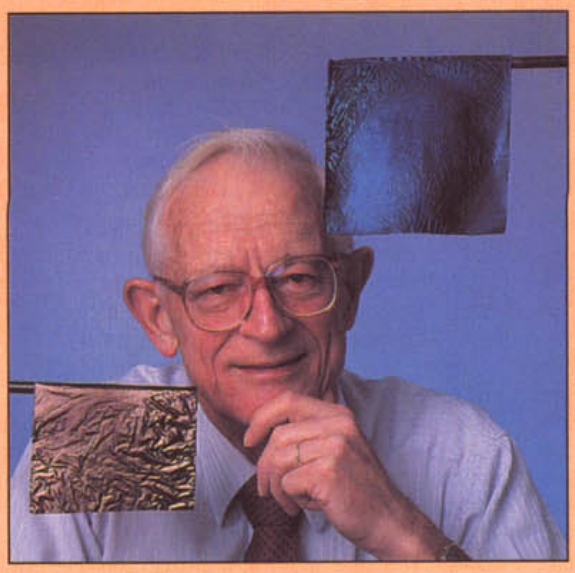
POLYMERS THAT CONDUCT IN ONE DIMENSION

It was 1975, and Alan G. MacDiarmid, a chemist at the University of Pennsylvania, had just given a guest lecture at the Tokyo Institute of Technology. His hosts treated him to a cup of green tea, he recalls, then took him on a tour. In the laboratory of Hideki Shirakawa, the New Zealander saw a silvery film that delighted him. "I had never seen a silver polymer," MacDiarmid says. "It looked pretty. So I invited Shirakawa to work at our laboratory."

Polymer chemists had not gone looking for one-dimensional electronic systems, but they found them in Shirakawa's polymer films. The materials turned out to be a novel form of polyacetylene, a simple polymer that has a backbone of carbon atoms with a hydrogen atom attached to each carbon. Like most organic compounds, polyacetylene was an insulator: its atoms, which are linked by single covalent bonds, have their full share of valence electrons, leaving no room for additional electrons to carry current. But in synthesizing the material, Shirakawa had accidentally created a polymeric film with a useful bond structure between atoms—namely, alternately double and single bonds—and so forged a path for electrons.

Working together, MacDiarmid, Shirakawa and Alan J. Heeger (also then at the University of Pennsylvania) soon tried doping the polymer films—adding or removing electrons. In doing so, they created energy bands between the valence and conduction bands. As a result, the silver films took on golden hues and became conductors.



ALAN G. MACDIARMID was an early developer of conducting polymers. Doped polyaniline **(right)** *will conduct; the undoped sample* **(left)** *will not.*

Since then, researchers have found families of other conducting polymers, such as polyaniline, which includes nitrogen atoms in the backbone chain, and polythiophene, which has sulfur [see "Plastics That Conduct Electricity," by Alan G. MacDiarmid and Richard B. Kaner; SCIENTIFIC AMERICAN, February, 1988].

MICROSCOPIC TWEEZERS. The physical characteristics of these polymers—namely, that they are exceptionally lightweight conductors—provoked early excitement. Lightweight aircraft skins and automobile batteries were among the first proposals. Since adding and subtracting electrons from conducting polymers changes them from conductors into insulators, rechargeable batteries have been built from the materials.

Doping and undoping also changes the length of conducting polymers by as much as 10 percent. As a result, Raymond Baughman, a scientist at Allied-Signal, envisions using conducting polymers as an efficient means for converting electrical energy into mechanical energy. He and his co-workers have designed microactuators, such as microscopic tweezers for plucking micron-size objects.

Exploiting the electronic possibilities created by the polymers' quasi one-dimensional structure, however, has taken longer. Investigators are still puzzling out just how polymers carry charge and how to better that conductivity. What they do know is that electrons travel along a polymer chain—a one-dimensional wire—until they run into a defect or a break in the chain. Because electrons act like waves, they bounce off the barrier, doubling back along the path they came. If the electrons continue to bounce back and forth between two defects, they will create a standing wave. This action can pin the charge to one area of the polymer, reducing the overall conductivity of the polymers.

CHAIN HOPPING. Electrons can escape this trap—and dramatically improve the conductivity of the material—if they "hop" to a nearby polymer chain before establishing a standing wave. (This sideways hopping is what makes polymers quasi one-dimensional systems.) Electron hopping could be much like the tunneling that electrons do when confined in semiconductors, Baughman points out. The overall conductivity of a polymer will depend on how far electrons travel before running into defects, as well as how easily they hop from chain to chain. Both factors are related to the concentration of defects along a polymer chain.

Some polymers exhibit interesting optical characteristics. The polymers can transmit light from a laser. And because of the way the polymers share electrons, increasing the intensity of light will tune the materials' optical properties.

LIGHT SWITCHES. Some workers hope to use this trick to make all-optical switches, which use light to control light. Shahab Etemad of Bellcore is developing one such polymeric switch based on two identical threads of polydiacetylene that run parallel to each other in a block of glass. The lines, which are no thicker than the wavelength of light that they will transmit, are coupled waveguides. As a result, shining low-intensity laser light along one line causes the light to oscillate back and forth between the two lines.

To turn the waveguides into a switch, Etemad increases the intensity of laser light, which immediately changes the index of refraction of the top line. This make the lines no longer identical, and so the waveguides become decoupled. By shortening the lines precisely, Etemad ensures that only high-intensity light will emerge from the top line and low-intensity light from the other. The time it takes to "switch" on (or off) one polymeric thread is only a femtosecond (10^{-15} second) laser pulse. This change is far faster than any semiconductor switch can manage. "I'm not saying that it's going to be used in the telephone system tomorrow," Etemad says, but at least in the laboratory the switch looks good.

As is the case with semiconductors, just how far investigators will be able to push the conductive and optical properties of polymers depends on how easily the materials can be processed and on how precisely their electrical properties can be controlled. Points out Baughman: "The dream of the future—of easily processable conducting polymers—depends on our being able to manipulate defects and increase the strength of the chain interactions."