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**PROFESSOR:** We'll be talking about the diode and charge separation inside of a solar cell. So at the end of last class, we ended with this little demonstration right here, where after much discussion about band gaps and light absorption, we agreed that that little piece of silicon there should be absorbing the light and free charges should be generated inside the silicon.

But without some fixed fields, some built in field inside of the silicon material, it wasn't possible to measure any current output once we shown light on it. And that made sense. There were free charges being generated, but due to Brownian motion, there was no net charge flow. They were just moving around with no net movement. And as a result, there was no current.

Now if we attach the batteries in series, the batteries apply to field across this little piece of silicon resulting in current flow-- more precisely, drift current across that piece of silicon.

And today we're going to be talking about how the solar cell device has a built in electric field. So obviously we don't want an external power source. We don't want to have a set of batteries attached. That defeats the purpose of an autonomous energy generation device. We'll be talking about how the built in field inside of a solar cell comes into being.

As we've followed in the last few classes, we will be discussing physics when it is necessary, taking a very engineering approach to this so as to keep everybody from a business background, from a mechanical engineering background, and from a material science background on the same page.

We will have, in the lecture, I think n plus 2. Very physics-y lecture, and we'll be

getting to the nitty-gritty of semiconductor physics and how it relates to solar cell devices. So for those of you who are already experts in this material, bear with me. And again, try to relate to the solar cell device. You may not have had that connection in previous lectures in previous classes.

So we'll jump right on in. To remind everybody, you're here in the fundamentals. We'll be getting to the technologies and cross cutting themes after we really have a good, solid understanding of how a solar cell works.

The conversion efficiency is the output energy versus the input. We have our inputs in the solar spectrum, the outputs in charge collection, and we've been steadily making progress down toward the outputs here. We discussed the solar spectrum, then light absorption, the charge excitation, and finally now we're on to charge drift and diffusion.

So we have the total solar cell efficiency as a product of all the individual processes. And any one of these processes can kill the efficiency of the device. That's why it's important to think about your device like so. And just not to make this introduction so boring, I want to really emphasize this point. So I'm making it over and over again. But I wanted to relate this to other engineering devices as well.

Namely, today it's a Toyota Prius. These are all the components inside of a Prius that have to work well for the car to function. If one of these components, let's say this one, the inverter, is broken or not functioning well, you're not going to have the car in an autonomous mode.

So in a similar manner, in a solar cell we have to have all the different pieces working well together. So the essence of charge separation, we're going to begin our exploration of charge separation using the diode analogy. And just to situate everybody, I brought in a number of small discrete components, small diodes. Those are the ones that are orange-ish that have two leads coming out.

There are a bunch of transistors in here as well. Those have three little leads coming out. You'll be able to distinguish them. But just to situate ourselves, these

are diodes.

The essence of a diode is that you have a dissimilar material on either side of the device. That's why I've worn these dissimilar colors today to denote that on different sides. And of course, you have this mixed region in the middle.

We have here an n and a p on either side. And if current is attempting to flow in one direction, it will be barred. But if it attempts to flow in the other direction, it will go through rather easily. That's the essence of what a diode is. How is it made?

Well, we're manufacturing materials of the same base element. Let's say, silicon. But we're doing something special to the material to add particular types of charges on either side. We call doping. And we'll get to that in a few slides. Why do we care about diodes?

Well, this is the essence of charge separation. And this is what drives the voltage inside of a solar cell device. That's why we care. It's pretty important for at least understanding the traditional semiconductor-based solar cells like this one here.

So for those history folks, I figured I would add a quick at description. You typically see the diode represented like this in an equivalent circuit diagram, a little triangle and a line orthogonal to the direction of the current path. And does anybody know where that comes from? No? All right.

So back in the day of that, we used to have vacuum tube components for a lot of our-- I would say the discrete components within our circuits. In the case of a diode, you could envision a very simple one where you have a filament that by thermionic emission heats electrons off of the filament, and then they're collected by this other collector up top.

If you remember our etymology in Greek, ana is above, cata is below. Catatombs, right? Catatonic, below. So the anode up above is collecting these electrons, and then the electron flow is moving like this, which means that our current flow, defined as the flow of positive charge, is moving the opposite direction. And that's why we have a similar representation right here from our vacuum technology. You could

envision also a point where the field is concentrated at that tip and electrons are spreading off.

So learning objectives. Today is going to be rather intense, rather dense. And so we will be trying to hold as much as possible in our RAM, so that by the end of class we can really truly understand the solar cell as an entirety. If you get lost along the way, come back to these learning objectives. They're like flag posts along the way. So you can find yourself again.

What we're going to do first is describe how the conductivity of a semiconductor can be modified by the intentional introduction of dopants. What this means is we're going to learn how to create the n and the p over here.

So if we look at a semiconductor such as silicon-- this is a little piece of silicon right here. Here's a silicon-based solar cell. It's a fairly easy semiconductor to understand. It's what's called a unary semiconductor. It means it's comprised of one element. Silicon right here in the periodic table. This is just an excerpt from the rightmost side of the periodic table.

And silicon has 4 valence electrons. So it forms what are called  $sp^3$  hybridized orbitals when it's in a crystal structure. It has four bonds with its nearest neighbors, all of equivalent type. And those are covalent bonds. So you can envision that if you were to introduce an atom and substitute out one silicon atom in that lattice for something else that has 5 valence electrons, such as a phosphorus, it's almost of equivalent size. So those material scientists in the room from the Hume-Rothery rules, you should be able to estimate that the miscibility is rather large. In other words, that you could mix in a high concentration of phosphorus into your silicon given the similar size and similar atomic structure. Electronic structure, rather.

So you substitute here a group 5 element. Silicon is a group 4 element, as is carbon, germanium, and tin. So we substitute in a group 5 element. Let's say a phosphorus atom in for one of our silicon atoms right here. And this phosphorus atom will have 4 plus 1 valence electrons. So those 4 valence electrons will bond to the silicon atoms, the nearest neighbors. And that one extra valence electron will be

left over. It will have nobody to bond to. And we'll describe mathematically what happens to that electron in a minute.

But in principle, just intuitively you should be able to understand that that electron should be able to be removed rather easily and move around the lattice with relative ease. Likewise, instead of moving one to the right, if we move one to the left into our group 3 column here, we can dope our material with a boron atom, let's say. Substituting one silicon atom for a boron atom. Boron has 3 valence electrons.

Now, those 3 will form bonds with the 3 silicon atoms. And then you'll have a missing bond, a missing electron if you will. That will be a hole. So with phosphorus, or group 5 elements in silicon, we can dope the material with electrons. And with group 3 elements in silicon, we can dope the material with holes.

And this is interesting because now we can arbitrarily change the density of charge carriers in our bands. As long as these holes and electrons can become dissociated from the dopant atoms and move freely around the lattice. So that's a big question, how easy is it to remove that electron around the phosphorus atom?

If you want to think about this electron just from a quantum mechanical sense, you could almost envision that this electron is attracted to the phosphorus atom because the phosphorus has one extra proton than the silicon, right? So it has a positive charge here in the nucleus. And here's a negative charge. In net, they balance out. But if the electron goes too far away, it will feel that attractive potential back and be drawn back towards the phosphorus atom. So the big question is, what is the binding energy of that electron to the phosphorus atom?

And a simple way to think about it is through a hydrogenic model. If you consider a hydrogen atom to have an electron surrounding it, then that binding energy is well-defined. But in the case of a phosphorus atom within a silicon lattice, it's a little trickier. Because now we have to worry about the electron screening coming from the other elements in our lattice. And we also have to worry about a property of the electron in a crystal, which changes the mobility of that electron through the crystal.

So what we do is we treat this as a hydrogen atom, 13.6 eV binding energy. But then we do a couple of things. We account for electron screening and we account for what we call effective mass. We'll get back to this in a few lectures and describe exactly what this is here. We need a little bit more semiconductor physics to understand it in its entirety. But think about an electron moving in a crystal as moving differently than moving in free space in a vacuum. That's what this term here is about.

This other term, the epsilon, is rather straightforward. It's the electron screening. It's the fact that you have so many other electrons in your system here that screening the charges, screening the electron from the extra positive charge in the nucleus here. And so it becomes easier for that electron to move away.

This is about a factor of 0.1, the effective mass. And that's about 1/100. And so overall, we're reducing the binding energy by about a factor of 1,000 down to about 10 m eV in practice. So if we were to run through the calculation for silicon, the binding energy of that electron around the phosphorus atom in the silicon lattice would be around 10 m eV on that order. And that is very, very small compared to the thermal energy in your system, just  $kT$ , Boltzmann's constant times the temperature in Kelvin, we have a thermal energy somewhere on the order of 26 m eV. And that's enough to dissociate that electron and allow it to move freely throughout the lattice. Question?

**AUDIENCE:** Is that electron screening related to the [INAUDIBLE] constant at all?

**PROFESSOR:** Yes, absolutely.

**AUDIENCE:** I just had a [INAUDIBLE] question about the holes. So I understand that-- I can imagine an electron moving around in the lattice. But I imagine that a hole moving would be forming a bond-- breaking and forming bonds over and over. Does that actually happen, or are the electrons more free to move?

**PROFESSOR:** Yeah. This is an excellent question. The question, if I may paraphrase, relates to the hole and electron mobilities. How easy is it for them to move around the lattice?

And typically, the hole mobility is about a third of the electron mobility in silicon. So absolutely, it is a little bit more difficult for those holes to move around. Holes, you may recall, are quasi-particles.

OK, so we have an understanding of doping, a rough understanding at this point. We understand that if we dope a certain type of material, let's say our n-type material, with phosphorus, we have an excess of electrons. And if we dope another type of material with an excess of, say, boron, we would then introduce a large number of holes and the material might have a majority conductivity through our holes. Hence, we call it p-type. n and p comes from negative and positive. Negative being the electron charge and positive being the hole charge. So that's where the n- and p-type come from. Great.

So now, pictorially we're going to draw a pn-junction or a junction with our fixed and mobile charges. OK, so let's start out with a simple review of Gauss' law. Spatially variant fixed charge creates an electric field. What do I mean by that?

I mean that if you have a high concentration of fixed charge over here and a lower concentration of fixed charge over here, an electric field will develop. And that's the expression right there that relates-- that describes this in mathematical terms where we're using  $\psi$  here as our electric field. We're using  $\psi$  instead of  $E$ . You probably remember your physics textbooks using  $E$  as the electric field because we're going to reserve that variable for the electron energy. That will come in several slides forward. So the charge density will be given by that  $\rho$  and the material permittivity by our  $\epsilon$ .

And an example is a capacitor here. All I've done is expanded the dimensionality of the derivative here. I'm looking at the capacitor. I have fixed charge on either side. And I have electric field in between.

Now, this right here, obviously in the case of a capacity, you're under high vacuum. Just as a very quick aside, this is-- I can't resist. This is really an interesting historical note.

This space right here in the diode as we recall, where you have the thermionic emission of the electrons going off to the other plate, this space right instead of here is called the space charge region. Keep that name in mind. We're going to come back to it in several slides. So a bit of history there.

So we have the capacitor as our prime example. We have fixed charge on either side and electric field in between. And note that the charge will move parallel to the electric field.

If there's no electric field-- in other words, if we're just exciting charge inside of a bare piece of silicon with no electric field applied-- imagine our batteries here are taken out of the circuit. We'll have simple Brownian motion of those photo-excited electrons until they decay back down into their ground state.

However, if we apply an electric field, now we have the Brownian motion. But superimposed on top of it, a certain drift of the electrons in response to that electric field. And we can describe this mathematically as well. The drift currents for holes and electrons being described by the charge  $q$ . Note that the charge  $q$  is going to be different for the electrons and the holes-- the same value, but negative or positive.

The mobility of holes and mobility of electrons. The density of holes or electrons. And then finally, the electric field right here.

And the reason in this equation you typically see the  $q$ 's being the same value here, although no minus sign is put in front, is because under the same electric field, you'll have electrons drifting in this direction and holes drifting in the opposite direction. So it's important to keep these signs straight in your mind. Yeah, question?

**AUDIENCE:** [INAUDIBLE].

**PROFESSOR:** Absolutely. So  $p$  and  $n$  denote the concentrations of free electrons or free hole-- actually, free holes for free electrons, respectively. So you can almost think of  $p$  as being synonymous with the density of boron atoms.

If every hole is ionized, meaning dissociated from the dopant atom and free to move around the crystal, then the density of holes and the density of boron atoms is going to be almost identical. Likewise, for phosphorus atoms and/or the donor atoms and the electrons, you'll have almost an equal number. So that's right here. The  $n$  is related to the number of electrons that are free to move around the crystal. The  $p$ , the density of holes that are free to move around in the crystal.

And these are given in units of number of particles charge carriers per unit volume. So per centimeter cubed, let's say. Question.

**AUDIENCE:** [INAUDIBLE] you're creating more holes. So is that not on the same order of magnitude as the number of holes introduced by [INAUDIBLE]?

**PROFESSOR:** Yeah, absolutely. So the density of holes and electrons here in the dark is dictated by the dopant density. Where are we?

Right here, for instance, the dopant density. If we add light, that's a complicating factor. The intrinsic population of electrons and holes and the dopant concentration of electrons and holes, we are adding a photo-generated population as well. Let's leave that for next lecture and try to simplify things. So we just discussed the diode in the dark. Perhaps we turn the light off here just for effect.

So we're trying to take this piece by piece, so that we can really construct everything and not add too much into the pot at one time. I wanted to discuss the notion of electron drift. And I also wanted to review the concept of diffusion, which everyone should be familiar with.

This is the reason why we're breathing right now, and why all the air molecules aren't crowded into that corner of the room. It's because of Fick's law, the process of diffusion.

If we have a concentration of a particular species in one spatial location, the natural tendency through random motion is for that concentration to distribute itself equally throughout. And this is described very nicely by Fick's law.

If we want to describe a current to it, we would then describe the current of holes and the current of electrons by, again, the charge. The diffusivity, this is a quantity typically given in units of centimeters squared per second. And the gradient. In other words, the concentration gradient. In this case, in one dimension. And that, again, should be review for most folks from physics.

And so we can see here two different methods of currents, two different methods of current flow inside of a semiconductor device. We can have diffusion or we can have drift. Drift occurs when there's an electric field present and diffusion occurs when-- well, in this case, diffusion can occur in the absence of an electric field simply when there is a concentration gradient present.

So we can envision, just quickly, that if we have an electric field confined to a certain region of our solar cell device, the electric field will be dominant in one portion. And if the rest of our device we don't have a strong electric field, but the electrons nevertheless can sense the electric field far away because of the concentration gradient, diffusion can drive those electrons-- can drive those electron toward the electric field.

So in our solar cell device, the ratio of drift and diffusion current will change as a function of distance from the pn-junction, from the built-in field. OK, so I want everybody to upload into their RAM the checkerboard example that we went through. Because this will be important for understanding the next few slides.

So let's imagine these n-and p-type materials are in contact, but there's this imaginary barrier right between them. Here are p-type materials, here are n-type materials. And let's parse through this figure. Let's dwell, just a minute.

So we have this imaginary boundary between p-type material over here and n-type material. The boundary is right here in the middle.

The blue dots here are representing mobile holes, holes that are free to move around the material. And while there's this imaginary barrier here, these holes are just moving in Brownian motion. There's no net current. There's no net charge flow.

These minus signs that are left behind are the boron atoms. The boron atoms have one less proton in their nucleus than the silicon atoms do. And so the hole plus the negative charge that's within the boron atom core if you will, that combination is neutral. So we haven't perturbed the net charge of the entire system.

But locally, if we draw a little circle around these two for instance, the boron atom that's fixed, that's not moving. The boron atom is bound to the neighboring silicon atoms. It's not moving around. And the hole, which is free to move around the material, now we have net charge neutrality. But if that hole moves too far away, then you could have a field building up.

On the other side, very similar. Here we have phosphorus atoms embedded within our silicon lattice. The phosphorus atoms have one extra proton in their nucleus than the silicon atoms do. Hence, we denote that as a positive charge right here. And there's an extra electron associated with the phosphorus atoms.

Now as those electrons move around, when it's in isolation, again, there's no net charge flow. There's no current. And we have a situation of net charge neutrality. Question is, what happens if we remove the barrier in between the two?

Let me ask you just a basic question. Would the phosphorus atoms diffuse over to this side?

**AUDIENCE:** No.

**PROFESSOR:** Probably not, because the phosphorus atoms are bound to 4 silicon neighbors. Those bonds are really tough and it's probably not going to break. Unless you heat it up to a pretty high temperature.

But the electrons are free to move around. They're in the conduction band. They're able to move. And because the binding energy to the phosphorus atoms is on that order of 10 m eV on that order, the thermal energy here at room temperature is enough to dissociate them, and to allow those electrons to move away from the phosphorus atom thanks to the screening potential of the surrounding lattice and thanks to the fact that the electrons inside of a crystal are more easily-- can more

easily move than in vacuum. So when we remove that boundary in between, what begins to happen?

So we've removed the boundary. We have these two materials in direct contact. The nuclei are not moving. The fixed charge associated with the boron atoms in this side and the phosphorus atoms on that side are not moving. However, the instant you remove this boundary in between, there is a high concentration of electrons over here and a very low concentration of electrons over there, which means that you will have a diffusion process. So the concentration gradient drives the electrons over to this side.

Likewise, holes are being driven from here over to here. Now, notice what happens.

Holes carry a positive charge. The fixed charge from the phosphorus is also positive. So you have a buildup of net positive charge on this side of the junction. Electrons are negative charge carriers. The boron atoms have a net negative charge here. And so you have a net negative charge building up on this side. And now you have a field beginning to develop, an electric field.

And at some point, this built-in electric field will counteract the diffusion process. The diffusion current is driving electrons in this direction, but the field will be driving them back the other way. And it's that equilibrium that establishes the pn-junction. It's that equilibrium that defines the width of this region here, this transition region, which comes in a variety of names.

The transition region is also called the depletion region. And it's also called the space charge region. Interesting how these words and terms come back into use. So that's the essence of the formation of this junction.

We have this diffusion process that drives the carriers from this side into this side. And then as we have the electrons moving over here, and summing to the boron nuclei that are left behind once the holes, likewise, have moved over to the other side. We have a buildup of net negative charge on this side, a buildup of net positive charge on that side, and the establishment of a built-in electric field.

That's cool. It takes a while to really get it. And so the chessboard example was brilliant. I thank Joe for that. And hopefully, this as well reinforces several of those concepts. And it might take some time studying it on your own or setting up special office hours with Joe or coming to my office hours on Mondays. But whatever it takes, make sure that you understand this concept well-- the fundamental-- gaining an intuition about the concept. We'll be getting into the math soon. And if you don't have a good, solid understanding of the intuition of where charges are moving around, it becomes less easy, let's say, to really get the math.

So we have a buildup of net charge on either side of the junction. We have a buildup of net negative charge on one side of the junction and a buildup of net positive charge on the other side of the junction. And this line right here is meant to represent that dividing line where the two materials initially came together.

So the dashed line is meant to represent the real charge distribution and the boxed colored rectangles, the rectilinear boxes, are meant to represent an approximation that we'll use for the rest of today's class.

We're making successive approximations here because we want the mathematics to be manageable. You can, of course, discretize this entire material in one dimension, for instance, and do a finite element solution. We'll show you the equations that you can use to do that later on in today's class.

So we have the net charge distribution on either side of the junction shown here. We also have, as a result of that net charge, an electric field. And this goes back to Gauss' law, or the derivative form there of. And so we have here a built-in electric field as you can see. And the field reaches a maximum right here in the middle. So that kind of makes sense.

If you're too far away from that junction, you're not going to-- if you're a charge carrier, you're not going to see the field. But if you're right there in the middle of that junction, that field is going to be very strong. You'll be swept out of there pretty quickly. That's why the field reaches a maximum right here in the middle. So that

intuitively makes a lot of sense.

Now, if we take one further integral of the electric field, here the electric field, arc psi. If we integrate our arc psi, we will get the potential. And this potential right here essentially follows this wave-like curve, where you have a lower potential on this side and a higher potential on that side.

And if we take this potential and translate it into something that we can understand, which is electron energy, by multiplying the potential by  $q$ . And  $q$  in the case of an electron is a negative number. That's why we're flipping this. So we're flipping this upside down because we're multiplying this value here by a negative number.

Now, what we can see is that there's an energy gain for the electron by going from the p-side to the n-side. This is the electron energy.

Obviously, if you give them an opportunity, all the electrons would want to come down to this side. But why wouldn't all of them come down over here?

**AUDIENCE:** Because of diffusion.

**PROFESSOR:** Because of diffusion. So there's that balance of the two effects. So there is a net energy gain for the electrons, but diffusion is what's driving some of the electrons back across the other side of the junction is that equilibrium, which is establishing the final energy band diagram of the pn-junction, which is really looking something very much like that.

So this right here describes for you how you go from atoms and charge carriers up at the top to charge distribution, electric field, potential, and finally electron energy. Yes.

**AUDIENCE:** Are these four diagrams specifically for electrons? Would the hole ones be [INAUDIBLE] the reverse of that?

**PROFESSOR:** So if you wanted to look in terms of hole energy, this equation here would be equally valid, but your charge would be a positive value. And so you'd have a curve that looked very similar to this one right here, where there'd be a net energy gain for

the holes to go on to the other side. And that's what establishes the separation of charge.

**AUDIENCE:** So the bottom one is the only one that would change [INAUDIBLE]?

**PROFESSOR:** That's correct. Yep. Everything else identical. So this is important, this electron energy. And this jump right here confuses a lot of folks. Because in books, they don't often describe very clearly what is potential and what is energy, almost using those two terms interchangeably. But it's that cue, the fact that the electron has a negative charge that sets things right.

OK, this is pretty important. This is the foundation, the fundamental, of how a pn-junction comes into being. And the summary of our understanding so far is that when the light-- here we go.

When light creates an electron-hole pair, a pn-junction can separate the positive and negative charges because of the built-in electric field. Let me repeat that one more time. When light creates an electron-hole pair, a pn-junction potentially can separate the positive and negative charges because of that built-in electric field.

For very small light intensities, very small light intensities, such that you can think of that photo-generated carrier as a perturbation to the system, not fundamentally altering the energy levels yet-- it does eventually happen. But if you have, say, one photon coming into your material exciting electron over here, that electron can move down, can be swept out of the device, because of that built-in electric field.

Again, assuming that we have a very small impact on the electrostatic [INAUDIBLE] system that it's just a small perturbation, maybe one single electron in our system is not going to affect you much because we have  $10^{23}$  or so atoms per cubic centimeter. We have a very small perturbation to our system, that charge carrier will be swept out very quickly.

The built-in electric field is established at a pn-junction because of the balance of electron and hole drift and diffusion currents. Let me be more precise about this one

point right here. Because the built-in electric field is established at a pn-junction because of the balance of electron drift and diffusion. We talked about that. But hole drift and diffusion as well.

So if you go back over to here, notice how the electron drift and diffusion are opposed and equal and opposite to the hole diffusion and drift. So let's think about it from this perspective right back here.

This is clear, our electron diffusion is going in that direction because we have a high concentration of electrons that tend to move toward the low-concentration regime. So our electron diffusion current is pointing toward the left. Our hole diffusion current is pointing to the right. And the hole drift current, because of this built-in field, is pointing opposite the hole diffusion. So the hole drift current will be pointing to the left. Whereas, the electron drift current would be pointing to the right. So we have, in total, four currents here.

The way to think about it would be, for example, let's take the electrons first. Electron drift or electron diffusion and drift counteract. And then you can take the holes. Hole diffusion and drift counteract. They're all balanced. And this is resulting in zero net current flow when you have no illumination and no external field applied to that device. That's pretty nifty.

So the built-in electric field is established at the pn-junction because of the balance of drift and diffusion current for both electrons and holes. So we have a small in-class exercise.

I'd like you to take out these. And I'd like you to work in pairs. So that if anybody reaches a small stumbling block, you can help each other work through the problems.

So first off, let's focus on this upper left-hand portion right here as shown right there. This is a replica of the sheet that you should have in front of you. So what we're doing is we're dividing-- we're considering the pn-junction under no bias. That means that we're not applying a battery to our pn-junction. So we have a pn-

junction and we don't attach a battery in series. We just have the pn-junction under zero bias conditions.

So the way we'd represent that in that equivalent or model circuit diagram right here is notice how we have these little lines extending from the p- and the n-regions and going above. Those represent the external circuit outside of the actual device. The device would be this one right here where we have p and our n.

We have our positive and negative charges here representing the charges that have built up in that space charge region that are creating the built-in electric field. And under no bias conditions-- I'll give you the answer. It's pretty straightforward. We would just draw a straight line across right there bridging that external circuit because there is no external bias. There is no battery applied.

And so from an energy band diagram,  $e$  versus  $x$ , for  $e$  being the electron energy in this case. And our p-type material being on this side and our n-type material being on that side, let's draw the energy band diagram, just like we've done or we've alluded to so far. Sketch out the energy band diagram for this pn-junction.

And I'll give you a hint. It's going to look something very similar to that right there, except that you'll have to take into account both the conduction and valence bands, because they're both affected in a similar manner to that. So why don't you go ahead and give it your best?

Draw the energy band diagram in terms of the electron energy and position. Notice your p-type on one side, n-type on the other. You can assume that the point of division is like right here in the middle.

And for those who are a little quick, you can go on and draw the relative magnitudes of electron drift and diffusion currents. So why don't we give that a quick, little shot? Maybe 30 seconds to think about it and another 30 seconds to draw and chat over it with your colleagues.

So we want to draw the band diagram, just to make sure everybody's in the same page. So we're going to be starting out with our valence band and our conduction

band over here. And as we move toward our space charge region, as we move toward our depletion region, our transition region here in the middle, we're going to see some effect. We're going to see some bending of the bands, if you will.

So your question is to figure out, do the bands do something like this? Or do they do something like that? Do the bands go up or do they bend down? And that should be a relatively easy copy and paste from two slides prior.

The correct answer is, indeed, we have the band bending down like this. So we would have the bands higher on one side, lower on the other. The electron energy is higher on the p-type side than the n-type side. So if we add one electron to our system, for example a photo-generated carrier from one photon coming into our device, that electron will have the natural tendency to go onto this side. It will be swept down.

Note that the net current flow inside of the device, in the absence of an external excitation, like light or a battery pack over here, an external bias voltage source, the net current flow is zero. Because electron diffusion is pointed in that direction and electron drift pointed in that direction.

All right, good. So now that we've done one example, I wanted to-- oh, one last thing. So hole diffusion. So this is electron diffusion pointing to the left and electron drift pointing to the right. Hole diffusion is pointing to the right and hole drift pointing to the left as one might expect. Let's try these two right now, forward bias and reverse bias.

And your trick is to figure out, if you have a battery for instance, if the battery looks like this. This would be positive terminal and negative terminal. If you have a battery, which way would you align the battery to induce a forward bias or reverse bias? It's perhaps a little bit beyond my expectation of what you would get. Let me add that for you. Let me just give that to you right here.

The forward bias would look like that. The reverse bias would look like that. OK. And now the big question is, what do the band diagrams look like? How would these

look?

If we forward bias, if we forward bias our device and we inject electrons into this side right here, what would happen to our bands? What would you expect would happen?

We'll prove this out in the next few slides, but I want to see how people's intuition is doing this morning. So as you bias a device, you're shifting one level relative to the other. And so the basic question that you have to answer is, should it shift up or should it shift down under Forward and reverse bias conditions?

Spend a minute. Talk to your neighbor. Discuss it.

All right, folks. Why don't we tie it in?

We should be able to get band diagrams that look something like that. I saw several of you have already begun reaching this consensus here. Rationale?

An easy way to think about this is, if our battery is aligned with our pn-junction in that way, and we're injecting electrons into one side, we then have a large electron diffusion current. We have the bands shifting in this direction. Now the barrier, the energy barrier for the electrons to overcome, to go from the region of high concentration to the region of low concentration, is smaller. And you'll get a larger diffusion current as a result. More electrons will be moving over that n-type silicon into the p-type silicon. And the drift current will be smaller.

Notice here, the balance of the two, if you add them together, you have a net electron flow in that direction, which means you have a net current flow as defined by the flow of positive charges in the other direction. A lot of definitions to keep straight.

Whereas, under reverse bias here, you're shifting the bands like so. Because you have the large electric field, the drift current will be increased, but only slightly. Because there's a limited number of carriers here that you can pull from the p-type material. And the diffusion current is going to be drastically reduced because now

the energy barrier is so large that the electrons have a very hard time getting from the n-type material into the p-type material. And then that net current flow is in the opposite direction. Does this make intuitive sense to folks? Ashley.

**AUDIENCE:** So when you touch the battery [INAUDIBLE], is the minus side injecting electrons [INAUDIBLE]?

**PROFESSOR:** OK. So in between these two, the easiest way to go from battery to electron energy band diagram is to follow the same sequence that we did over here. And if you're thinking battery, and you're thinking positive and negative, you're shifting the potential of one side relative to the other. Then, take that potential shift and flip it for the electron.

**AUDIENCE:** I follow why the diagrams are the way they are. But is it conceptually accurate to think of the negative side as putting more electrons into the n-side?

**PROFESSOR:** One could.

**AUDIENCE:** Like injecting carriers?

**PROFESSOR:** The way I prefer to think about it is that you're changing the energy levels, the potential one relative to the other. And as a consequence, you have more electrons flowing from that n-side to the p-side. And that's what's pulling the current through the circuit. It's almost a tail wagging dog, dog wagging tail. But I would take a slight preference toward understanding it from the perspective of if you change the potential one relative to the other, and allow for a greater diffusion current, that motion of electrons, the electron moving from here to here, will pull current through the entire circuit. And that's what you'll be measuring with your external-- essentially, all of the electrons in the circuit are moving through.

**AUDIENCE:** [INAUDIBLE] so we've opposed the field that was set up [INAUDIBLE].

**PROFESSOR:** Exactly. We are opposing the field that was set up by the balance of the drift and diffusion currents initially. Yeah.

**AUDIENCE:** Under the first bias, how come the many electrons in the anti-material aren't

[INAUDIBLE] through the entire circuit and injected into the [INAUDIBLE].

**PROFESSOR:** Certainly. So the reverse bias is such that the battery is aligned to prevent that. perhaps one simple way of thinking about it. Yeah, I think that would be the way I would describe it most accurately.

You could-- and you are dragging some of the electrons out through the external circuit. But what is driving the current is mostly the drift current. It's pulling carriers from-- essentially, through your external circle. Because carriers are moving from the p-type to the n-type and creating that charge imbalance resulting in the drift current. Why don't we continue moving on just a little bit because we have some nice demos we'd like to get to. I do know this is really, really important. And I would welcome you, actually urge you, encourage you to come to some of the office hours and our recitation as well.

I'd like to continue moving forward for the benefit of several of those who may have seen similar material in the past. But let me, before we move too far ahead, on our I-V characteristics, we still don't know how to map an I-V characteristic of that device. We don't know how the current voltage, I current V voltage, we don't know how the current voltage response is going to look like for that particular device. But we do know that under no bias conditions we're at bias voltage equals 0. So V is at 0.

And we know that we have no net current flow. And so our current is going to be at 0 as well. And so we know that we're going to have one point on our I-V curve that's going to be situated at 0, 0.

Likewise, in this case over here, we have electron diffusion driving the circuit. And in the other, we have electron drift, which is in the opposite direction. And so you'd expect that the current flow in I under forward bias conditions-- forward bias is positive-- would be somewhere up here. And likewise, under reverse bias, that our current would be opposite the sign. So whereas we had positive current over here, we would expect negative current over there.

So our I-V characteristic is going to look something like a combination of one point right here and some function up in this quadrant and some function down in this quadrant, just by glancing at the net current flows and the type of bias that we've applied to our diode. We'll come back to this at the end of class and confirm it using those small apparatus over there.

So current flow in a pn-junction. We're going to describe the nature of the drift, diffusion, and illumination currents in a diode. Show the direction and magnitude in the dark. Eventually, we'll do this under illumination as well, but let's just focus in the dark.

In fact, we've already done this. I've already-- I've already tricked you into doing learning objective number 3 on your own, before even describing the math. But I will show you the mathematics as well so that you have the complete picture. We have the diffusion current. This is the essence of diffusion current. We talked about Fick's law as well for holes and for electrons.

We have our drift current. We spoke about the nature of the drift current as well for holes and electrons. And we know that by combining the two, we can describe the net current flow across a pn-junction. So by combining the two, by combining drift and diffusion-- drift and diffusion for electrons and holes-- we can describe the current flow across that pn-junction.

So when the electric field is large, the drift current term is going to dominate. If you have a large field, that's going to be the dominant current source if you will. And when the electric field is small, diffusion is going to dominate. So if we have a device like this right here. And if I told you that the built-in electric field was located pushed up toward the top 1/100 of the device. So it was located very close to the surface. You might surmise that the drift current is going to be having a large influence.

If you're a single electron, you'll feel the influence of the electric field near the front surface of the device. And deep within the bulk, the diffusion current is going to be driving the carriers toward that junction.

There's a relationship between the mobility and the diffusivity of carriers. It's known as the Einstein relation. And that's given to you over there on the right-hand side for a band conductor. Note that if you have-- this is an advanced concept. But if you have a dispersive hopping mechanism, for instance, you may need to become a little bit more sophisticated in how you relate the diffusivity of a carrier to your mobility. But let's assume that is valid for nice, well-behaved semiconductors. It's just a warning for those who work on organic materials. I'd be happy to talk to you more about that in a bit.

So again, we have Gauss' law. The question is, what is that electric field? What is  $\rho$ ? What is our built-in electric field?

Well, we know that the charge density is going to be comprised of the free hole density, the free electron density, the fixed density of our donor atoms. You could think of these as the phosphorus, the ionized phosphorus atoms, and our fixed density of ionized acceptor atoms. We can also think of this as our boron atoms and silicon. And so that is our fixed-- actually, not our fixed.

These are fixed charges. These are mobile charges. But under equilibrium, they've distributed themselves in a certain way. That is our charge density, our  $\rho$ . And that will figure into Gauss' law and allow us to calculate  $\rho$ .

And so in summa, we have here  $\rho$  as a function of  $x$ . We have an expression that relates the electric field to the density of dopant atoms inside of our material.

Note that we made one critical assumption going from here to here, where we went from the ionized donor and acceptor concentration to the total dopant concentration. We're assuming that everything is ionized. Again, because the ionization energy, because the binding energy of those free carriers to their dopant atoms is so small that under  $kt$ , under thermal energy at room temperature it's enough to dissociate the charge.

OK, so we've gotten to here. We can describe quantitatively using this approximation, using the box function approximation. We can describe the electric

field quantitatively. And now we have to get to the potential and find the electron energy as well.

So we do a little bit of accounting. If we want to account for all of the electrons flowing through our system, we would have to consider as well, in any voxel of our material, in any unit volume of our material, we have electrons going in, electrons coming out. And within it, we could have electrons being generated, say by light, or electrons recombining. Meaning they're losing their energy and falling back into a ground state where they're bound. And that's this  $U$ -term right here. And so the continuity equations are essentially a set of accounting equations that just describe the difference, the net change, going in and out.

If something changes on either surface, it's because you either added carriers or took them away. And the way you add is by shining light on your sample and generating more carriers.  $G$ , for instance. That's one way of generating carriers by adding light. Or recombination.

And one way of recombining is, for example, through a defect in our material, where the electron is moving along. It finds a defect and it falls back into a ground state.

So the continuity equations are nothing more, nothing less than housekeeping, bookkeeping. But it's very important as you'll see in the next slide right here where we combine five equations that describe current transport in a pn-junction. We have drift and diffusion up here. Those are the equations we just saw. We have the equation describing the electric field. And we have our accounting equations down here.

And if we look at these equations in unison, we'll notice that, oh, well, we have our hole current appearing twice here. We have our electric field appearing in two cases. Sorry. Back. Back. There.

We have our electric field appearing in those three equations right here. And we have a system of non-linear equations as a result. It is not possible to solve these analytically in their entirety. We'll have to make a series of assumptions to really get

to the full solution. But it's possible to solve them numerically using computer simulations.

This is important because we want to be able to define the current coming out of our solar cell device. Without solving these equations, we really don't understand what the current is out of a pn-junction, out of a solar cell under different bias conditions. That's why these equations right here are important.

What I want to do is not to just dwell on the current. I want to emphasize that to calculate the voltage across the semiconductor-- sorry, a semiconductor device, a pn-junction-based solar cell. To calculate the voltage across a solar cell, we have to understand a little bit more.

So far, we've been assuming that each electron is a unique individual. That an electron over here is a small perturbation to a larger system in that it will flow down based on that electric field.

For a voltage, we're really talking about an ensemble of electrons. All of the electrons in the system. And so we have to define some chemical potential for our system. We have to define some-- one could think of it as an average energy for our system. So let me define chemical potential for you in a semiconductor.

If we describe the semiconductor-- here's our valence band and our conduction band. This is our band gap right here in between the two bands as described by  $E_g$ , our conduction band, valence band. And these little red dots here are representing our covalently bonded electrons in the ground state at 0 Kelvin.

If we heat this material up just a little bit, there will be some fraction of carriers moving across into the conduction band just through simple probability. And we'll get to the precise equation that describes the probability distribution function in a few lectures. But for now, let's just assume that a certain number through thermal processes are able to be excited across the band gap. So these are thermally-excited electrons.

And we call these-- this is the intrinsic carrier concentration. So these carriers up

here are free to move around the crystal. They can conduct electricity. They can conduct charge. We could measure a current flowing through if we applied a bias voltage across material like this.

Those are our charge carriers. These holes as well. And so this is the intrinsic carrier concentration.

To give you an order of magnitude of the intrinsic carrier concentration in silicon, it's around  $10^{10}$  carriers per cubic centimeter. That's  $1$  over  $10^{22}$  per atom. So each atom of silicon is generating roughly  $1$  over  $10^{22}$  free carriers due to this process. Very small concentration of free carriers in the material. Around  $5/10^{22}$  atoms per cubic centimeter and only  $10^{10}$  free carriers per cubic centimeter due to this thermal process at room temperature. So it's a very small effect in silicon.

As you shrink your band gap, the energy necessary to excite across a band gap becomes less since you have more thermal carriers. So the chemical potential is describing the average energy necessary to remove an infinitesimally small quantity of electrons to the system.

And again, infinitesimally small quantity meaning it's a mere perturbation. You're not changing the volume. You're not changing the electrostatics of the system. You're just adding one electron to the system, or taking it away, and determining how much energy was required. And so we describe that chemical potential, we call it by a different name. We call it Fermi level, but it is the exact same thing. It's the energy necessary to remove that electron from the material.

So you can envision that it's going to be the Fermi level on either side of the pn-junction that will determine the voltage output of our solar cell device. And that's why we want to be able to calculate this.

So let's look, first off what happens to our Fermi level when we dope our material, when we intentionally add, in this case, boron atoms to make it p-type or phosphorus atoms to make the material n-type. What happens?

Well, we end up shifting our Fermi level toward the valence band or shifting the Fermi level toward the conduction band by the addition of holes or electrons. An easy way to think about it without getting into complicated semiconductor math is the following.

If I'm adding more electrons to my system, by doping at n-type, essentially I'm shifting the energy level up. It's an easy way to think about it. If I'm removing the electrons from the system by adding holes down here, then I'm shifting the Fermi level down. Easy way to think about it. We'll get to the math. Actually, if you're really curious, I think I included one slide of the derivation of the precise chemical potential so you can walk through that as well.

So voltage across a pn-junction. Under zero bias conditions, this is in the dark and without a battery pack attached to it. So this is an unperturbed pn-junction just in the dark without any external bias. We have the Fermi level constant throughout. Both the p-type and the n-type flat. Notice the bands are bending, so the distance of the Fermi level from the valence band here is smaller than the distance from the Fermi level to the valence band in the n-type material. That's because in the n-type material we have more electrons, and we're pushing the Fermi level higher.

The vacuum level follows these bands. It just happens to be way up there. And so the amount of energy necessary to remove the electron from the system, to move it to the vacuum level, changes from the p-type to the n-type. But for the purposes of our diagram right here, we're drawing the Fermi level constant throughout.

Now, we have that transition region, the depletion region, the space charge region-- all anonymous, same thing. We have that transition region here in the middle.

So if we begin quantifying the different parameters here, we have a Fermi level distance from the valence band. So that's this distance right here. We have the distance between the Fermi level and the conduction band in the n-type material. And then we have our built-in potential. And when we multiply our built-in potential by  $q$ , we get an energy. Essentially, an energy gain across that pn-junction. So that quantity here is equal to the band gap minus these two parameters. Minus this,

minus that. And so you can see that the built-in potential across the junction is benefited by higher doping. The higher we dope our material, the more we shift our Fermi level toward either band. And the greater the separation we get, the smaller this quantity is, the smaller that quantity is, and the more our built-in potential approximates the actual band gap of the material.

This built-in potential will relate to-- it won't be identical to, but it will be associated with our maximum voltage that we can get out of the device. And so we'll want to engineer our material in such a way so as to maximize that quantity. That's important.

The relation between our built-in potential and the dope intensity is shown here. For now, you'll have to take my word for it. I'm sparing you a lot of semiconductor physics. It's written on the next slide right here if you care to look in some detail. It's also described in, I believe, Chapter 2 in Martin Green's textbook. But for now, let's assume that the built-in junction potential is a function of the dopant concentrations just by our intuition.

If we're adding more electrons to one side, we're going to be shifting the Fermi energy up. OK, so the voltage across a pn-junction. Now, let's bias our device.

We have under zero bias conditions this expression. Sorry, there we go. Under zero bias conditions, we have that expression there. And under biased conditions, now we have an applied biased voltage, our  $V_{sub a}$ . We're applying a bias voltage. We've effectively shifted-- notice here, we've shifted our bands when relative to the other. So we've shifted this side up by a certain  $V_{sub a}$ .

And now if you'll notice the quantities here, we have a separation of the Fermi energy on one side to the other. There is a bias now across this device. There is a driving force for electrons to go and complete an external circuit, to travel through the external circuit. Because the electrons that are over here have a higher energy net than the electrons over there-- the ensemble, on average.

The transition region, likewise, will get smaller. Sorry for that animation. But if we

keep track here, the transition region becomes smaller under forward bias. Because we're depleting-- we're removing the amount of charge that was over here. We're squeezing it back. We're reducing that barrier height.

And so over here, if we go back to this diagram, you can now draw in what's written in these red circles. You can draw in the actual depletion width, the width of the space charge region on your diagrams, just like that. I'll give you just a second to complete that diagram there.

Under reverse bias, likewise, the width of the depletion region will increase. And the depletion region is increasing, the built-in charge is increasing, the amount of band bending is increasing, and the amount of drift current also increasing. So it all fits together. It's beginning to really come together nicely in one nice picture in our minds.

So yes, one question.

**AUDIENCE:** So I understand that for our solar cell, we wouldn't want to actually use a battery to drive current.

**PROFESSOR:** Let's get to illuminated current next class. For now, we'll just focus on the battery. Yeah.

**AUDIENCE:** So should we not quite yet understand why forward bias and reverse bias applies to [INAUDIBLE]?

**PROFESSOR:** Let's leave that for next class. For now, let's assume that the illumination current-- if you really want to satisfy your curiosity, your illumination current is going to be one additional arrow to this. It's going to be in addition to everything else that's going on. But the majority of the field is going to be created by what is doped into the material.

So think of the illumination for now as a small perturbation to the system. That's the easiest way to think about it. To justify to yourself why we need to understand first the solar cell in the dark, and then because of that small perturbation, we can treat it as a linear superposition of effects. And we'll add the illumination next class. But

bear with me in the dark first. Because if we really don't understand this, we're not going to understand fully how the solar cell operates in the light either.

So next, we'll draw the I-V response. We'll want to really get to this last point right here where we can draw the current voltage response. And we want to recognize that minority carrier flux is what's regulating the current.

So to do this well, to do this properly, we have to shift our focus from here where we were talking about ensembles and individual particles. Here we're going to be discussing in terms of carrier densities on either side of the junction. Densities of electrons and holes.

And unfortunately, I'm going to have to move rather quickly through these slides. This is the essence of why a solar cell behaves like a diode. And it's really something that is best done by studying on your own. I'm happy to walk you through the most salient points, the most important approximations that we have along the way, but this is best understood by going home, looking up the readings on stellar, and walking through the derivation yourself. It's not something that very easily I can convey a series of equations in the class.

So before we go into detail into current flows, I wanted to touch on this with the space charge region. We can describe the width of the space charge region now by the built-in bias across the junction. The applied bias right here and some fundamental material properties as well.

And this little epsilon right here is essentially the dielectric constant and the vacuum permittivity, a constant. And so you want to take that into account when you're running your actual calculations. It's very easy to be off on the width of the space charge region by several orders of magnitude if you don't do the proper accounting for those fixed variables.

And so if you walk through the equations to describe the width of the space charge region, you'll find that in a typical solar cell device, it's on the order of a micron. And this is related to one of your homework problems, so stash that away somewhere in

your brain. It's on the order of a micron. The width of that space charge region typically could be on that order. So it's going to be some multiple.

And the reason that's interesting is because the entire solar cell device is about 100 to 200 microns. That's for a crystalline silicon device. That means that in a crystalline silicon device, the diffusion current is what's driving most of the current flow inside of the solar cell.

If our solar cell is much, much, much thinner, say in the order of a micron, then our drift current would be dominating. This is a more advanced topic and we'll return to that when we describe the differences between thin film operation and crystalline silicon solar cell operation.

Device capacitance. For those who are running experimental measurements and want to determine the RC time constant necessary to have the device settle into a measurable state, that's there.

And the capacitance is described, again, by the various properties as well as the built-in potential which is related to the dopant density.

OK, so under zero bias, we have a concentration of holes on one side of our junction that's high. In the p-type material, the concentration of holes is high. And it's approximately equal to the acceptor concentration.

On the n-type side of our junction, the whole population is drastically reduced. And the flip side, our electron concentration is very high and it drops into the p-type side. So we have predominately holes on this side. Predominately electrons in that side. But a small concentration of holes on the n-type side and a small concentration of electrons in the p-type side. And we call this the minority carrier. And we call that the majority carrier. The majority carrier is in the majority. The minority carrier in the minority.

And an interesting thing happens when we bias our device. When we bias our solar cell device, populations of both carriers increase. But because this is on a log scale, we're increasing this-- shall we say the minority carrier concentration in an absolute

sense by a lot. And it's because of this drastic uptick in the minority carrier concentration right at the edge of the space charge region that we have current flow across that junction.

And that's described by a series of equations here. Let's see, the way to walk through the derivation, there's a series of approximations to make. Think of it in terms of electron and hole fluxes on either side of the junction. You can make a series of assumptions as to what currents matter and which don't. You can, of course, make the assumptions as to the charge distribution as well, fixed using that box potential. And you can consider the cases in which the minority carrier concentration here is dominating to be the regions of interest for a current generation inside of our device.

And so if we walk through, again the diffusion equation, the diffusion of carriers at the edge of the space charge region. And from the previous slides here, add our approximations in, we will ultimately derive an expression that has an exponential relation between current and our voltage.

And if we continue through the series of calculations, including the continuity equation for accountability, we wind up with an expression that looks like this right here, where the total current flowing through the device will be equal to the electron current at the edge of our space charge region coming from the p-type side. The hole concentration coming from the n-type side. The addition of the two together. And that's effectively, this equation right here, where we have an exponential relation between current and voltage.

So again, this we really need to go home and study. And if you'd like to do this pictorially, I provide you with that link right there so you can see it visually. If you're more of a math type, Chapters 3 and 4-- actually, Chapter 4 in Martin Green is probably the best place to go.

And the important thing to keep in mind is that in the pn-junction, the current flow across that junction is determined by the minority carrier current flow at the edge of the space charge region. And that's why we wind up with the exponential relation

between voltage and current.

I decided the best way to emphasize this voltage-current relation is actually to measure it, to run it. To do it. And we have around 10 minutes left before the end of class. Do you think that is time for our demo? Cutting it kind of short.

**AUDIENCE:** Probably wait for Tuesday.

**PROFESSOR:** Probably wait for Tuesday on the demo.

**AUDIENCE:** [INAUDIBLE].

**PROFESSOR:** So we're going to run the demos on Tuesday, I suppose. Because we're running a little bit short on time. I know David is really disappointed because he's been working hard to get these in perfect ship-shape condition. But we'll have another couple of days to work out some of the bugs in the software, so we don't need to restart it every time we take a new I-V measurement.

But by and large, what we'll do is we'll measure the current voltage relation for a real solar cell device. And we'll see that it definitely does follow, at least under forward bias conditions, this exponential relation. So as  $v$  goes forward, as  $v$ -- this  $v$  over here is our applied bias condition. As our  $v$  increases, we have that exponential current output from our device. As  $v$  goes towards a negative number, we have pretty much a flat lining of our current. It goes into a slightly negative condition and a flat lining of the current.

So if we look at this again right here, our  $I$  versus  $V$ , now we can plot the same equation. Or essentially, the same curve on all three of these. We'll want to plot the same curve-- this one over here. And for now, let's assume that this big lump over here is a constant. And so we just need to plot an exponential function, something similar to this right here. And under zero bias conditions, we'll be right there at 0, 0. Under forward bias conditions will be further up. And the reverse bias conditions will be down there.

And let me give you a second just to draw this down. And please do. We'll be

validating it to ourselves on Tuesday. My sincere apologies for not having enough time to really go into the demos as well. But suffice to say the following.

Under forward bias conditions, when we reduce the barrier height between the n- and the p-type side, we're now allowing that diffusion current from the n to the p to take over. And as we reduce the barrier more and more and more, we have this exponentially increasing density of electrons flowing through our system. And that's why we have this exponentially increasing curve here.

As we reverse bias-- our device, we're increasing the barrier height for the electrons to pass over. So our diffusion current practically vanishes. And our drift current stays, more or less, constant all the way throughout because there's only a finite carrier density, a finite minority carrier concentration inside of the p-type silicon. The thermally excited carriers for instance, that are finding their way to the junction and being drifted across. And that concentration is virtually finite.

At some point, you'll reverse bias this so much that the carriers will begin tunneling across from the valence band into the conduction band over here and you'll have a catastrophic failure of your device, but that's more of an advanced point. Yeah.

**AUDIENCE:** So does the x indicate the coordinate of I and V at steady state?

**PROFESSOR:** So the entire line represents the I-V characteristic under all biased conditions. The x represents the current and voltage for this particular operating point on the solar cell. On the I-V characteristic.

So if you're under forward bias condition. In other words, your v is positive, you will have a positive current flow through your device. Positive current flow, electrons flowing that way. And under reverse bias, notice the sign of the current is flipped because now the electrons used to be going that way. The electrons are predominately moving the other direction. The net current flow is in the opposite direction. And the voltage is also changing sign.

**AUDIENCE:** You can say, OK, I'm going to put myself in this voltage?

**PROFESSOR:** Exactly. And that's important because we want to be able to describe what our current voltage characteristic is of a solar cell because the product of the two is the power. For efficiency, we want to know what the power out of our solar cell is. And it's the product of current and voltage that will give us the power of our solar cell device.

Time for a few questions, actually. About five minutes of Q&A since we had to forgo the demo.

Promise me you'll do one thing. Promise me you'll go home. And sometime between now and Tuesday, you're going to read through these chapters and do the derivations that will work through to this ideal diode equation right here. Because this is pretty important. And you have to convince yourself that that's indeed the case.

I can wave my hands and phenomenologically describe, OK, we have an energy barrier. I kind of get it. I should have an exponential probability of passing over an energy barrier. At least from quantum mechanics that kind of makes sense. So I kind of get how if I forward bias my device, I'll have an exponentially increasing diffusion current. I get that if I go into reverse bias conditions, there's just a finite density of carriers, minority carriers, in my p-type material. If I'm not, say, shining a light on the material, I'm not changing that concentration by much. And I'm going to flat line.

Yes, they'll be drifting across, but they'll be limited more by their ability to reach the junction.

You can hand wave all you want, but this is really-- whoopsie-- the equations that describe the ideal diode equation. Those are really where it's at. With that equation, you can really understand how material properties will impact solar cell performance, let's say. Yes, question?

**AUDIENCE:** I have a question about the band diagrams. For all three diagrams, the energy levels [INAUDIBLE] the same. We're just changing where the n-type side is. Both of

them [INAUDIBLE]?

**PROFESSOR:** Exactly. Yep, absolutely. The point was here, what we've done for simplicity is shifting one side relative to the other. Yeah. In energy-- see, energy is a funny thing because you can redefine your zero. Yeah. So depending on where you're defining your zero point at, you can move things relative to each other. But let's assume that you're changing both sides relative to some universal ground potential that's off on an external component of your circuit.

**AUDIENCE:** [INAUDIBLE].

**PROFESSOR:** That's a great question. So the question was, when you dope your material, what are the experimental methods that you can use to really determine whether or not the atoms have occupied a substitutional position?

One of the methods is called Rutherford backscattering or channeling, IN channeling, where you introduce ions down your lattice. And if there is an atom here, for example, an interstitial site, it will scatter some fraction of those introduced ions back at the detector. And so channeling is one characterization method for determining the interstitial to substitutional ratio inside of a semiconducting material.

Another way that we have very strong evidence that boron is occupying a substitutional site and not an interstitial site is we can calculate the binding energy of this hole to the boron atom here on the substitutional site. In principle, if the interstitial was also-- if it was a charge to defect, we could calculate the binding energy of the charge to that defect. And the density functional theory could tell you which is the more likely given your experimental observation that you get about one hole for every one boron anatomy inside of your sample.

Boron has been studied to death in silicon. It's pretty well-known that it's substitutional. But if you're working with a new semiconducting material, you never know. You have to run the experiments. Yeah, question.

**AUDIENCE:** Under bias [INAUDIBLE] diagrams, are the p- and n-sides far away from the [INAUDIBLE]. Are those bands actually-- do they actually have a slope to them

because of the applied field?

**PROFESSOR:** Yeah. So the question was far away from the space charge region here, do these bands have a slope?

My argument would be that if we go back to the way we derive-- there we go. The way we derive this band to begin with, it's predicated upon an electric field, which is predicated upon a charge distribution. So the biggest question is, what does this real charge distribution look like?

Most of the time, it's relatively concentrated to the near space charge region. If you get too far away, OK, yes, it decays exponentially. But it falls below the background intrinsic carrier concentration and effectively doesn't matter.

**AUDIENCE:** Under applied bias, [INAUDIBLE]?

**PROFESSOR:** Yes.

**AUDIENCE:** Usually they're just drawing it flat, but is it such a small effect they're just drawing it flat [INAUDIBLE]?

**PROFESSOR:** Yeah. So under applied bias, what happens to these charge distributions?

Well, if you reverse bias it, you're essentially increasing the amount of charge on either side of the junction. If you forward bias, you're reducing it. So under forward bias, probably you wouldn't see the effect you're describing.

Under reverse bias, the width of the space charge region, let's say, increases from, let's call it 1 micron to 3 microns. And the thickness of the entire device is 200 microns. So still, I think it would be a relatively small effect several 10's of microns away from the junction. It really depends on the length scale, the geometry of your device relative to the length scale of your space charge region.

Good? Well, to give you time to reach your next class, thank you. We'll come back on Tuesday, and we'll have a great demo set up for you.