Study Questions
Article: ***Computer Chips***
Chem Matters, Dec. 1997

______
10 pts

Name ______________________________
Period ________ Date _____________

Integrated circuits and computer chips are based on a device called a *transistor*, which was invented at Bell Labs in Murray Hill, a section of Berkeley Heights just a few miles from here. They are primarily composed of silicon, a metalloid that forms a network covalent solid with electrical conductivity that can be controlled using chemistry. Read the article explaining what they are and how they are made and answer the following questions.

1) What are transistors and how do they work?

2) What is an integrated circuit?

3) Silicon is a "network covalent solid" like diamonds, which are made of carbon rather than silicon. Describe how the atoms are bonded—i.e. the *electron and molecular geometry* at each Si atom.

4) One property of metalloids is slight electrical conductivity. How can the number of charge carriers be increased to improve conductivity—what is added to the silicon? Give two examples.

5) What is the ratio of doping atoms to silicon atoms (1 part–one doping atom–in how many silicon atoms)?

6) In an n-type semiconductor, electricity is carried by the extra valence electrons. In a p-type semiconductor, the positively-charged "hole" left by the missing valence electrons moves to conduct electricity. This is like having one empty seat in a movie theater. How would the empty seat "move" [hint: if the person next to the empty seat moves into it, what happens to the location of the empty seat]? What subatomic particle must be moving into the empty hole to "move" the hole [remember: positively-charged nuclei can't move]?

7) Where is the production of computer chips carried out? Why is it important to use such high-tech conditions?

8) What is the ratio of impurity atoms to silicon atoms in purified silicon?

9) The photolithography used to create the circuits on the silicon wafer is a complicated process. In short, masks are used to “expose” areas of the silicon wafer to be doped and mask those areas not to be doped. How many masking layers may be used on a typical chip? How are the doping atoms (“impurities”) put into the silicon? What keeps them from infiltrating the regions that should not be doped?

10) Why do the photolithography methods used for these chips not work well and reach the end of their usefulness? [What happens to the edges of the components?]

Computer Chips

Loaded Bits

by Roberta Baxter

They are everywhere these days! Little bits of silicon that run our calculators, computers, CD players, even the fuel injection system of our cars. How did these minuscule scraps become so important and how are they made?

First, some electronic lingo. Transistors are devices that control current between two terminals, or, in other words, they control and amplify the flow of electrons. Integrated circuits, or ICs (as they are called), are organized groups of interconnected components contained on a single piece of a semiconductor, usually silicon. The components include transistors, capacitors (which store electric charge), and resistors (which control the amount of current).

As integrated circuits became more complex, they also got more expensive to produce and more specialized. The solution to the problem came in the form of the microprocessor, introduced by the Intel Corporation in 1971. A microprocessor can read and respond to instructions to carry out different tasks. It is also contained on a single chip, so it is sometimes called the “computer on a chip.”

Computer chips are made of silicon, an element found in common sand. Silicon is the second most abundant element in the Earth’s crust, 27.7 % by weight. Only oxygen with 46.6 % by weight is more abundant. Silicon is the foundation element for most rocks and minerals. Elemental silicon has a gray luster and forms crystals in the tetrahedral configuration similar to a diamond. Silicon dioxide, SiO_2, is found as quartz or sand.

With 14 electrons, silicon has exactly the correct properties to be the main ingredient for use by the electronic industry. Silicon has four electrons in its outer energy level, so it can form bonds with four other atoms. The silicon crystallizes in the stable “diamond” formation, with a center atom and four others in a tetrahedral shape (see figure 1). In silicon, some of the electrons will move out of the lower energy state into a higher level. However, the number of charge carriers moving between energy states in silicon can be increased by doping the silicon with other atoms—adding a tiny but controlled amount of an impurity to enhance certain properties. It takes only a minute amount of doping, one part per 10 million.

If an atom with only three valence electrons, such as boron or gallium, is next to a silicon atom, there is a hole or gap in the outer shell. This is called a p-type semiconductor. If an atom with five valence electrons, such as phosphorus, is next to a silicon atom, there is an extra electron that will move easily. This is called an n-type semiconductor. Only movement of electrons from an n-type to a p-type forms a current. When two n-parts are separated by a p-section, a transistor is formed.

Computer chips must be produced in the cleanest atmosphere possible. The circuit elements on the chip are so tiny that one speck of dust will make a chip useless. The production is done in a clean room. Air is filtered and forced to flow from the ceiling to tiny holes in the floor to force out any particles of dust. Workers wear “bunny suits” to keep dust from their clothing or skin particles from contaminating the chips.

Silicon is purified until it is 99.9999999 % pure: Only one atom in a billion is not silicon. Then a single large crystal of silicon is formed. The silicon is heated to just above its

The History of the Transistor

The first transistor was invented in 1948 by American scientists John Bardeen, Walter Brattain, and William Shockley while working at Bell Laboratories. Transistors used small crystals of semiconductors to control and amplify the flow of electrons. They soon replaced vacuum tubes. Their great advantage was that they were much smaller than tubes and consumed much less power. This led to the development of the pocket-sized transistor radio. Bardeen, Brattain, and Shockley received the 1956 Nobel Prize in Physics for their invention. 1998 is the 50th anniversary of the transistor.

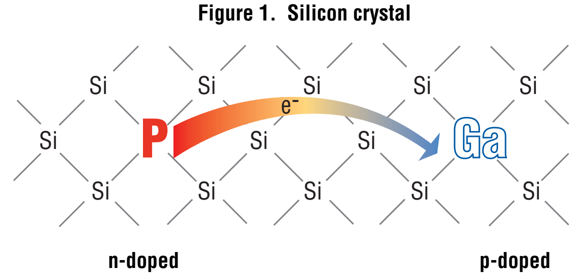
melting point, about 1500 °C, and then a tiny seed crystal of pure silicon is dipped into the molten silicon. The seed crystal is rotated and pulled from the mass, and it grows as a single large crystal of silicon. The crystallized silicon is in the shape of a long cylinder, 4 in. (10 cm) in diameter and perhaps 12 in. (30 cm) long.

Slices are cut from the cylinder, like slicing bologna, to form the wafers that the chips will be built on. When the silicon wafers are cooked in an oven at 1000 °C, they react with the oxygen in the air to form silicon dioxide, SiO_2, which is similar to rust on a metal object. The SiO_2 does not conduct electricity; this process prevents the chips from short-circuiting once they are finished:

$$Si(solid) + O_2(gas) \rightarrow SiO_2(solid)$$

Computer chip design engineers develop sheets of circuits to be applied to the wafer, one layer at a time. The large-scale designs are reduced through a set of lenses to create a chip-size pattern. There are about 200 chips on each wafer. A special layer, one micrometer (1μm) thick, of a photoactive chemical emulsion is spread on the wafer. The emulsion is most commonly a polymerized polyvinyl alcohol. When irradiated with ultraviolet light, these long chains form cross-links that produce an insoluble network. The wafer is placed in a 60 °C oven to cure the emulsion and then cooled.

Figure 1. Silicon crystal



Doping silicon and creating n-type semiconductors by adding phosphorus and p-type semiconductors by adding gallium. The flow of electrons is shown by the arrow.

A mask is made over the wafer. The mask has cut-out places where transistors and connections will be on each chip, much like a stencil. The wafer is exposed to ultraviolet light, and the parts that are exposed harden. The unexposed parts are washed away with photographic developer.

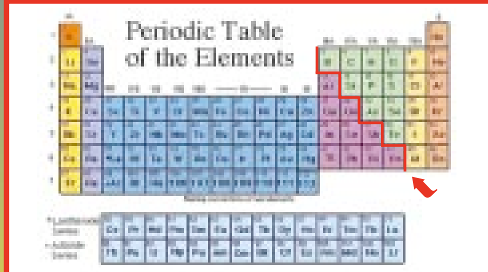
The etching process is next. The wafers are immersed in a solution of ammonium fluoride and hydrofluoric acid. This caustic solution removes the silicon dioxide layer that was under the unexposed photoresist. The hardened photoresist layer is removed with hot sulfuric acid and scrubbing. This layer consists of bare silicon where the chip was exposed and etched, but inert silicon dioxide where it was masked. The wafer is now clean and has its first layer.

Next is the doping step. The impurities of boron or phosphorus will diffuse into the wafer at the parts that are not covered by the silicon dioxide layer. The wafers are placed in an oven filled with PH_3, or B_2H_6 gas. The dopant atoms infiltrate the silicon of the wafer to form the n-type or p-type transistors.

Sometimes a process called ion implantation is used to introduce the dopant into the chip. The dopant atom is transformed into an ion and accelerated so that it shoots into the silicon layer.

These steps of photolithography and doping are carried out layer by layer until the chip is complete. The chip may have up to 20 layers. Tests are performed to ensure that the manufacturing process has been done correctly.

The wafer is cut into the separate square chips with a diamond saw. A final process is carried out under a microscope: tiny connection wires are inserted. The chips are put into plastic cases so they can be plugged into computers, calculators, and other equipment. The cases are much bigger than the chips.



Metalloids fall between the metals and the nonmetals on the periodic table. Many metalloids exhibit semiconductor properties.

A problem that develops when more and more transistors are crammed onto a chip is the size of the components. A human hair has a width of about 100,000 nanometers (nm). In 1970, transistors on a computer chip were about 12,000 nm wide. Today, a Pentium chip contains 3 million transistors with the components down to a width of 800 nm.

Photolithography methods for producing the chips do not work well at these sizes. As an example: If you draw a line with a very fine point pencil, the line can look very smooth and straight. But under a microscope, you would see bumps and rough edges. The same thing occurs with lithography onto computer chips. As the parts to be produced get smaller, the equipment used in the lithography process reaches its limit of usefulness.

Research is being done all over the world to overcome these barriers. Some scientists are developing processes to dope chips one atom at a time. Others are studying transistors that would work by the movement of a single electron. The search goes on for ways to cram more memory and calculation ability into a smaller space and make it perform at faster speeds: smaller chips, loaded with more bits.

Periodic Properties Point the Way

There are three main groups on the periodic chart: metals, nonmetals, and metalloids. Metals have electrons in partially filled outer shells—and thus transfer easily—so they conduct electricity. Nonmetals do not conduct electricity easily, so they are insulators. Metalloids are between metals and nonmetals on the periodic chart and in their characteristics. Many metalloids are semiconductors. These elements are insulators at low temperatures. As temperatures rise, some electrons begin to flow, so the elements become conductors. This is the reason for "semi" (meaning "partly") in their name: partly conductors. Silicon and germanium are semiconductors. The electronic industry takes advantage of this property and enhances it to make computer chips.

Make Your Own Chip

As you have seen making chips is a lengthy process. The basic process is to build up layers of silicon that have different electrical properties. When the layers are completed, different parts become transistors and the other electrical components, according to the arrangement of the layers. You can make your own "computer chip."

You need some index cards, scissors, colored pencils or markers, a hole punch, and paper. Cut a half dozen or so 7 x 7 cm squares from the index cards. (Why 7 cm on a side? The most common form of crystal is a thin wafer of silicon about 7 mm square. Unless you have a very sharp knife and good eyes this is a difficult size to work with, so we have scaled it up.) Make a mask out of each square of index card by cutting a pattern in it. You can punch holes with a hole punch or cut other shapes with the scissors. (Be careful not to hurt yourself.) These holes represent transistors and other electrical components on the chip (don't forget the wires!), so make sure that you use the entire area of the masks.

Cut a 7 x 7-cm square of paper. Place the first mask over the paper and color over the cutouts with one colored marker. Repeat with each mask, using a different color. Make sure the final mask connects the different components, or they will not be able to perform useful functions (see figure above).

The paper square is your finished "chip." Remember this chip is 10 times larger in area than a computer chip and computer chips have millions of transistors on them.

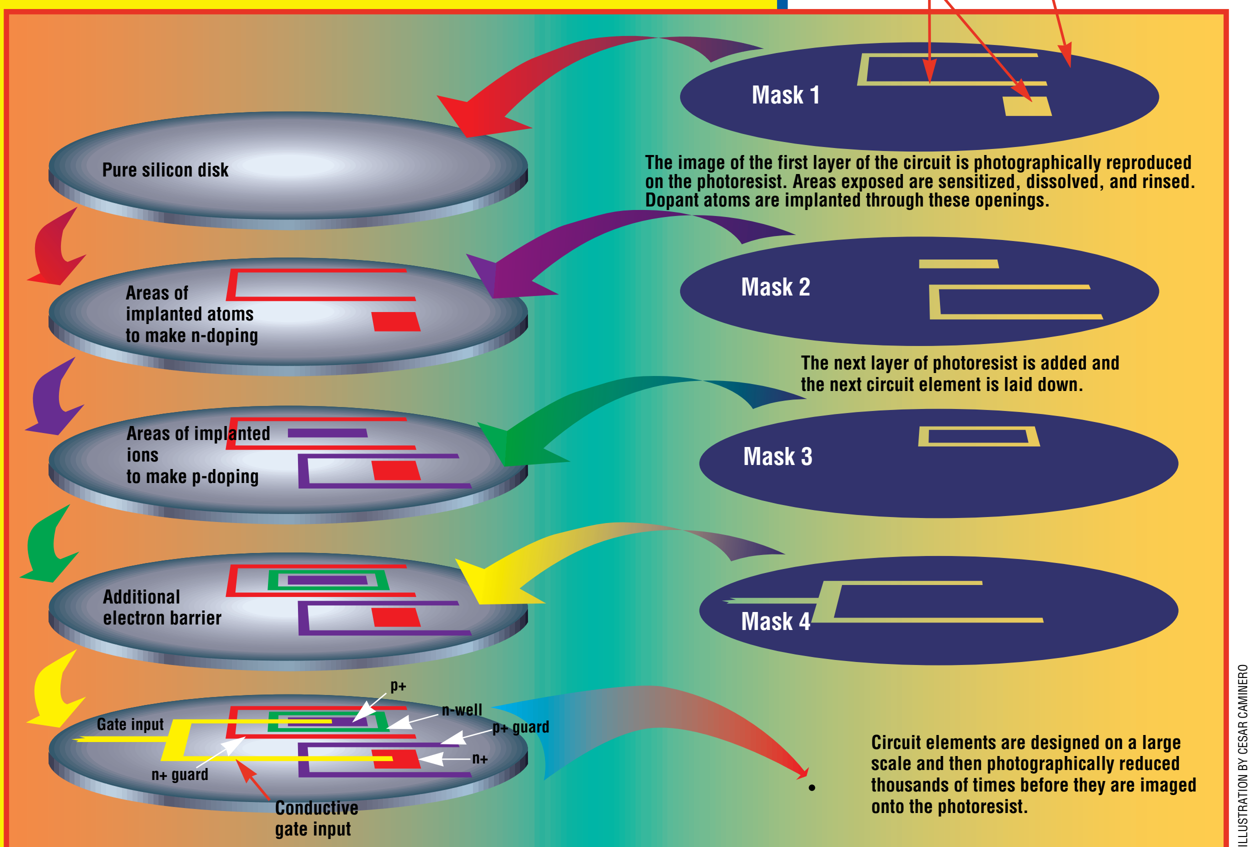


Figure 2.
The making of a transistor—the masking process.

Roberta Baxter is a freelance writer who lives in Colorado Springs, CO. Her article "Mouthwash: What's in It for You?" appeared in the December 1996 issue of *ChemMatters*.

FOR MORE INFORMATION:

Bridgman, Roger. *Eyewitness Science: Electronics*. Dorling Kindersley: London, 1993.

Grolier Multimedia Encyclopedia. Grolier Interactive: Danbury, CT, 1997.

IBM Web site, **www.ibm.com**

Integrated Circuits: Design Principles and Fabrication; Raymond M. Warner, Jr., Ed. McGraw-Hill: New York, 1965.

Macaulay, David. *The Way Things Work*. Houghton-Mifflin: New York, 1988.

"Protein has potential as cheap computer disk." *Gazette Telegraph* (Colorado Springs, CO), July 26, 1997, p. A3.

Ross, , Frank, Jr. *The Magic Chip: Exploring Microelectronics*. Julian Messner: New York, 1984.