Silicon - The Internet's Favorite Element: Crash Course Chemistry #35

Crash Course: Chemistry
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If they know it at all, most people know silicon from the valley in California that bares its name. The birthplace of modern computing where technological dreams became reality. Where brilliant twenty-somethings became millionaires.

But we chemists know silicon first and foremost as the most abundant element in the earth's crust. Oxides of silicon, known as silicates, make up sand, which covers not only every desert and shoreline on the earth, but also most of the ocean floor. Silicates also include quartz and most types of clay and they're found in living things, like little spikes and nettles. And as a polishing agent in toothpaste. It's everywhere!

And, of course, because of their uniquely wonderful chemical properties, crystals of elemental silicon form the basis of semiconductors. These crystals can be combined to make diodes and transistors acting essentially as chemical on/off switches that make binary code, and, therefore, computers possible.

Fascinatingly enough, only a few minor differences in atomic arrangement allow an element found on the bottom of the ocean to make the computer that you're watching me on possible.

As with carbon, everything comes down to the network these atoms form. Once you learned the chemistry of these networks, you'll come to understand why glass is glass and clay is clay. You'll understand what chemists mean when they talk about 'doping' and you'll finally get why a valley in California is named for arguable one of the most intriguing element in the universe.

[intro music]

This sand, and this glass, and this quartz are basically the same thing, just the atoms arranged a little differently. The chemical name of this substance is silica made up of silicon and oxygen in a 1:2 ratio. For that reason we say that the chemical formula of silica is $SiO_{2.}$ Even though it doesn't actually exist as separate individual molecules. Like graphite and diamond, the two forms of pure carbon, silicons and it's oxides are network solids.

And also like graphite and diamond, the different forms that they take are all about bonding differences. The form of the silica that makes sand, is exactly the same as the form that comprises quartz. In fact the silica in sand is basically just tiny bits of quartz.

Silica structure is based on a tetrahedral arrangement of a silica atom bonded to oxygen atoms. That's right - 4, not 2. The trick is that each of the oxygen can form two bonds, so they also bond to another silicon atom on the other side. So each silicate is bonded to 4 oxygens, while each oxygen is bonded to silicons. Si_2O_4 simplifies to SiO_2, and that's where we get the formula.

As the molecule continues to build on itself, it can make various crystal structures depending on the orientation of the little tetrahedrons. These are different forms of quartz, clays and other minerals. They can make two dimensional forms as sheets, or three dimensional crystals. And each form has its own properties and behaviors.

Ceramics, and other clays, get their strength from the two dimensional types. When the clay is wet, silica sheets move around freely in the clay and as it dries they move closer to each other and bond to together forming a rigid framework. This resulting composite is extremely hard and heat resistant. Both of these properties make ceramics useful in tons of ways that you've probably been exploring since you were a toddler and got your first box of modeling clay.

Three dimensional silicates can take lots of shapes, too. Although not all of them are true crystals. Glass is an enormously important example of a three dimensional silica based amorphous solid. It's worth mentioning here, even though its not a crystal because it's molecular structure is extremely similar to the structure of quartz, just not as orderly. The arrangement of silicon and oxygen in quartz is very regular and rigid. The molecular structure of glass, on the other hand, looks like Mother Nature tried to build a quartz crystal while she was a little bit drunk.

The atoms are attached in random numbers and shapes, creating a gradual structure with no definite order. This is why glass can be formed into almost infinite shapes when it's heated while quartz keeps it's characteristic crystal shape.

Because it's an amorphous solid with bonds of varying strength, glass doesn't have an exact melting point. Instead, it softens when it as heated and becomes honey-like, except extraordinarily hot and not sweet at all. Quartz doesn't do that. It's melting point is much higher but it melts at an exact temperature and has no pliable in-betweeny state.

Like all silica crystals, quartz, glass and ceramics are electrical insulators, because they have no free electrons to transfer charges over a distance. The atoms have 4 valence electrons and they form 4 bonds so all the electrons are perfectly well used. For this reason, these materials are used widely as insulators in electrical applications. Ceramics, for example, are used to hold live wires and power lines and to make capacitors, which are basically layers of electrical conductors separated by layers of insulators.

But all of these silica based network solids I talked about so far contain both silicon and oxygen atoms. Crystals made up of silicon are insulators too, in their peer state, but they can be made to transfer electricity by a process called doping. And no, we are not gonna make a Lance Armstrong joke. We might make an analogy though - it's like much like a perfectly fit athlete injecting himself with all kinds of weird foreign stuff.

Silicon doping involves incorporating impurities into a crystal that mess up its electron balance. It can do that in one of two ways. If the impurity is an element with more electrons than silicon has, like Phosphorus or Arsenic, the resulting crystal will contain excess electrons. But, if the impurity is an element with fewer electrons, like Aluminum or Boron, then it leaves holes where electrons are missing from the normal structure.

Doped silicon crystals are known as solid-state semiconductors. Those doped with elements that add electrons are called N-type, or negative semiconductors, because of the resulting charge from the additional electrons. With N-type semiconductors, the charges carried by the excess electrons and because there's no room for them to integrate into the structure, they move freely about the crystals.

Similarly, crystals dope with elements that create an electron deficiency are called P-type, or positive semiconductors, because they have a more positive charge than pure silicon would have on its own. P-type semiconductors work a little differently. Because they have empty spaces available here and there, the electrons that are normally part of specific silicon atoms are able to jump around from one atom to another. Each jump fills a hole and creates a new one, allowing another electron to move in the same way.

So if both N-type and P-type crystals are both electrical conductors, why do we call them semiconductors? Well, thank you for asking.

The reason semiconductors are so valuable is that they have the amazing ability to conduct electricity freely under some conditions, but completely refuse to conduct it under other conditions. So yes, they are partial, or semi conductors.

So these properties become most useful when a P-type and N-type semiconductor are placed next to each other to form a diode. Because their charges are opposite, the free electrons in the N-type are attracted to the P-type and tend to migrate to its holes. And when an electrical field is applied to this arrangement, so that the N-type is attached to the positive terminal, also called the anode, and the P-type is attached to the negative terminal, or the cathode, all of the free electrons are pulled completely into the N-type.

These free electrons are attracted away from the holes, not into them, so any further motion is blocked and no more current passes through the diode. This type of arrangement is called reverse bias. However, just by reversing the polarity of the electron flow, if you will, we can create a very different situation.

If the N-type side is attached to the negative terminal, and the P-type side attached to the positive terminal, then the electrons are pulled in to the P-type making this part an electrical conductor again. This process called forward bias is self perpetuating, it allows the current to readily flow through the diode. The fact that this conduction only works in one direction is extremely useful!

You know AC and DC right? Back in Black for those about to rock? AC is alternating current, where the flow of electrons alternates in one direction to another. In DC, or direct current, is exactly what it sounds like, the electrons go directly where they're headed without backtracking.

And simple arrangements of diodes can be used to convert AC to DC like in this power supply for my laptop. P and N-type semiconductors can also be combined in sets of three. These are called transistors and they've completely revolutionized the field of electronics, also the entire world since they were invented in 1947. One of the main functions of a transistor is to switch an electrical signal on and off. Basically when it allows a current to flow in the forward bias direction, the switch is turned off. When the current drops below the minimum the switch is turned off. This switching is the basis of binary code. Ones and zeroes representing the on and off states of the transistor.

And that code is how we store and process information using computer chips, which are just collections of transistors working together. Such a tiny simple device made mostly from one single element, and yet revolutionizing our entire world. That my friends is how Silicon Valley got its name and how network solids of silicon made this conversation we are having today possible.

Thanks for taking advantage of all your tiny transistors today by watching this episode of Crash Course Chemistry. If you paid attention you learned that sand, and glass, and ceramics, and computer chips, and must more are all really just different types of network solids that can be formed by silicon and its oxides. You learned the differences in their arrangements and bonding of atoms, and you learned how those differences result in wildly varying properties among the solids. You also learned what a solid-state semiconductor is, both P-type and N-type, and you learned how they can be combined to create diodes and transistors. Finally you learned how transistors are combined to make computer chips, and how their switching mechanism tells computers what to do. I don't know about you, but it blows my mind!

This episode was written by Edi González. And edited by Blake de Pastino. The chemistry consultant was Dr. Heiko Langner. And the script supervisor was Michael Aranda, who was also our sound designer. It was filmed, edited, and directed by Nicholas Jenkins. And our graphics team, as always, is Thought Café.