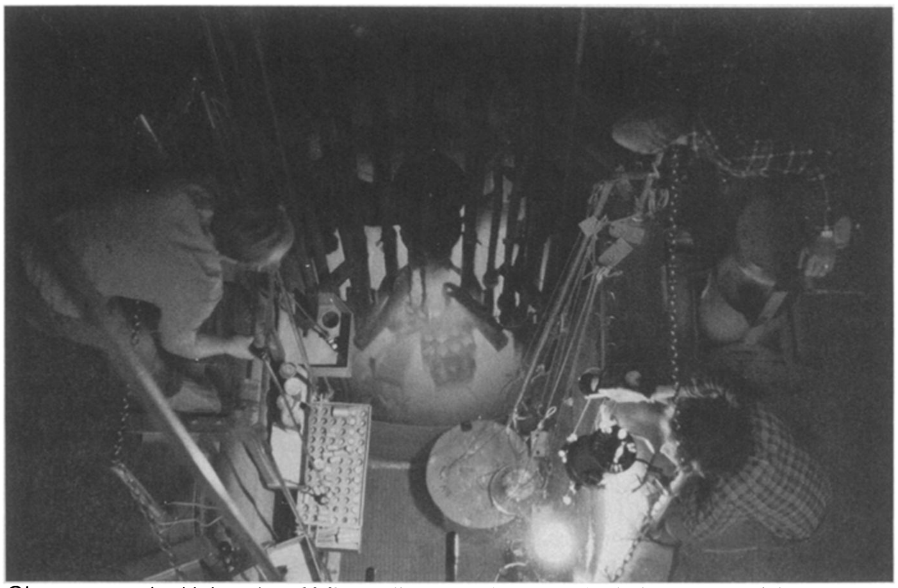
# A Nuclear Change for Silicon

Transmuting a small fraction of a crystal's silicon atoms into phosphorus atoms produces a unique material useful for electronic devices



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*Observers at the University of Missouri's research reactor look down toward the reactor core where neutrons irradiate silicon samples.*

By IVARS PETERSON

Row upon row of silicon atoms, arranged as neatly as marbles stacked in a box, make up a single crystal of pure silicon. Imagine being able to pluck out individual silicon atoms anywhere within the array and to replace them with phosphorus atoms. Add more phosphorus atoms, and the electrical resistance of the material decreases further. Imagine being able to do this so that the phosphorus atoms are sprinkled evenly throughout the crystal. Using a process called neutron transmutation doping, researchers are able to do just that, and they don't even have to remove silicon atoms.

The method involves slipping a pure silicon crystal into a beam of neutrons from a nuclear reactor. When the neutrons whisk through the crystal, almost as if it weren't there, a few are captured by silicon atoms. If these happen to be atoms of silicon-30, one of three silicon isotopes typically present in a sample, they become radioactive and decay into phosphorus atoms. After the sample is removed from the neutron beam and the radioactivity dies away in a matter of days, the result is a piece of silicon uniformly doped with phosphorus. The material is now ideal for manufacture into electronic devices that handle high voltages or high currents in electric locomotives, high-power machinery and even television sets.

The more conventional method of preparing doped silicon is to grow a single crystal by carefully cooling a liquid mixture of silicon and a trace of phosphorus. For high-power applications, this method isn't good enough. Some parts of the crystal grow faster than others, and inevitably pockets of phosphorus atoms build up in some areas while deficits occur elsewhere. The electrical resistance across a wafer sliced from such a crystal is uneven. A spot that carries more current than the rest of the wafer gets hot. If the current is high enough, the device burns out.

One of the first major applications of power control devices made from neutron transmutation doped silicon was for electrical transmission lines in Europe. It was a matter of energy conservation.

Traditionally, electricity is distributed long distances as high-voltage alternating current. However, energy losses occur due to heating in the cables and through the corona, seen as a blue glow or heard as a crackling sound near transmission lines. High-voltage, direct-current transmission is more energy-efficient because it has no corona losses. In addition, direct-current lines can be thinner and require less insulation and right-of-way.

At a power plant, electricity is generated as alternating current. Transformers raise the voltage (while lowering the current) for transmission. For direct-current transmission, a power device such as a rectifier converts alternating current to direct current; that is, restricts current flow to one direction. These power devices must be able to withstand the high voltages and high currents involved without breaking down and provide the rapid switching times required. Semiconductor devices made from neutron transmutation doped silicon meet these requirements. Another electronic device called a stacked diode performs a similar function in a television set where household current must be transformed to about 10,000 volts and then rectified.

The neutron doping method also allows the uniform addition of as little as $10^{12}$ phosphorus atoms per cubic centimeter (1 phosphorus atom for every 50 billion silicon atoms). This is useful for producing high-quality infrared detectors. Silicon usually contains trace amounts of boron. By adding the right number of phosphorus atoms to compensate for the residual boron, manufacturers are able to produce the world's best silicon detectors.

The current world production of neutron transmutation doped silicon is about 50 metric tons annually. The material is used mainly in Europe and Japan, where emphasis on energy efficiency encourages the use of semiconductor high-power switches and control devices that regulate current or voltage.

In the United States, only the University of Missouri's research reactor in Columbia, Mo., applies the process commercially. John W. Farmer, senior research scientist at the Missouri reactor, says the facility processes about 12 metric tons of silicon each year, mainly for Monsanto in St. Louis and for a Japanese company. They receive single-crystal, high-purity silicon ingots, 2 to 3 inches in diameter and 10 inches long, from their customers. After the ingots are cleaned, they are sealed in leak-proof aluminum cans. The cylinders are placed near the reactor's core to be irradiated for several hours, depending on the concentration of phosphorus needed. Afterward, the now-radioactive cylinders are stored underwater for a week until the radioactivity dies down.

"The activity has got to be below a certain specified limit before we can ship it to anybody," says Farmer. "Maybe one in a hundred times, there will be some sort of impurity in the silicon that got activated and requires a longer holding time, but that's very unusual." The residual radioactivity of the final manufactured product is so small compared to background radiation that it is negligible.

Recently about 50 scientists from around the world met at the National Bureau of Standards in Gaithersburg, Md., for the Fourth International Neutron Transmutation Doping Conference. They looked at new research findings and reviewed the progress that turned a long-known scientific curiosity into an important industrial process in less than a decade. Despite discussion of applying the process to other materials like gallium arsenide or germanium and the possibility of increasing phosphorus concentrations further for use in integrated circuits, the participants recognized that the chief limitation on future production was nuclear reactor capacity. Thomas G. G. Smith of the Harwell Atomic Energy Research Establishment in Great Britain predicted that demand could exceed worldwide capacity some time in the next twenty years, especially as older research reactors shut down. Commercial power reactors are unsuitable for this purpose because they are designed to generate steam rather than to provide access to neutrons.

Jon M. Meese, senior research scientist at the Missouri reactor, says one of the problems facing the United States is that no new university research reactors have been built since about 1963, and older reactors are nearing the end of their lives. In the future, this could restrict research and commercial development in a variety of fields, he says. "Even today, there is probably a lot more research coming out of Europe on applications of neutrons than in this country," Meese says.

Fritz G. Vieweg-Gutberlet of Wacker-Chemitronic GMBH in West Germany says neutron transmutation doping has matured as an industrial process. Questions about some aspects of the method remain, but more attention is now being paid to the nature of the electronic power devices made possible by the new material. Because many of the unsolved problems concerning power devices are similar to those in integrated-circuit manufacture, Vieweg-Gutberlet suggests power device and microelectronics specialists would benefit from an exchange of information. The next neutron transmutation doping conference, scheduled in two years, will be held in conjunction with another group to promote this exchange. □