treated by ion implantation with silicon, titanium, boron, and other elements, to reduce deformation under pressure and retard oxidation—two common modes of failure. Even organic polymers have been modified by ion implantation to give them certain electrical properties, making possible the advent of plastic electrical wires.

The list of applications of ion implantation is long. Even so, its dominant uses remain firmly established in the semiconductor industry. With ongoing research by Basic Energy Sciences, the technology continues to evolve to increasing levels of sophistication.

Today, industrial laboratories worldwide conduct research and development on ion implantation. These and many other individuals and organizations must be credited with state-of-the-art contributions to its continued advancement.

The story of this technology's emergence, from radiation damage to metallurgical tool, is one that spans more than three decades. Also, it is illustrative of some of the key elements of the process of technological innovation.

Systematic and sustained investments in basic research pursued interesting atomic phenomena. The results of such work, in turn, opened new avenues of exploration. Eventually, basic research filled out a body of scientific knowledge in sufficient detail to lend confidence to insight and speculation, which motivated applied research by others. Private laboratories sensed opportunities, built on the foundation of prior work, and successfully labored to bring the technology to fruition. The end result was a cascade of benefits for society.

SQUID

Imagine a device so sensitive that it can locate hot areas of the earth's interior by measuring tiny changes in the earth's magnetic field, or measure the faint magnetic signals given off by the human brain while thinking! Superconducting Quantum Interference Devices, or SQUID, can do all of this and more. Seldom does a new invention hold so much promise for physical research as do these tiny devices measuring less than a tenth of an inch on a side and operating at temperatures just a few degrees above absolute zero.

SQUID are based upon a device made from two pieces of superconducting material separated by a very thin insulating layer. These low-temperature "sandwiches" are called Josephson tunnel junctions after Brian Josephson who won a Nobel Prize in 1973 for predicting their properties. The most sensitive type of SQUID consists of two Josephson tunnel junctions incorporated into a conducting loop of wire that senses magnetic field. The key feature that makes the junctions so useful when employed in a SQUID is that their electrical characteristics change significantly when a weak magnetic field is applied. SQUID convert a tiny change in the magnetic field, which is a difficult quantity to measure directly, into a change in voltage which can be easily measured by conventional electronic equipment.

Sensitivity of early models of the two-junction SQUID was limited by intrinsic electrical noise. In the mid-1970's, Basic Energy Sciences researchers at the Lawrence Berkeley Laboratory developed a systematic theory that showed how the intrinsic electrical noise depended upon the size, shape, and other design parameters of the two-junction SQUID. Primarily, what they found was that "smaller is better" and that if it were small enough, a two-junction SQUID was potentially much more sensitive than alternative designs. Fortunately, the development of their theory coincided with the availability of thin-film technology, then under development at IBM. With this new technology, film "wires" less than one-thousandth of an inch wide could be deposited onto a glass or ceramic surface. This process made the miniaturization of SQUID a straightforward production technique and their commercial manufacture soon followed.

The group at Lawrence Berkeley Laboratory as well as other researchers have made steady improvements in the fabrication of ultra-small SQUID. They are now about 10,000 times more sensitive than the ones made prior to 1980. The most sensitive SQUID produced to date was developed at Lawrence Berkeley Laboratory in the early 1980's and is very close to the theoretical limits of sensitivity.

The SQUID's incredible capabilities first proved useful in the laboratory for measuring tiny voltages and current. Their role has diversified in recent years to include, among others, sensing brain waves and the detection of subterranean resources and collapsing stars.