

MITOCW | MIT3_091F18_lec16_300k

We are talking about semiconductors today.

Yeah.

I finished our exam 2 concept math that I thought maybe you guys would find useful.

This is much like the last time, when I gave you guys the concept map.

I'm just giving it a little earlier this time.

And here, you can see all the connections between the lectures, the recitations, the problem sets, the quizzes over here, the goody bags, and the exam topics.

Speaking of the quizzes, tomorrow, there's a quiz.

And so you can look up here and say, OK, well, what's going to be on that quiz?

Might cover some molecular orbital theory.

Might cover the band gap stuff that we did on Monday and that you covered in recitation yesterday.

Oh, and intermolecular forces we also did.

And you're asked to bring to the quiz the voltmeter and these large LEDs.

Now, I'll talk about that, a little bit more about this, in a few minutes.

So remember to bring that.

Laura will also send a reminder email about that.

OK, you have voltmeters.

You and voltmeters.

How many of you, this is the first time you're using a voltmeter?

How many of you haven't used one but you've never seen one-- you've used it before, but you've never had one this accurate as the 3091, right?

Yeah.

You never know when you need a voltmeter.

You should always carry it with you with the periodic table.

Now, on Monday, this is what we had.

This was a conduction band.

This was a valence band.

And then we had a conduction band and valence band that were a little bit closer together.

And then, we had this case, where maybe it's filled up somewhere in the middle of the band.

And remember, the valence band is filled with electrons, and the conduction band is not, right, in the simplest picture.

And this difference in energy between this VBN-- that's the VBN, the maximum level of the valence band-- and the CBN-- the minimum level of the conduction band-- that energy difference is the gap of the material.

Here, you can see energy gap equals zero.

Well, in this case, it's a metal.

Or if you want, it's a conductor.

And we'll talk about why it's a conductor more on Friday, but a little bit today, why metals are conductors.

Today, I really want to focus on this case.

All right, so that's a metal when there is no gap in the material.

If the gap is large, then that is an insulator.

What do I mean by large?

Well, what I mean is it's not in the range of this special case, which would be, say, zero less than the gap less than around 3.5 electron volts.

This is the case that I want to talk about today.

I want to spend today talking about semiconductors.

Those are called semiconductors.

Let's write that here.

Semiconductors.

Sometimes you'll see them called metalloids.

Sometimes you'll see them called insulators with small gaps.

They're all kind of right.

Metalloid, thank you.

Now, the reason why we classify these and why this range of gap is so important is what I want to convey to you today.

These are really special materials, these semiconductors.

Now, before I do that, I want to just clarify one thing.

And I'm going to use diamond and graphite as an example.

On Monday, what we did is we talked about the concept of bands with a very simple 1D model, right?

This was a 1D model of s orbitals, 1s orbitals.

I said, well, if I have a mole of 1s orbitals, then that goes into a band.

And I called it a 1s band.

I always say, well, if you fill it in different ways, that is what determines the properties.

But I want to be clear-- and I stressed this on Monday, and I want to stress it again.

Whether this forms this and then the next set-- you know, whether you get a 1s that forms a band like this and then a 2s that forms a band like this and then another one, maybe 2p, like this.

Or whether there's breaks in them, or maybe these kind of overlap-- so you get overlap, and you get sort of something like that.

All that depends on more than just those atomic orbitals.

It depends on more.

It depends on how these things are bonded.

This is such a great example.

I've got the same element here.

Its carbon.

There's nothing else in this system.

Carbon, pure carbon.

Everywhere is carbon.

But on the one hand, I've arranged it in a certain way.

And on the other hand, I've arranged it in another way, and their properties couldn't be more different.

So just to take this a little further, if I think about diamond on the left, diamond is an insulator.

Diamond has a gap of 5 and 1/2 electronvolts.

5 and 1/2 electronvolts.

It's an insulator.

But OK, that makes me think of methane.

Remember, methane, you had these SP3 states-- SP3, SP3, SP3.

And the reason it formed SP3 is because all these H1s states came along-- H, H, H, H. These are 1s's, 1s.

And so carbon came along, and it said, well, if I arrange-- if I got four of you here like this and I arrange myself-- if I arrange my orbitals in such a way that then I can arrange so that they're minimizing repulsions, that gives me methane.

That gives me the ground state of methane.

But the only way to do that is to have four equivalent orbitals.

Those are hybrid orbitals.

We talked about this when we talked about hybridization.

The idea being that if I took one of these and one of those-- so now you can imagine how it's going to look.

You know all this now, right?

There's a 1s orbital of hydrogen.

You know that those will form a sigma and a sigma star and occupy that bonding orbital.

That's the idea of methane.

That's the idea of molecular orbital theory with some hybridization.

And it's going to form those bonds along each direction.

But now I'm talking about something different.

I'm not talking about such a simple case.

I'm talking about one mole of sp^3 .

That's what diamond is.

Look, the carbon atoms have done the same thing.

They said, hey, wait a second, OK, it's not four hydrogens.

It's like 10 to the 23 carbons all in one small space.

How can we organize to lower our energy?

And so they form-- well, we know this, that it's going to form a band.

But it doesn't just form a band and then half fill it.

That's not what diamond does.

No, actually, diamond breaks this apart so that you have a huge gap.

And those are filled, and then those are not.

The SP³ band in diamond breaks apart into a valence and a conduction band.

The valence band is full.

The conduction band is empty.

Why?

Well, you don't need to learn the specifics of how to get from there to there.

But I wanted to show you how complicated this is.

I will ask you whether the SP³ band splits or not.

I just wanted to show you how dependent this is.

Because now, look, you can understand this now, right?

So I've got four electrons per atom going here.

There's a huge gap, and then nothing in there.

That's diamond.

5.5 eV gap.

One mole of SP³ in diamond.

Now, it depends on the structure.

If I had just put them together in some amorphous soup with no-- oh, amorphous.

That's a word that's coming later.

But if I just put them together with no order, I wouldn't get this, this splitting.

You take graphene, which is one of those sheets, and make stacks and you've got graphite.

It's another form of pure carbon.

In that case, you've got your SP² bonds to form in the plane, and those also split and they fill.

But now you've got your pi bonds, and those don't split.

So in graphite, what you get is you've got your SP²'s.

You've got a mole of those, and you've got your P electron.

Remember those?

Now you do a mole of that, and you've got the same thing.

But see now, you've got-- these are the SP² bands.

It also split.

Remember, I've got my electrons here, my SP² electrons and those there.

But now, I've got the pi bands that didn't split.

Graphite is a metal.

You can understand it by looking at the bands of these materials.

Now, again, let me emphasize, I am not going to ask you to know when something splits like this or not.

Why didn't the pi band split into two like these did?

When does an S and a P become a single band versus an S band separated by a P band?

I'm not going to ask you to know that, but I wanted you to see it.

It doesn't just depend on the initial states.

It depends on the structure of those atoms.

It depends on how those atoms are bonded together.

Now, what about this semi-conductor?

What about this semiconductor?

Well, if we take a semiconductor and we look at it-- I told you this on Monday.

There are two things that you can do in your goody bag, especially.

One is you can take an electron, and you can shine a light on it, and it's going to excite this electron up, just like in the Bohr atom, right?

You can absorb photons if the photon energy is the energy between one state and another.

We did a lot of this earlier.

But see, in a semiconductor, remember, I've got an almost infinite number of states here.

And so what I need is for that photon-- there's not an exact value here.

There's a continuum.

But here, it's forbidden, just like in the Bohr atom.

There's no states.

There's no electron.

So here, the energy of the photon absorbed-- let's write this out-- has to be greater than the energy of the gap.

This is the energy of the gap.

This is the energy of the gap.

Now, by the same token, I can take the same semiconductor and run it the other way.

I can put a current on it and feed electrons, electrons from current.

So I can attach it to a battery, and there you go.

This is a semiconductor where I'm literally-- all I'm doing is I'm feeding electrons into its conduction band.

But now, when those electrons fall down into the valence band, they emit a photon.

Photon emitted.

And just so I have room, with energy of the photon emitted is going to be exactly equal to the energy of the gap.

You can see that because these electrons, I might inject them into the conduction band anywhere, but they're going to wind up very, very, very quickly going to this minimum conduction band state.

And that gets me to another important point, which is on the absorption side, I can overshoot this.

Like I said, I can absorb higher than the gap.

I can't absorb lower, but I can absorb higher.

And if I do, if I absorb higher than the gap-- so let's say this is my state.

So if my photon comes in and it kicks in electron up really high, it's a high-energy photon, then that electron very quickly will go back down.

And that's called thermalization.

So what happens is that electron loses energy to heat to get to the CBM.

We'll come back to this later.

That's thermalization.

So the electron can be kicked up by light to any level, but it's going to very, very quickly go to the CBM.

That's why when I inject it-- that's why these are the same color.

These are high-quality LEDs, clearly.

Well, they work.

That's a good thing.

So the batteries might be slightly different, and the currents might be different, a little bit.

I might be injecting electrons at different parts of these conduction bands, but this is always green,

and this is always red.

And that's because those electrons very quickly get down to the CBM and the VBM.

And the CBM and the VBM are determined by the semiconductor inside.

Well, you've also got-- so this is a photon emitter right here.

I've made a light emitter, right?

But I've also got a detector, which here's what I said on Monday.

So now, I take an LED, and I hold it-- gesundheit.

And this is what's inside of the emitter.

It's the same thing.

It's a semiconductor.

But these two semiconductors have different band gaps.

That's why the light is different.

They have different band gaps.

Now I've got one with some band gap, and I hook it up to my voltmeter, and I just look.

Is there a current or not?

If this thing conducts through it, it means that electrons have been promoted from here to here.

And that's something we're going to talk about today.

Electrons cannot move around easily if they're in the valence band.

But once they're in that conduction band, they're free.

How do I get them there?

Well, you've got power.

Shine red light on it.

Does it conduct?

Check the voltmeter.

I'm literally holding two semiconductors and doing these two processes right here in each hand.

It's a power that I have.

I have semiconductor making light, semiconductor absorbing light, or maybe not.

If I shine right on this and I get no current, well, it means that the energy of the photon from a red light source is too low.

Maybe it's able to excite it up to here but not up to here, given whatever the gap in here is.

You see that?

So the semiconductor has this powerful-- maybe I take a different semiconductor and red excites it.

Or maybe it doesn't, so I go to a higher energy photon.

With this goody bag, you're touching and feeling semiconductor physics and chemistry.

Because band gaps in materials are rare.

You see, if you look at the periodic table and you classify it by metals, metals and nonmetals-- so insulators, conductors, and then these weird things in between-- there aren't that many of them.

There aren't that many of them.

But as you can see, these are really, really important technological materials.

Why?

Because this is visible light.

This semiconductor range here is in the range of light we care about-- visible, UV.

So I've got an electronic material where the electrons in it can interact with currents, small currents even, and wavelengths of light that are things we can see.

You can imagine how important this could be, for example, for making LEDs.

But I need a lot more flexibility in my material set, and that's where chemistry comes in.

So this is, one, why this matters for today.

So, look, I mentioned that getting red was hard back in the day for color TV, because the red phosphorus were difficult to make.

For LEDs, it was blue.

In fact, there was a lot of work around gallium nitride.

Here's gallium nitride in one structure.

Notice this.

There's gallium nitride.

It's not on here.

Darn it.

Gallium nitride in other structures have different gaps.

Oh, there it is.

There's one.

But the point was they wanted blue.

They wanted blue, and they needed to make a material that was both cheap to make and lasted, so it didn't degrade, and gave you a blue light.

And that was really hard.

And that's what the Nobel Prize was given for in 2014.

Because without blue, you can't make white light.

So there's all sorts of technologies you simply can't go into with LEDs until you get blue.

How did it happen?

It happened because of chemistry because people figured out how to change the how to take one element another element and then maybe alloy them together.

Maybe you take gallium nitride and you alloy a little bit of aluminum in here.

That means mixing it in.

Now, all of a sudden, you've got a different band gap.

Band gap engineering is really the centerpiece of the semiconductor revolution.

Now, the connectivity.

We've been talking about connectivity.

And we'll talk about metals on Friday.

Here we are.

Insulator's really low.

Least conducting, 10 to the minus 25.

Hook your voltmeter up to Teflon.

10 to the minus-- wood.

Low-conducting materials.

But we're interested in these, and these are kind of in-between.

They're not very good conductors.

That's why they're called semiconductors.

But the fact of the matter goes back to what I've been saying.

And this is the next point I want to talk about, which is I cannot have-- so in a semiconductor, there's no electrons.

If there's no electrons in the conduction band, then there's no electron conduction.

Now, I've said this before.

I said this on Monday.

I said it already.

Why not?

On Monday, I said, well, these electrons are stuck.

What does that mean, they're stuck?

Stuck in the bonds, stuck in the anti-bonds.

They're stuck in states.

The point is, here, that this valance band is filled.

Now, if I want an electron to move through a material, which is what conductivity is, after all-- by the way, siemens, conductance, one over ohms.

If I want electrons to move in a material, they need freedom.

They need freedom.

What does that mean?

Well, it means that I'm trying to move through this wire.

And for an electron, freedom means I can go to any state that's nearby.

State, a wave function, a state of probability that I can move to.

And then to that one.

And then over here.

And then there's is something there.

I don't want to be.

I've got to go this way.

There's a bad thing over there.

It's scattering me.

I'll go this way.

But if electrons don't have the ability to move into a free state, they're not going to conduct.

That's why you've got to get the electron up here.

Why?

Because the conduction band-- I shouldn't really fill this in.

I'm just showing you empty states there.

The conduction band has 10 to the 24 states.

Freedom.

Freedom.

So as soon as an electron gets up there, it's like, oh, I can go anywhere I want.

I can be there.

I can be there.

I can move in response to this field that's pushing at me.

I can conduct.

I can't do that unless I have conduction, unless I get electrons into the conduction band.

This is OK.

Now, this is why, you can see right there, metals are clearly good conductors, based on our band picture.

Because those electrons near that line there, you fill them up, and they're halfway in a band.

But right up above there, an almost infinitesimally small energy away, is an empty state and another empty state.

These ones you can see, it's going to be hard.

I'm going to have to shine really high energy light to even get-- or really high temperatures.

Again, semiconductors are special, because their gaps are right in that range where I can get electrons to go from the valence band to the conduction band in different ways.

And there's two different ways that I want to talk about.

The first way is simply with heat, and this is why I mentioned this on Monday.

Actually, no matter what, there's some probability for an electron to have a high enough thermal energy.

Yeah, electrons get hot, too, right?

Everybody feels the heat.

So that the thermal energy can be enough to get the electron to knock it up above.

So with thermal energy, you can get-- let's see.

At room temperature for silicon.

So this is the case of silicon, which has a 1.1 electronvolt gap.

Silicon, 1.1 electronvolt band gap.

It's a really important semiconductor.

And for silicon, at room temperature, I got about 10 to the 10 electrons in the conduction band per centimeter cubed of material.

This is how we think about it.

We think about how many of these do I have per volume.

It's a good way to measure it.

These are also an electron in a conduction band also is called a carrier.

So for silicon at room temperature, I will have-- just because I can't help it, because there's that

many-- about 10^{10} to the 10^{15} carriers in the conduction band.

Now, carrier is a carrier of electricity.

That's why it's called a carrier, right?

It carries electricity.

So those are the ones that are carriers, the ones that made it up.

But if I go to 600-- so now I'm going to go to 600 kelvin.

Oh, we only use kelvin.

Kelvin is the thermodynamic energy scale, temperature scale.

10^{15} to the 10^{15} carriers per centimeter cubed.

This seems like a big number, but is it a big number?

What's a big number we know and like in this class?

The mole.

So like roughly-ish, is this all a big number per centimeter cubed or not?

It's actually very small.

But I need them to be there if I want better connectivity.

If I want conduction in these semiconductors, I've got to put electrons up in the conduction band.

Do you remember, just as an important point, I mentioned the energy of room temperature, the thermal energy of room temperature $k_B T$ is about 0.025 electronvolts.

That seems way smaller than 1.1 eV.

It is.

But that's because that's not what temperature really looks like.

Temperature is a distribution.

There's a distribution.

Now, you don't need to know that for the band gaps.

We're going to come back to distributions, Boltzmann distributions, when we talk about reactions, reaction kinetics, later.

But that's why, at room temperature, the tails-- hot means a range of energies.

Hotter means a wider range of energies.

And it's those tails that have enough energy to get over the gap and into the conduction band.

It's those tails.

That's why I've got a little bit of electrons that get up there at room temperature.

Now, if you look at a plot-- here's a great way.

There's the log connectivity of silicon.

It's from [INAUDIBLE].

And there's the log connectivity on this side of tungsten.

That's a metal.

Totally different behavior.

How is that possible?

Well, we're going to explain the metal on Friday.

Today, we're interested in this.

This one, now we understand.

Thermal energy excites carriers into the place where they can be free and conduct.

So as I increase the temperature hotter and hotter-- there's the temperature in kelvin.

I just gave you examples from down here, and now we're going higher and higher.

I can get the connectivity up orders of magnitude higher for silicon.

You know why now.

I'm populating.

I'm getting over this gap, and I'm populating the conduction band.

So the answer is we just need to run our semiconductor industry and our phones and our lights at around 1,000 kelvin, right?

No problem.

All our devices.

No, that's obviously not a good idea.

How do we get around this?

The answer, such a good word, it's chemistry.

Chemistry gets us.

Chemistry saves us, as always.

You've got to know your chemistry.

And in particular, this is not the doping that you may read about in the news related to Olympic athletes.

This is the introduction of some small amount of an impurity.

An impurity is something that wasn't there normally.

It's like something I mixed in that's not normally there.

If I put a small amount of something in it, then I can tune the properties.

And in this case, I'm talking about the connectivity.

So how does this work?

If I look at this case-- I'll do one case here.

I've got my silicon atoms arranged in the solid that gave me a band gap.

And again, that is due to the arrangement of them.

If I didn't arrange them in this particular way, I might not have that band gap.

I might not have the same band structures.

It depends.

But this is what I get for the silicon arrangement when the band gap is 1.1 eV, which is the one we use in most of our electronics.

But the thing is, I want-- so this would be silicon.

This is just silicon by itself, valance band, and here's the conduction band, CB, VB.

Now, I want to add electrons into this material.

And so you can just kind of imagine how this would work, right?

If I just look at a Lewis dot diagram for silicon-- let's just forget about this structure for a second.

Silicon has these four valence electrons.

So you can imagine silicon might look something like this.

And OK, I'm going along, and I'm going along.

It's tetrahedral and stuff.

But now, I'm going to take one out.

I'm going to take this out, and I'm going to make it phosphorus.

What is phosphorus?

It's, wait, where did it go?

Panic, and then-- I'm recreating what happens for you guys-- I found it.

That was close.

But phosphorus is right there.

It's right next to silicon.

It's group 15 instead of 14.

But it just has one extra electron, right?

So maybe it could do the same thing, but then have this one extra electron.

That's doping.

Where does it go?

It's all about freedom.

It looks down and says, wait a second.

There's no states here I can go to.

No states.

I can't go anywhere here.

So I will have a state, because I have picked phosphorus carefully.

And because of the way the chemistry and the bonding worked with phosphorus in silicon, this will introduce a state near the conduction band, and that's the key.

So now we've got the valence band, and we've got the conduction band.

And what's happened is there's a new level here that is called the donor level.

That level is where the extra, extra key electron goes.

It can't go in here, remember.

This is all filled.

So now, I've doped with P. But look, if I've got an electron here, now this difference in energy is really small.

It's really small.

I've engineered it this way.

I've thought about it.

So if I put phosphorus in here, that extra electron isn't sitting far away anymore from the conduction band.

In fact, now it's so close that room temperature just kicks it right on up.

So effectively, it's going to go up here, because that's a small ΔE between the donor level and the conduction band.

This is how doping works.

This is how doping works.

So I put a phosphorus atom in.

There's an extra electron that comes out of that.

The extra electron needs a state.

It gets a state.

That's called a donor state.

Donor makes sense, right, because it's donating an electron into the conduction band.

Once I get the electron into the conduction band, I'm home free.

Because now, I've done what temperature was doing before, but I did it with chemistry.

And so you could ask questions like this.

How much phosphorus do you need to substitutionally dope?

Substitution meant just what you-- substitution was I took a silicon atom and I substituted it.

That's substitutional doping.

To substitutionally dope a mole of silicon and get a free electron density of 5×10^{17} .

I'm going big here.

Because look, temperature-- gesundheit.

OK, maybe I'm willing to run my semiconductor in a really hot room, my phone at 600 kelvin.

I'm still only at 10 to the 15 .

I want 10 to the 17 now.

How much phosphorus do I need?

You can solve that problem.

I'll just write down a couple of the steps.

So the volume of one mole of silicon is one mole times 28.1 grams per mole.

Oh, and I got the density on there, too, right?

Divided by 2.33 grams per centimeter cubed.

How did I get the density?

I looked it up in the periodic table.

And so one mole of silicon is going to give me 12 centimeters cubed of silicon.

One mole of silicon is 12 centimeters cubed.

I need 5 times 10 to the 17 electrons in the conduction band per centimeter cubed.

You see why per centimeter cubed is a good measure here.

So that means I need 12 times that total.

So I need 12 times that.

So I need 5 times 10 to the 17 P atoms.

Why do I need that many P atoms, times 12 ?

Let me just write my units here to be very careful.

P atoms per centimeter cubed times 12 centimeters cubed.

That's how P atoms I need in this mole of silicon to get what?

It's one to one.

Because each P atom had one extra electron.

Those other electrons are in the bonds.

They're not going into the conduction band.

It had one for one.

One electron went to this donor state, went into the conduction band per phosphorus atom.

So if I want that many carriers, if I want that many free electrons, I need that many atoms.

Well, you guys can look up the phosphorus grams per mole, and you can get that this is 0.0003 grams of phosphorus.

That's really not much.

You see why it's called an impurity, right?

You see why it's called an impurity.

That's not much.

I have all this silicon, and I only need 0.0003 grams of phosphorus, and I've bumped up the number of carriers by orders of magnitude.

Not only that, I've done something really important, as well.

And you can see this, because now, if I plot something like temperature versus number of carriers-- well, you saw the graph for temperature before, right?

It was like this.

That's the graph from a couple sides ago.

But now, if I do it with chemistry, it's flat.

Until the temperature gets really hot, I could-- give myself more room here, because that's kind of the point, right?

Number of carriers.

I can make this now flat.

From doping, from temperature.

And so you can see, OK, at a certain point, the temperature goes up, up, up.

And at a certain point, the temperature is going to be so hot that I'm adding electrons, even beyond this.

But you saw the temperatures there, 1,000 degrees kelvin.

No, this allows me to have a predictable, flat number of carriers in the conduction band no matter the temperature.

Just think about how important that is.

Semiconductors are kind of discovered in the 1800s.

But it wasn't until physicists and chemists were able to control the band gap and how to put carriers in and out of it until they could really work on the semiconductor revolution, which is what led to Snapchat.

Did I get it?

Snapchat is still used.

I knew that.

Slack.

Now, you can do the same thing going the other way.

You can do the same thing going the other way.

If I now put gallium, so if I dope with gallium, well, you see, gallium has one too few electrons.

And so if I dope with gallium, what I have-- so the gallium is there.

Where is it?

It's on the other side.

Where's silicon?

Silicon.

Phosphorus is over there, group 15.

Silicon is group 14.

Gallium is group 13.

One fewer electrons, but it really wants to make those four bonds.

The material isn't happy if you break one.

And so what does it do it?

It steals an electron.

It takes it.

It says, I need an electron to be happy, so it takes one out.

And that's called an acceptor level, where what's happened is the gallium has actually pulled an electron out of there.

And that leaves behind a positive charge.

This is called a hole.

That's called a hole.

Think about it.

If I take an electron off of an atom, it's positively charged.

If I take an electron out of the VBM, there's a positive charge in there.

That's really important, because these positive charges effectively are like electrons.

They're like negative charges, but they're positive.

So they also can conduct.

They also can conduct, right?

And that's really important.

So these are two different types.

And you can imagine the brilliance of the naming.

These are P type, because it's a positive charge.

And these are N type, because it's a negative charge.

Those are N type semiconductors.

What does that mean?

I've used a little chemistry, sprinkled a little something with extra electrons.

It's got negative charge in the conduction band.

P type, P means positive.

It means that I have introduced states here, because I needed an electron.

I say, I need an extra one.

I'm going to grab it from somebody.

I don't care who.

And so you create a positive charge in the valence band that can conduct electricity, just like a negative charge in the conduction band can.

This is what the entire semiconductor revolution has been based on.

And really, so much of the focus was on simply taking these elements-- in particular, silicon and

germanium.

But then, many, many more, as I showed you in the LED graph, many, many more have been used to make, to engineer, these simple-- what are seemingly simple properties, the band gap and the doping.

And so I'm not going to go through this in detail.

I'm just leaving it here so you have it.

But you get charts like this.

Here, you have, OK, carbon is up there.

Well, if you dope it with boron, you can see that it's P type.

You see that?

Because I've got one fewer electron than carbon.

So I'm going to grab that from the valence band, create a positive charge P type.

I could also dope silicon and germanium.

I'd say carbon, silicon, germanium.

So I'm looking at this middle column, doping it with either side.

Why can't I put aluminum in carbon?

Why didn't they list that?

Well, because if I try to put an aluminum inside the carbon network, the network gets all messed up.

Doesn't fit.

So that's also important.

Can it fit?

But it's through this that the semiconductor revolution started.

It's only through this, this kind of control and this knowledge of atomic orbitals, really, if you think

about it, and the structure of the atom.

Now, I'm not going to talk about transistors, but this did lead to the development of the transistor.

There's a really nice video there.

It's, like, eight, nine minutes.

I suggest you wait until your Friday night social.

But if I take a P type and I take an N type and I take a P type and I put them together, some really important things happen.

So important that it led to this, which is the very first transistor.

That's a transistor.

It's a dope semiconductor, one type, next to a dope semiconductor, another type.

Now, those are the three people-- Bardeen, Shockley, and Brattain-- who won the Nobel Prize for this work.

And that's the first transistor.

Does anybody know how many transistors we make today?

Per second.

That's the only time metric we can use.

Yeah, it's something around 10 trillion.

We make 10 trillion transistors per second today.

This is a big deal.

This started it all, and it's all about chemistry and the physics of this device.

This led to diodes and photodiodes.

This led to the whole revolution.

And what I want to point out here is that this also led-- it called on chemistry.

So I love this chart.

Unfortunately, they didn't update it, but this is an Intel chart that they used to show.

And what they're showing is how are they making chips.

How much of the periodic table do they need to make the current chip?

Well, in the '80s, there's almost nothing lit up here.

There's a little bit over here that you can't see, stuff we just talked about.

But look at the '90s and look at the 2000s.

And today, it's 75% of this.

It's literally 75% of this is in your phone.

Yeah.

Why?

The reason is exactly what we've talked about today, because they need more and more and more flexibility and ways to tune the band gap and the semiconducting properties of these materials and the doping.

Why do they need new ways?

Because they're making them so darn small.

They're so small, it gets harder to figure out how to do it right, how to do it in a way that's also stable over time, for example.

So they need new chemistry.

This is a call to action to the field of chemistry, and chemistry responded.

And there's the data on the cost.

I thought that was kind of cool.

So these are orders of magnitude of cost and number of transistors.

And I'll just say one more why this matters.

Because the semiconductor is also the same thing we use to take electricity from the sun, to generate electricity from the sun.

And you can imagine, you are doing that in your goody bag.

You're literally using this semiconductor to generate electricity by shining light on it.

Why is this important?

Well, I like this comparison.

All the coal, oil, and gas known to humans is what you get from the sun in about 20 days.

This is the sun.

Now, we've seen the sun before.

This is how we see it in our class.

The sun is a spectrum of different wavelengths and intensities.

And this is already on planet Earth, because you can see those chemistries that are in the atmosphere have already absorbed.

Remember ozone down here, helping us with UV radiation?

And out here, you've got a lot of water and other things, CO₂.

Those are absorbing.

That's why it doesn't look smooth.

But the point is, I want to semiconductor to absorb as much of this as possible.

If I want a good solar cell, I should absorb as much of this as possible.

But the problem is that it's a constrained optimization problem.

So let's see, if I-- I'll just use this.

This goes back to Bohr, by the way.

Remember, Bohr, I'm absorbing light.

It's just now, I've got an actual solid.

I don't have an atom.

I've got a solid, which is what you need if you want to generate a current.

I've got to hook leads up to it.

But my solid is a semiconductor.

And you can imagine, say, well, if my gap were really, really tiny, then any amount-- almost any amount of this spectrum would excite electrons.

And I might grab most of that spectrum.

I might absorb most of it.

But the problem with that is that, then, all of these will thermalize, like I said in the beginning.

Loss to heat.

Loss to heat.

So if my band gap is really small, I absorb a lot of the light, but I lose most of it as heat.

If my band gap is really big, then there's so much of this light that I cannot absorb.

By the way, also, the voltage that you get out of your solar cell is essentially this band gap.

So if I get to really, really small band gaps, I have almost no voltage.

That's bad, too.

But if my band gap is too big, you think, oh, I'll get a high voltage.

No.

You won't absorb any photons.

So it's a constraint problem.

It's a constraint problem.

You can actually solve this, and you can plot-- in fact, here's a little animation.

Energy comes in from the sun.

It excites an electron.

This is how PowerPoint sees it.

Leaves behind a hole, and you get them out.

That's a solar cell.

And this is the chart I want to show you.

Because you see, if I take this constraint into account, that I don't absorb light if the gap is too big, but I do absorb light and it all goes to heat if the gap is too small, it means there's some sweet spot.

There's some sweet spot.

And that's what is plotted here.

This is the band gap of a semiconductor, and this is the maximum that that solar cell efficiency could be.

That's the maximum that it could be for that gap.

So you can see the sweet spot is right there.

That's a thermodynamic derivation called Shockley-Queisser of the maximum efficiency you could ever get out of a single material.

And notice, if you put the materials here, silicon is 90% of the solar cells you buy today.

And notice that it's not quite at its maximum potential.

It's also not quite in the middle, where you'd want.

It should have a slightly higher gap, and you'd get to higher efficiency.

But these materials out of gallium arsenide, they do have the-- what is GS?

That's not an element.

Gallium arsenide, it does have a better gap, but it's much more expensive.

And so we go.

And a lot of solar cell research is on getting as close to this point as you can.

See you guys on Friday.