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PROFESSOR: Hello, everyone. Today we'll talk about doping, which is the process of intentionally adding impurities to a semiconductor in order to change its electrical properties. Doping is a critical process in the tech world.

It's used in manufacturing almost all semiconductor technologies today. Without doping, the solar industry would not exist, but even though doping is common today, the effects of impurities confused semiconductor physicists in the 1950s, who had trouble reproducing results. Eventually, they realized that contamination levels, as low as 1 in a billion, were vastly changing the electrical properties of their samples.

Today, we'll show you how this works with a very simple experiment. We'll be measuring the electrical conductivity of two silicon slabs using an ohmmeter. One is doped with impurities, phosphorus in our case, and the other is ultra-pure, or what we call intrinsic.

Let's go over our experiment. We'll start with a slab of silicon, which we attach metal contacts to. We'll use an ohmmeter, that we connect to our sample with metal wires to measure the conductivity. The conductivity describes how well electricity can flow through the material.

The measured resistance from our ohmmeter is related to the inverse of the conductivity. The resistance also varies according to the physical size and shape of our sample, which adds a length over area term to our equation, like so.

Rearranging this equation, gives us what we're looking for, the conductivity. Let's measure our samples, and estimate the conductivity.

Here are two samples, notice that the doped sample looks identical to the intrinsic one, or undoped sample. Because we've only added trace impurities, the optical properties are nearly identical between the two samples. Let's hook up the ohmmeter to the intrinsic sample. We can see that the resistance is 130,000 ohms,

which roughly corresponds to a conductivity of 0.0002 inverse ohm centimeters.

Let's compare this to the doped sample. We read a resistance of 34 ohms, which corresponds to roughly 0.6 inverse ohm centimeters. So we can see that the dope sample is around 3,000 times more conductive. But why would adding small amount of our doping, about one phosphorus atom for every million silicon atoms, make our sample 3,000 times more conductive?

On the periodic table, we see that silicon is in the fourth column, which means it has four valence electrons. Phosphorus, which is just to the right in column five, has five valence electrons, one extra compared to silicon. I'd also like to point out boron in column three, with one fewer valence electron than silicon. Later, I'll explain what happens when you add boron as a dopant.

We'll start with a 2D representation of a single silicon atom, with the nucleus in the center, and its four valence electrons in a silicon crystal, each silicon atom bonds to four other silicon atoms around it. These rigid covalent bonds, shown here, keep all of the electrons effectively immobile, and are therefore, unable to aid in the full electricity. Our intrinsic silicon, or undoped example, has this material structure, which is why it has a very low conductivity.

Let's quantify this relationship between conductivity and mobile electrons.

Conductivity is defined as n times μ times e . n is a number of free or mobile electrons. Again, in this drawing of intrinsic silicon, all electrons are covalently bonded so there are no mobile electrons, and n is 0.

The symbol μ represents the mobility, a material parameter which you can look up in a textbook, or online, and it basically describes how well the charge can move around in the material. e is simply the amount of charge that each mobile particle possesses, which in all of our cases, is simply the charge of an electron. So let's ask, what happens when we add dopants like phosphorus and boron to the silicon lattice?

Now, let's dope our material by replacing one of the silicon atoms with a phosphorus

atom. First, we'll remove a silicon atom, and for contrast, we'll dim the background silicon lattice so we can emphasize the dopant atom. Notice that the inserted phosphorus atom has five valence electrons, four of which form four covalent bonds with their neighboring silicon atoms and are immobile.

The fifth electron is not bonded, and as a result, is free to move around the lattice. When the negatively charged electron leaves, the phosphorus dopant is now positively charged. So we see that each phosphorus atom that is added will contribute a single mobile electron. So basically, in our case, the number of mobile electrons is roughly equal to the number of phosphorus atoms in our system.

Now, let's remove our phosphorus atom and put in an element with three valence electrons, such as boron. We see here that boron lacks the necessary valence electrons to form covalent bonds to its four neighboring silicon atoms. This missing electron is actually referred to as a hole, and is represented by an H^+ symbol.

This hole acts as a mobile positive charge because it can swap places with neighboring covalently bonded electrons and move around the crystal. When the positively charged hole leaves its nucleus, the boron atom becomes negatively charged. So we've demonstrated that introducing atoms that have one more, or one less, valence electron than silicon, can add mobile charges and make the material more conductive.

In our examples, the conductivity of silicon is proportional with the density of either phosphorus or boron atoms. While phosphorus and boron both affect the conductivity in a very similar manner, they introduce mobile and static charges of the opposite sign. Phosphorus introduces mobile negative charges and immobile positive charges, while boron creates mobile positive charges and immobile negative charges.

This subtle difference between phosphorus and boron dopants will be crucial in our final video when we discuss solar cell operation. Today we learned that we can use doping to control the conductivity of semiconductors by changing the number of mobile charges in the material. When we look at the range of conductivities that

silicon possess, it is truly amazing.

Through doping, we have a very powerful way of varying the conductivity of semiconductors. This is something that is not possible in other classes of materials, like metals. Next time, we'll be discussing how light can be used to generate mobile charges in silicon, so watch our next video. I'm Joe Sullivan, and thanks for watching.

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