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Chapter 2

ELECTRO-MATTER

It's a stormy morning, and the clock radio wakes you for school. You turn on the lamp and crawl out of bed. The buzz in the bathroom tells you that your big sister is shaving her legs.

You pound on the door. "Hey, it's my turn!" you complain. "You should've done that last night"

"Be patient," she whines. "I'll be out as soon as I dry my hair."

You reply with a special insult you had saved for the occasion, but the whir of the hair dryer drowns you out. Grumbling, you head for the kitchen. You get some waffles out of the freezer and pop them into the toaster. Its coils glow red. You put some hot chocolate mix into a cup, add water, put it into the microwave oven, and push a few buttons.

By the time your sister dashes in, you're eating breakfast and the sound of your favorite group, the Beethoven Blasters, is blaring from the CD player. Your sister hates them. "That's what you get for hogging the bathroom" you say with a grin.

She shows you a computer diskette and holds it just out of your reach. "And this is what you get for hogging the computer" she snarls. Your multimedia presentation for science class is on that disk. How could you have forgotten to take it out of the disk drive? She hands you "Mangled Mozart" by Danny and the Declassifiers. "If you ever want to see this diskette again, take that CD out and put this one in," she orders.

"One of these days, I'll show you," you threaten as you take the CD and diskette from her hands. "Just for one day, I wish you would have to live without your razor, your hair dryer, your CD player, and your computer." Suddenly, a lightning bolt flashes across the dark sky, and a crash of thunder shakes the house. The lights flicker, and then the power goes out.

"What did you say?" your sister asks, eyes widening. "I wonder how long this will last."

"Maybe for a whole day" you gloat. "At least I've had my breakfast."

CONDUCTORS, INSULATORS, AND SEMICONDUCTORS

What if the electric power would go off for a whole day, not just in your home but everywhere else in your town? You'd certainly discover how important electricity is in today's world. Still, you would probably never stop to think of the materials that make it all possible--unless you had read this chapter. Over the next few pages, you'll read the inside story of this electric world. You'll discover the Techno-Matter behind the electrical and electronic machines that we would never want to live without.

Of all the forms of energy that people use to run their machines, electrical energy is the most versatile and controllable. Electrical energy is carried by an electric current, or the flow of electrical charges. Our electrical and electronic machines depend on getting the electric charge to flow--or not flow--exactly where we want it. To do that, we use different kinds of materials with different kinds of microstructures. We classify those as conductors, insulators, and semiconductors, according to the way an electric charge passes through them.

Electricity in Matter Electric forces create the bonds between atoms in molecules or in a material. They also hold each atom together. As tiny as an atom is, it contains even smaller particles held together by electricity.

To understand the electrical properties of materials, we have to begin with those smaller particles. Each atom has a central part called a nucleus. The nucleus contains most of the atom's mass and is made up of two kinds of particles, protons and neutrons. Each proton carries an electric charge of a type scientists call positive. Neutrons carry no electric charge. The number of protons determines the type of atom. Carbon, for example, has six protons in its nucleus.

Surrounding the nucleus like a cloud are very light particles called electrons. The electron cloud is several thousand times as large as the nucleus. If the nucleus were as big as a basketball, then the electron cloud would be a ball a mile across. Each electron carries the same amount of electrical charge as a proton, but of an opposite type that scientists call negative. An atom is electrically neutral, because it has the same number of positively charged protons and negatively charged electrons. For instance, an oxygen atom has eight protons and eight electrons. Adding charges of +8 and-8 gives zero.

When electrically charged bodies come close to each other, they pull on (attract) or push against (repel) each other. Pairs of like charges (both positive or both negative) repel, and pairs of unlike charges (one positive and one negative) attract. The closer together the charges are, the stronger the force between them. An atom stays together because its negatively charged electrons are attracted to its positively charged nucleus.

Because electrons are light and relatively far from the nucleus, the holding power of the electrical force is not always enough to keep every electron in its place. It isn't hard for one or two of the outer electrons to be pulled away from an atom. Likewise, it isn't hard for an atom to attract an extra one or two outer electrons. In many materials, neighboring atoms can share pairs of their outermost electrons.' That sharing creates the bonds you read about in the previous chapter.

Electrical Conductivity and Resistance When electric charges move or flow from one place to another, scientists call that an electric current. In some materials, electricity flows easily. They are said to be good conductors or to have high electrical conductivity. Other materials do not allow electric charges to flow easily. They are said to be poor conductors or to have high electrical resistance. If they block the flow of current almost completely, they are called insulators.

What makes one material a good conductor while another is an insulator? It is the atoms or molecules in the material and the way they are arranged. In other words, it is the microstructure.

Metals are excellent conductors of electricity. They carry an electric current easily, without much loss of energy. Each atom in a metal has electrons that it shares with all the other atoms in the crystal. Because those electrons are shared, they easily move from place to place. When their motion is in one direction more than another, the metal is carrying an electric current. For example, shared electrons flow in the copper wires that carry the electricity from your wall sockets to your appliances. Those shared electrons are commonly called "conduction electrons."

In contrast, the rubbery material around household wires is a good insulator. It protects you from the electricity in the metal. Many materials besides rubber, including glass, ceramics, plastic, and fabrics, are also insulators. They block the flow of an electric current because they have almost no conduction electrons. Nearly every electron in an insulator is bound tightly to its atom and molecule, so it is very hard to drive an electric current through.

Semiconductors Materials called semiconductors also have high electrical resistance, but not nearly as high as insulators. They have a few conduction electrons, but not very many. It takes a lot of electrical pressure, called voltage, to drive an electric current through them. The most important electrical property of a semiconductor is not its conductivity, but rather the way that its conductivity changes under certain conditions. Small changes in their microstructure can mean big changes in the way they carry electricity.

The most commonly used semiconducting material is silicon. Like carbon, silicon atoms have four bonding electrons. Unlike carbon, the atoms of silicon do not form graphitelike crystal structures with one weakly bound electron per atom. Nor are the bonds in their crystal structures as powerful as the carbon bonds in diamonds. Electrons in silicon bonds can be shaken loose fairly easily by the normal vibration of the atoms. When that happens, they become conduction electrons.

For each conduction electron that shakes loose, a silicon atom is left with an empty bonding site. We call that empty site a "hole." As soon as the hole forms, the atom it leaves behind becomes a positively charged "ion" and that has powerful attraction for nearby electrons. Usually, one of the electrons from a neighboring atom falls into the hole soon after it forms. Thus a hole disappears from one atom and reappears "next door." It behaves as if it is a positive charge, moving from one spot to the next through the silicon.

Pure silicon always has an equal number of conduction electrons and holes. When it warms up, the atoms vibrate more; so at a higher temperature, it has more conduction electrons and holes. New pairs of conduction electrons and holes form constantly, but their number does not grow indefinitely. Sometimes a conduction electron falls into a hole and both disappear. That is called "annihilation." When the electron-hole annihilation rate matches the creation rate, the number of conduction electrons and holes remains steady.

When people change the microstructure of semiconductors in small but carefully controlled ways, the movement of conduction electrons and holes--and therefore the conductivity--can change dramatically. For that reason, pure silicon turns out to be far less useful than "doped" silicon--silicon with small amounts of added impurities.

Let's examine what happens when we add a small amount of phosphorus or aluminum to a silicon crystal. A phosphorus atom has one more proton in its nucleus and one more electron than a silicon atom. The extra electron gives a phosphorus atom five bonding electrons. As an impurity in silicon, the phosphorus atom easily fits into a spot in the crystal arrangement, replacing a silicon atom. The replacement is not perfect, however, since only four of its five bonding electrons can find a place to connect. The fifth electron either becomes a conduction electron or fills a hole. Thus adding phosphorus creates a semiconducting material with an excess of conduction electrons and very few holes. We call that an "n-type" semiconductor because it has more negative than positive charges that are free to move.

Adding aluminum, which has one proton and one electron fewer than silicon, has the opposite effect. It also fits easily into the crystal arrangement, but with only three bonding electrons, its spot is one electron short. Soon a conduction electron comes along and is trapped, leaving a hole somewhere else with no electron to match it. The presence of aluminum atoms has created "p-type" silicon, a semiconducting material with positively charged holes but few conduction electrons.

SEMICONDUCTORS IN ELECTRONIC DEVICES

Semiconductors get down to business as Techno-Matter when people make them into electronic devices like diodes and transistors.

Diodes, One-way Electric Current Valves Putting a piece of p-type silicon next to a piece of n-type silicon creates a device that allows current to flow in one direction but not the opposite. Electronic engineers call that device a diode. The region where the two different types of material are joined is called a junction. Let's look at how it works.

Diagram A shows a battery with its positive terminal connected to the p-type portion of the diode and its negative terminal connected to the n-type. Since like charges repel, the positive terminal drives holes in the p-type semiconductor toward the junction. Likewise, the negative terminal drives conduction electrons in the n-type semiconductor toward the junction. There, the electrons and holes combine.

Meanwhile more conduction electrons flow from the negative terminal of the battery into the n-type material. Those replace the electrons that fell into holes at the junction. At the same time, the positive terminal of the battery attracts electrons from the p-type material. This creates holes to replace the ones filled by electrons at the junction. That means when the battery is connected as shown, electricity can flow steadily through the diode.

Now suppose the battery terminals are connected in the opposite direction, as in diagram B. Since unlike charges attract, conduction electrons flow away from the junction and toward the positive battery terminal in the n-type material. Holes in the p-type region also move away from the junction. With neither electrons nor holes at the junction, current cannot flow across it.

Transistors, Electric Current Controllers A more complex arrangement of semiconducting materials is a device called a transistor. A common type of transistor resembles a sandwich with n-type material on the outside and p-type in the middle (or the other way around).

Diagram C shows the way an n-p-n transistor operates. A small change in voltage across the p-n junction produces a large change in the current through the whole device. Thus a transistor can be used as an amplifier--a device that produces large signals from small ones. Or it can be a controllable on-off switch, allowing or blocking the flow of current according to the "instruction" sent by a voltage signal across the p-n junction.

When used as a controllable switch, a transistor becomes the most important device in an electronic digital computer. Modern computers have millions or even billions of transistors, switching on and off millions of times in the blink of an eye. They are amazing devices, and the way people make and use them is the next chapter in the story of Techno-Matter.

PHOTO (COLOR): Modern city life would not be the same without electricity: no street-lights or traffic lights or neon signs; no elevated railways or subways; no elevators in tall buildings; no telephone, radio or television...

PHOTO (COLOR): Metals conduct electricity well. Pictured here are some everyday items that would serve as excellent conductors: an iron nail, a gold ring, some braided copper wire, a keychain with a silver tag, and a small piece of aluminum tubing.

PHOTO (COLOR): Many common materials are insulators, which means float they do not carry electricity well. Those include wood, rubber, plastic, glass, and fabric.

PHOTO (COLOR): These ultrapure cylinders of silicon are semiconductors ready to be transformed into thousands of computer chips. First they will be sliced into thin wafers, Then special machines put even thinner layers of other materials on the silicon or change its microstructure by carefully adding impurities, creating patterns for tens or hundreds of electronic chips on each wafer.

DIAGRAMS: A diode is formed at the junction of an n-type region and a p-type region of a semiconductor. It permits electric current to flow only when a power source, such as a battery, is connected in the "forward biased" direction (diagram A), and blocks current from flowing in the "reverse biased" direction (diagram B).

DIAGRAM: A transistor is formed from two diodes back-to-back in an n-p-n or p-n-p sandwich.
