. So that's your maximum limit. No other recombination, only spontaneous recombination. But what's [INAUDIBLE] spontaneous recombination and coupling that up.

And I'm really impressed. I read a few papers. This is where every time, I do this, I have a place where I don't feel comfortable to tell you. And I want to tell you because I want [INAUDIBLE]. And this is not just I read it yesterday.

For many years, I tried to understand this. I still don't feel fully confident. This expression where it came up, and this is actually another Shockley paper. This is Henry's paper, and Henry had another paper [INAUDIBLE] and we all discussed different-- three different-- Shockley's paper, Henry's paper, Ross paper. Three different ways to write this expression.

And so when a PN junction has a voltage [INAUDIBLE]-- and what's the-- so we see the quantum state. The Fermi-Dirac-- the Bose-Einstein statistics. But what [INAUDIBLE] the photons which obey Bose-Einstein statistics?

In the PN junction, there is, it looks like, a Bose-Einstein, except that we add [INAUDIBLE]. [INAUDIBLE] is if you look at it, [INAUDIBLE] is really the Fermi level here in the [INAUDIBLE] in this region. That's the voltage [INAUDIBLE].

Expanding this term that I just feel I can comfortably derive it. You can go to expand so each paper you start from different place. And I encourage you to read. And again, if you have any idea to make my self comfortable [INAUDIBLE], because I, for many years, we were actually looking into this, seeing how we can really make [INAUDIBLE] derive some near-field-- [INAUDIBLE] near-field where it is surrounded [INAUDIBLE].

But see, so I can only just say take it from here [INAUDIBLE]. And the [INAUDIBLE] recombination in PN junction and [INAUDIBLE] you do later or [INAUDIBLE]. This is very important. This is very often where we will start.

But I haven't [INAUDIBLE] thermodynamics very easy. So that's the [INAUDIBLE] how mechanically [INAUDIBLE]. Now, starting from here, you can derive what [INAUDIBLE] recombination. You have a voltage-- voltage. What's the recombination part?

So you just integrate it again from the bandgap to any energy. And if you do [INAUDIBLE] statistics, you just elected one factor, one. And this is the-- I believe I didn't write the equation right-- copied from [INAUDIBLE] paper.

And this is solid angle integration, so that's essentially the photon density of states inside the [INAUDIBLE]. So the Fermi-Dirac Bose-Einstein statistics integrated [INAUDIBLE]. So this is the spontaneous emission due to the current [INAUDIBLE].

And everything is very similar to what we had before, except that [INAUDIBLE] is no longer due to-- if you look at the diode right here, this is the a for the diode. That's determined by actual material recombination.

And here, the ingenuity is now this is the [INAUDIBLE] dielectric constant refractive index bandgap of the material. So this is the maximum you can have-- the best you can have. [INAUDIBLE] really do recombination. no other defects [INAUDIBLE].

So because of that, it's free of any material. So now, you can derive the [INAUDIBLE]. But it's still one material that's [INAUDIBLE]. This is the only other material you can have.

But while I talk, you can also say, ah, how about the photonic crystal-- inside the photonic crystal? In this chapter, we checked [INAUDIBLE] spontaneous form. And maybe you've got a different [INAUDIBLE]. Maybe [INAUDIBLE].

So now, I have translated that if you look at the term, this is the current term, the diode equation. One is the diode current, the other is the photon generated current. This is the photon generated current. In this case, this is 1.

So I put in the best scenario. And the [INAUDIBLE] is the independent material except the bandgap-- only the bandgap. So that's where Shockley could derive what's the maximum efficiency.

And this is the curve not from Shockley, but from [INAUDIBLE] paper. And using this [INAUDIBLE] recombination current, photon generated electron-hole pair, so this is [INAUDIBLE] photon generated current.

And you do the rest [INAUDIBLE] we did before. We can find out what's the maximum power and what's the maximum efficiency. And this is what [INAUDIBLE] calculated.

And here, c is a concentration. What concentration? [INAUDIBLE] concentration. So what does is change jl. If you concentrate more, you generate more electron-hole pairs per [INAUDIBLE]. So if you concentrate, you get this larger-- you get a larger open circuit voltage. So concentration actually can help you increase efficiency.

So not too much increase, but reasonable increase. And what's interesting when you look at it, under one [INAUDIBLE] condition, where is the optimum bandgap? About 1.5. If you look at the material, where is [INAUDIBLE] material? 1.5. A lot of MOSFET is actually very good [INAUDIBLE].

1.1. Not too far from the optimum. So this is about 31%. So that tells you, if you build a [INAUDIBLE] cell, this is about the best you can do in terms of efficiency. [INAUDIBLE].

AUDIENCE: [INAUDIBLE] energetically focused compared to the [INAUDIBLE].

GANG CHEN: You mean the-- how many photon [INAUDIBLE] compared to bandgap or?

AUDIENCE: I mean, you have [INAUDIBLE]. What happens, for example, [INAUDIBLE]. They are absorbed [INAUDIBLE] energy as the [INAUDIBLE] 1,100. So the [INAUDIBLE] is [INAUDIBLE].

GANG CHEN: Exactly. So this is a blackbody curve. This is your bandgap somewhere here. And really, what's usable [INAUDIBLE] energy is because this is above the bandgap energy [INAUDIBLE].

So if I look at-- this is the fine structure. If I have photon generated electron-hole pair this way, this energy electron relaxes [INAUDIBLE] very fast. Hole relaxes here very fast.

So this is a key. And in fact, the people have been theorizing how the electron [INAUDIBLE]. If you can extract this electron-hole with this kind of energy, that's [INAUDIBLE]. Question of how you get it out before you relax.

This is about picosecond. So picosecond is very fast. If you times 10 to the minus 12 times diffusivity, [INAUDIBLE] travel nanometers of-- [INAUDIBLE] nanometers [INAUDIBLE] have no way to get it out.

And let's say if you have a good idea, that's something people have been thinking since the '70s. So that's a single junction maximum you can get.

And exactly on this issue, how about we do multi-junction? One cell-- so all the junction shown here-- the first one absorbs blue, so larger bandgap-- the topmost layer. And the lower-- longer wavelengths, lower energy [INAUDIBLE], so gets absorbed in second layer and get absorbed third.

[INAUDIBLE] idea. And of course, you can see with this stacking, each one generates a current. If you look at this, the key is that your current has to be continuous because you put [INAUDIBLE] on top, [INAUDIBLE] bottom.

So this still has to generate the same amount of current as a design [INAUDIBLE]. But people have done that. It's a material nightmare and the design nightmare.

Design in the sense you have to get a current match. So the electron goes-- come from the top layer, has to go to the hole of the next layer, or hole of the top layer has to merge with the electron-hole of the next layer.

The current is continuous. And you have to group different materials, because the recombination is the killer. So that's why people do molecular beam epitaxy and lattice-match. And you generate defects, you generate dislocations.

These were just the centers for the recombination. And then you kill the electrons before you can take it out. So to group those material, people have done molecular beam epitaxy like spectral diode-- spectral diode lab. And they were doing laser before. Now, they're doing probably 40%, 41% photocells-- [INAUDIBLE] cells, three junctions, and that rule match this.

And so this is-- I got one graph from the internet. I think it gives some idea [INAUDIBLE] in real world, about 15% to 18% [INAUDIBLE]. And then [INAUDIBLE] 30%. And now, this is a triple junction indium gallium phosphide, gallium arsenide, germanium bandgap. 1.8, 1.4, 1.7 [INAUDIBLE].

You have to look at what are the materials that match your current and that you can grow. So you have to look at both material and bandgap device. And if you [INAUDIBLE] much [INAUDIBLE] infinitely.

So this is a paper that shows the 72% [INAUDIBLE] multi-spectral [INAUDIBLE] 36-state. And if you have an infinite states, the theory is about 86%. So that's the best you can do [INAUDIBLE].

That's still lower than [INAUDIBLE] 300 and 1,500. That's about the line. If you do 1 minus 300 divide by 1,500. So that's the-- what people can do.

Because in theory, it says now you look at [INAUDIBLE] in the lab. This is the best in the lab. It's not the best deployed.

Silicon [INAUDIBLE] crystalline silicon. Crystalline silicon down here. This is a function [INAUDIBLE]. The best is about 95%, 96%. Remember, [INAUDIBLE] probably the biggest [INAUDIBLE] lab. They told me about [INAUDIBLE].

Remember, Shockley-Queisser gives you 30%, 31%. So [INAUDIBLE] really well compared to [INAUDIBLE]. Amazing. And also, that's why your potential is also limited. That's the best you can do.

But the fact that you can really do that at low cost, I think your problem's solved. [INAUDIBLE] you can always work in [INAUDIBLE] is only 10% [INAUDIBLE]. Of course, [INAUDIBLE].

And so the best multijunction cell [INAUDIBLE] lab. Here, it's less than [INAUDIBLE]. I think that now, the best that I heard is about 41%. And this is a multicrystalline. This is a single crystalline, multicrystalline.

And let's look at amorphous silicon [INAUDIBLE]. It's-- well, the real world, it's about 6% to 8% [INAUDIBLE]. If I say the lab, it's about 12%, but that's [INAUDIBLE].

And this is a, say, copper indium. [INAUDIBLE] copper indium [INAUDIBLE]. And so the best is about 19%. And [INAUDIBLE] telluride is [INAUDIBLE] here and here. And because, as I said, it's backwards because most people talk about 64, and now [INAUDIBLE] is probably the best most profitable company in the [INAUDIBLE]. And their CEO I think is about-- [INAUDIBLE] from lab to real production [INAUDIBLE].

And then this one is the polymer, I think, with the organic cells. And then there's a [INAUDIBLE] cell [INAUDIBLE]. So this one gives you [INAUDIBLE]. Not the most up-to-date in years, but pretty close.

What are the problems? I mentioned the one for solar cell-- the number one is [INAUDIBLE] device. That's [INAUDIBLE] cell. And our device, very sensitive to recombination. So what are the reasons for recombination?

Those [INAUDIBLE] bandgap. Deep level. Those are recombination [INAUDIBLE]. [INAUDIBLE]. And [INAUDIBLE] where you've got a lot of [INAUDIBLE].

So those are regions where recombination happens. And that's why people purify silicon. Crystalline silicon, for example, [INAUDIBLE] large [INAUDIBLE]. It's about $2 per gram-- per kilogram [INAUDIBLE].

If you want to make a solar cell, you can recrystallize it, purify it and [INAUDIBLE] $40 per kilogram. And then, of course, during the process, you introduce a lot [INAUDIBLE] heat up, melting [INAUDIBLE]. And in fact, last year, before the market crashed, everybody was on silicon. So the silicon was short, and that got $240 per kilogram.

So that's one. That's the same [INAUDIBLE] device Achilles heel. And in that sense, I can argue thermoelectrics is good because it's a majority carrying device. It doesn't have severe recombination.

And there are other problems with this [INAUDIBLE]. In fact, this, to me-- I say, OK, [INAUDIBLE] absorb. The second step is to charge it where it goes. So this is really the first step. And look at where the whole photon goes.

Of course, the relay interface and reflection [INAUDIBLE] reflection [INAUDIBLE]. [INAUDIBLE] coating and surface treatment. And once you get an input material, you don't have almost no other ways to control this profile anymore. It's material-intrinsic absorption.

So this is the absorption coefficient and-- because the intensity decays exponentially. So now, you think about it. In your [INAUDIBLE] photon generated electron-hole pair, let's say, in this region. And you want a space charge in this region to overlap it so that you can separate them.

You can use your field to drive the electron from one side of the hole to the other side of the hole. So the depth of this is 1 over r-- gives you exponential minus 1. So that's called the penetration depth. So this is where you look at the material, what I should choose.

The absorption coefficient. Absorption happens above the bandgap. So bandgap is the first step. And then you look at the material. You say, oh, silicon, we love so much because that's the [INAUDIBLE] of silicon. Why silicon is a problem? Because it's really just-- firstly, because this absorption.

You see here, absorption-- this is the photon energy. Bandgap is about 1.1 electronvolts. It's a very slow curve, and it's 1 over [INAUDIBLE]. So this is centimeter. So here, it's about 10 microns. So if I use a 10 micron-- so the energy is below 1.6 eV-- then those part of the energy is absorbed for very little.

It goes through [INAUDIBLE]. They don't get absorbed. So it means [INAUDIBLE] this part can go out. So that's the absorption. And that's why [INAUDIBLE] say like a [INAUDIBLE] sigma six [INAUDIBLE].

They have very sharp [INAUDIBLE] 5th power. So if you have 1 micron-- this is the inverse-- is 1 micron. 10 to the 4th inverse [INAUDIBLE] 1 microns. It's a centimeter. So if you want to use [INAUDIBLE] the bandgap [INAUDIBLE].

And that's why when people make amorphous silicon [INAUDIBLE]. It's pretty good here. This is useless here. You can generate that from [INAUDIBLE] but then you don't have [INAUDIBLE].

So solar cell is [INAUDIBLE]. First, you want to absorb it. Second, you want to get a charge to the electrode. So why is it so different from the [INAUDIBLE]?

This is the one I had mentioned before, whether it's a direct semiconductor gap or indirect gap. [INAUDIBLE] all the others that have sharp increased direct gap. So the photon goes from here to here. If the electron goes from valence to conduction band, you need to satisfy the energy conservation.

So the photon energy [INAUDIBLE] the difference of electron-hole energy. So that's an energy conservation. And second is the momentum conservation. So momentum is h over lambda. Lambda photon is a micron.

One level of electron is lattice constant [INAUDIBLE]. So in this, gives us 1 over [INAUDIBLE]. But so one more lambda is essentially vertical, so the photon doesn't give you much momentum. That's the problem.

In indirect gap semiconductor, the bandgap is here. When you want, let's say, the momentum doesn't match between electron-hole. So if you want to leave this electron here, the photon don't have enough momentum.

It has an energy. It doesn't have a momentum. It has to have something else. That's photon. You made a photon absorb a photon.

Photon doesn't have much energy, but it has momentum. So this is a widely-- So you've got to have either emission or absorption of photons. So you have to have [INAUDIBLE], like I said. Very much scattered [INAUDIBLE] together.

So the absorption is weaker because when the photon wants to do it, then there is no photon there. So that's the dilemma-- why they [INAUDIBLE] absorption there and near the bandgap. And of course, once you move to this region, it goes up. It goes from here to here.

So that's when I said solar cell, essentially, you solve one problem, maybe the other problem. Thick or thin and how you can address those issues. It's really, the electron thing is better. You just take it out. Before they recombine, you send the electron [INAUDIBLE].

Photons get absorbed. Of course, that's related to efficiency. And the single cell is directly related to how much material you use. That's a cost issue.

To have a low cost, you need a thinner. Less material, so always the material cost will be better. And we look at the cost. Now the lowest [INAUDIBLE] from [INAUDIBLE] and they have a manufacturing cost of about $1 per watt.

And this is where the [INAUDIBLE] assuming certain amount of years you're using [INAUDIBLE]. [INAUDIBLE] you have $1 per watt. And it's a good curve here in terms of the cost. But saying, look at a [INAUDIBLE]. It takes a long time.

Right now, the worldwide installation per year is about [? 67 ?] gigawatt. [? 67 ?] gigawatt. China put 100 gigawatts steam turbine every year. [INAUDIBLE] really just [INAUDIBLE]. It will take a lot of effort [INAUDIBLE].

Different type of solar cells. And a silicon cell is the most predominant. [INAUDIBLE] cost. Single crystal [INAUDIBLE] crystal [INAUDIBLE] is considered [INAUDIBLE].

And what's interesting is all those crystal surface [INAUDIBLE]. And that will trap the light so that we use refraction. We use refraction, not only reduce refraction. Once you get into the backside with metal, you reflect back. You don't want to go out.

Some of the photons [INAUDIBLE] more [INAUDIBLE]. And the difference between single crystal or multicrystal is single crystal, you can get a regular [INAUDIBLE]. Just the manufacturing process [INAUDIBLE] crystal [INAUDIBLE].

And then you got, let's say, electron and silicon here. You can see this question here. If you generate [INAUDIBLE] it has to diffuse. It can go both ways. You don't have a field. You have to design so that the [INAUDIBLE] field [INAUDIBLE] go one direction. Yes?

AUDIENCE: [INAUDIBLE]?

GANG CHEN: It must be related to the material [INAUDIBLE]. I would imagine probably [INAUDIBLE] recombination, but I didn't check. But most of the time, people use [INAUDIBLE].

AUDIENCE: [INAUDIBLE].

GANG CHEN: No, the material is not silicon, then, no. That I don't know. I didn't check. [INAUDIBLE]. And you can see here, [INAUDIBLE] contact.

We use that Schottky barrier. And you have [INAUDIBLE]. That's a shielding effect. [INAUDIBLE] the photon couldn't get through. That's not good.

So sometimes, people even bury the grid down or make it on the back side [INAUDIBLE]. So there are a lot of [INAUDIBLE] improvement. A little bit of improvement people done over the years.

[INAUDIBLE] here say [INAUDIBLE] amorphous silicon [INAUDIBLE]. Amorphous silicon [INAUDIBLE] in particular, so you can use it. But the electron amorphous material-- cell is very hard to move. A lot of [INAUDIBLE] recombination. So you've got [INAUDIBLE] the amorphous silicon cell is about 200 nanometers.

And if you can reduce that even thinner, it's probably better. Too thin, your manufacturing is a problem [INAUDIBLE] always [INAUDIBLE]. But this is actually showing you just a multijunction.

So if you look at it, this is [INAUDIBLE]. So unlike silicon, silicon, you look at the electrode on the top. It's spaced apart. So electrons go here-- actually diffuse to the electrode, naturally going to the electrode, right?

Silicon is reasonably good in terms of recombination. Amorphous silicon doesn't work. So you got to have electrode right on top of it. So it's a [INAUDIBLE] conductor. And this is [INAUDIBLE]. The active region is about 6 microns.

And this is [INAUDIBLE] space after [INAUDIBLE]. It's a trade-off between recombination and absorption. If you increase absorption, [INAUDIBLE] always better [INAUDIBLE] theoretically work better. If you can use [INAUDIBLE] the first [INAUDIBLE]. You can capitalize on those methods [INAUDIBLE].

AUDIENCE: [INAUDIBLE] the number?

GANG CHEN: [INAUDIBLE] here, it is, about 0.5 microns. I'm not sure whether that's the best way to optimize it. I'm just copy from where I was trying to show the scale rather than [INAUDIBLE].

So if you are [INAUDIBLE] you're also trying to improve the conductivity. Basically, you want a very highly conductive. So if you're highly conductive, then thinner is better because the free electrons in this material also absorb photons, which generally, you don't want that.

Polymer cell-- polymer, ideally, [INAUDIBLE] polymer reduces cost [INAUDIBLE]. The problem with polymer is that it's even worse than amorphous silicon. You generate-- it immediately recombines.

Recombination is very fast. In fact, when you first generate the bonded together, they are not even a separate electron or hole. This [INAUDIBLE] state for the exciton. So it maybe has an exciton center, [INAUDIBLE] center, [INAUDIBLE].

I have, let's say, maybe a solar thermal center [INAUDIBLE]. And there is-- the whole issue is to find how I can separate this exciton and make the electron go one way and the hole go the other way. [INAUDIBLE]. So in that case, you look at this really thin 220 nanometer [INAUDIBLE] separate.

But that's still difficult, so people are now doing the so-called bulk junction cells. So you put a [INAUDIBLE] of multiple. One conducts electron, one conducts [INAUDIBLE]. So locally, you generate electron-hole pair. Like here, you want [INAUDIBLE] separate so the electron goes one model, the hole goes another model.

[INAUDIBLE] cell. So this is not a solid cell. It's an actual liquid cell. And what it has is titanium dioxide nanoparticles, [INAUDIBLE] titanium dioxide nanoparticles [INAUDIBLE] all three electron-holes. Too large. Not much hole [INAUDIBLE].

And so what [INAUDIBLE] cell does is put a dye on top of that titanium dioxide, and this dye is a photosynthesizer. So this is where photons are absorbed. And photons are absorbed [INAUDIBLE] monolayer generated electron-hole pair exciton. Before they dissociate, they are exciton.

And you want them to dissociate-- separate into electron-hole. And electron will eventually flow into nanoparticle, so the nanoparticle diffuses. Now there is no field. Really, diffusion process.

So the [INAUDIBLE] run out, so that's why people try to do nanowires so that gives a better path to the electron rather than nanoparticles. But the problem is that if we do nanowire, your surface area for absorption also changes.

Here, you can have this surface area [INAUDIBLE]. Your nanowire is only this surface-- vertical. So the surface area [INAUDIBLE]. The particle has advantages. It's almost like a 3D wrap-around particle. [INAUDIBLE]. There's always a [INAUDIBLE] trade-off.

And the [INAUDIBLE] liquid. And this is a chemical reaction now. It's not just a hole diffused [INAUDIBLE]. So the hole oxidize the molecules in the case of [INAUDIBLE] iodide. Iodide in the liquid [INAUDIBLE] iodine(III) and this charged molecule diffuse to [INAUDIBLE]. So again, diffusion.

So electron diffused [INAUDIBLE] electrode, hole diffuse to the other electron [INAUDIBLE] reduce, and the reduced diffuse back. Sounds like a very cool process, right? And the idea is, again, you can [INAUDIBLE] pretty good in [INAUDIBLE].

And see, so this is a flat surface versus the [INAUDIBLE]. So that's pretty much what I want to say. And then we're right on time.

And this is the dream. The dream, in a sense-- here is the cost, here is the efficiency. You want a low cost, high efficiency,

Silicon is cheaper in the first generation for gen 1. Thin film is here-- lower efficiency, but lower cost. And in fact, they make the business, at least for first order [INAUDIBLE].

And people are [INAUDIBLE] gen 3. No winner in gen 3 yet. This is where you guys come in later. OK? I think that's it.