SQUID Sensors Penetrate New Markets

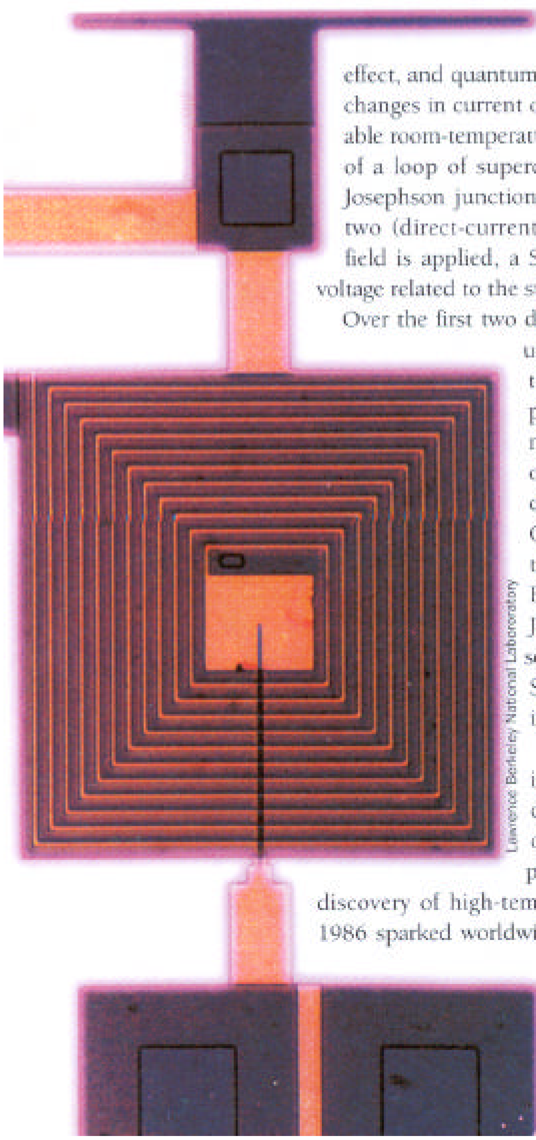
Feature

by Jennifer Ouellette

SQUID devices are making inroads in magnetocardiology, nondestructive evaluation, explosives detection, and geophysics

Superconducting quantum interference devices (SQUIDs) have long served as extremely sensitive magnetometers and gradiometers. Now a handful of commercial companies in the United States and abroad seeks to extend the application of these devices to a variety of emerging markets, taking advantage of recent advances in university and federal laboratories. In addition to today's well-established biomedical and research applications, companies are targeting SQUID sensors to such areas as magnetocardiology, nondestructive evaluation, explosives detection, and geophysics.

First developed in 1964, a SQUID is a device that uses superconductivity, the Josephson effect, and quantum interference to convert minute changes in current or magnetic field into a measurable room-temperature voltage. The device consists of a loop of superconductor interrupted by one Josephson junction (radio-frequency SQUIDs) or two (direct-current SQUIDs). When a magnetic field is applied, a SQUID produces a measurable voltage related to the strength of the magnetic field.



Lawrence Berkeley National Laboratory

Over the first two decades, the SQUID technology underwent several major innovations, from incorporation of pieces of niobium wire and machined niobium, to the use of fully integrated thin-film devices, according to John Clarke, professor of physics at the University of California, Berkeley, who last year won the Joseph F. Keithley Award, presented by the American Physical Society, for his pioneering work in SQUIDs.

Since 1982, little has changed in the basic technology for standard low-T_c SQUIDs, which operate at liquid-helium temperature (4.2 K). However, the discovery of high-temperature superconductivity in 1986 sparked worldwide interest in developing high-T_c SQUIDs. Although not as sensitive as the low-T_c devices, high-T_c SQUIDs offer an obvious potential benefit: they operate at liquid-nitrogen temperature (77 K). Not only is liquid nitrogen less expensive and more readily available than liquid helium, but it boils away more slowly and doesn't require refills as often.

"In the 26 years since SQUIDs first became commercially available, SQUID sensors have evolved from a specialized laboratory instrument measuring exotic quantities, such as femtovolts and nanokelvins, to instruments used in such diverse applications as medicine, materials science, nondestructive testing, and oil exploration," says Robert Fagaly, vice president and general manager of Tristan Technologies (San Diego, CA), which supplies high-T_c and low-T_c SQUIDs for many applications.

Only recently, however, have high-T_c SQUIDs advanced to the point of sufficient sensitivity for use in a variety of emerging new applications, and most of the established commercial markets for SQUIDs still employ the low-T_c technology. The most profitable market for SQUIDs remains the physics laboratory, where they are used either in research or as teaching tools, notes Ron Sager, vice president of engineering at Quantum Design (San Diego, CA). His company offers SQUID-based magnetic-property measurement systems that characterize materials over a wide range of temperatures and magnetic fields.

Biomedical applications

By far the largest commercial market for low-T_c SQUIDs is for biomedical uses, particularly imaging systems for the brain. The biomedical area generates revenues estimated at tens of millions of dollars annually, in part by sales to the $1 billion magnetic resonance imaging (MRI) market. Biomagnetics Technology, Inc. (San Diego, CA), CTF Systems (Port Coquitlam, BC), and Neuromag (Helsinki, Finland) are the three leading manufacturers of multichannel SQUID systems for imaging the brain. Up to 95% of the low-T_c SQUID sensors currently sold are used in brain imaging systems. CTF's Juri Vrba estimates that since 1972, when the first such sensors went into use, until 1992, only about 1,000 low-T_c SQUIDs were manufactured for all applications

CTF Systems, Inc.

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combined. Since then, approximately 5,000 low-T_c SQUIDs have been used in multichannel brain-imaging systems alone.

Profits from biomedical applications, however, have been limited because of the high cost of the large, complicated systems required for efficient operation. Nonetheless, "as medical applications grow," says Fagaly, "the term SQUID might become as commonplace as MRI or X-ray computerized tomography scanners." The high-speed response by SQUID magnetometers allows time-resolved studies of brain activity in such areas as epilepsy, presurgical cortical-function mapping, Alzheimer's research, and neuromuscular and prenatal-brain disorders. In a more novel application, the Kanazawa Institute of Technology in Japan has provided the Massachusetts Institute of Technology with a SQUID brain-imaging linguistics lab to study magnetic signals emitted by the brain as it processes speech and to locate the specific sector performing that function.

Hisashi Kado and Tomio Kuroda of the Superconducting Sensor Laboratory (SSL) in Chiba, Japan, have developed a 256-channel SQUID system that includes a sensor array to measure electromagnetic fields deep inside the brain. Kuroda maintains that the information obtained with this system enables the analysis of the brain and heart in real time and space. This provides more accurate medical information, especially when combined with the information obtained from conventional ultrasound and MRI scans. Furthermore, "the neural activities in the brain show a very powerful processing capability beyond the simple storage of information," says Kuroda, "especially that of the cerebral cells, which use far more complex associations than present computers." Analyzing these more complicated functions may lead to novel high-speed information processing. In addition, the SSL group has developed high-T_c 16- and 32-channel SQUID systems in conjunction with Sumitomo Electronics (Japan).

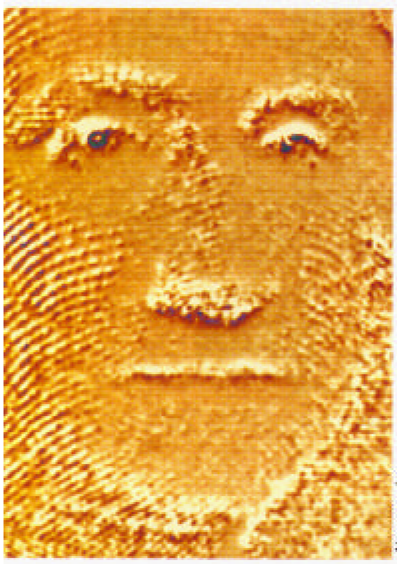
Other efforts aim at using SQUID sensors for magnetocardiology. Researchers envision the technology as an important supplement to conventional imaging techniques in studies of arrhythmia, heart-muscle damage, and fetal cardiography. Magnesensors (San Diego, CA) is developing a high-T_c SQUID magnetocardiography unit to noninvasively monitor fetal heart rates in the later stages of pregnancy. Tristan Technologies also offers a high-T_c SQUID magnetometer for cardiac measurements.

Clarke's Berkeley group and NKT in Copenhagen, Denmark, are among those who have recorded real-time, clinical-quality magnetocardiograms using multilayer SQUID magnetometers in a magnetically shielded room. Clarke's team is currently developing SQUID-based gradiometers for magnetocardiology in unshielded environments. At the Institute of Thin Film and Ion Technology in Jülich, Germany, the primary application of SQUID sensors in magnetocardiography has been to define risk profiles for sudden cardiac death, in conjunction with clinical partners. This year the focus has shifted to the study of cardiac ischemia, which is caused by heart-artery blockage.

Other potential medical applications of SQUIDs include gastroenterology, locating blockages to intestinal blood flow, noninvasive liver imaging, and assessment of nerve damage.

Beyond biological uses

Another promising area for SQUIDs lies in nondestructive evaluation (NDE). Magnetic field detection is an advantageous alternative to such traditional methods as ultrasound or X-ray testing in monitoring internal faults, especially in metallic structures. By far the most commercially advanced are the SQUID systems developed at the institute in Jülich and commonly called Jülich SQUIDs. One project—in collaboration with the University of Geissen, Lufthansa, and Airbus—uses SQUID sensors for aircraft-wheel testing. The sensors will soon be included in the standard eddy-current wheel tester system manufactured by Rohmann GmbH (Frankenthal, Germany). Another Jülich system has been successfully operated in a professional fuselage scanner, yielding promising initial results. Commercial service testing of critical engine parts has been conducted since 1996 using a stationary electronic gradiometer, a technology recently acquired by a small German company. In this application, the SQUID is used to locate magnetic impurities. F.I.T. Messtechnik GmbH is another German company that uses Jülich SQUID systems for NDE applications, as well as for magnetocardiography.


Neocera, Inc.

SQUID microscope image from a dollar bill. The ink on the bill has a magnetic dipole moment whose intensity varies with ink density.

Jülich SQUID sensors have also been used to evaluate aging prestressed-concrete structures, such as bridges, in a program that is now entering its second phase, according to Alex Braginski, who heads the effort at Jülich. His group provided its first primitive SQUIDs to a German government materials testing authority and a commercial company that conducts bridge tests, which used the Jülich equipment alongside their conventional equipment. In 1995, the Jülich system detected a dangerous crack in a major freeway near Nuremberg, which the conventional equipment could not detect. Braginski's group is now developing prototypical arrays of mobile SQUIDs to scan bridges and other structures more quickly.

Quantum Magnetics (QM) in San Diego, California, is targeting its low-T_c SQUID systems to the security industry—specifically for the detection of plastic explosives in airline luggage, which cannot be detected using conventional X-ray systems. QM uses a technique called nuclear quadrupole resonance (NQR), which employs radio waves to look for specific chemical signatures. "An explosive has characteristic NQR frequencies from nitrogen, which are very well defined," Clarke says. "So you employ SQUIDs to look for these specific frequencies, which may indicate the presence of an explosive." QM was recently acquired by EnVision (San Diego, CA), a leading supplier of X-ray luggage scanners for commercial airlines.

Of particular interest to QM is a technique called single-sided magnetic resonance. Here the magnetic field is projected outside an MRI machine, enabling examination of very large objects such as aircraft or bridges. "We're hoping to develop machines along those lines as an extension of our magnetic resonance for luggage scanning," says QM spokesman Andy Hibbs. "The only sensor that will work for that is a SQUID. You need the sensitivity, the bandwidth, and you need to be able to operate at very low frequencies."

Because human-made objects affect the surrounding magnetic field, SQUIDs are also well suited for military or other surveillance tasks. Roger Koch of IBM's T. J. Watson Research Center (Yorktown Heights, NY) is working on high-T_c SQUIDs to detect submarines and mines. Although he has achieved success under laboratory conditions, he notes that the U.S. Navy's interest in the technology is dwindling. "The trend in the Navy right now is to have cheap sensors that may be lower in performance, but to have more of them," he says. "Superconducting sensors are expensive and very high-performance." Magnesensors is also developing high-T_c SQUIDs to detect explosive material in plastic land mines using NQR.

SQUID microscopes

Scanning SQUID microscopes represent another promising development. According to Fred Wellstood, professor of physics at the University of Maryland, College Park, these systems work by scanning a sample closely under a low-noise dc SQUID. A computer records the output from the SQUID and converts the resulting data into a false-color image of weak magnetic fields coming from the sample. Such microscopes are now used to study the pairing symmetry of high-T_c superconductors, to image high-frequency fields up to 200 GHz, and to locate shorted current paths in microelectronic chips. For example, IBM's John Kirtley developed such a device to image new superconductors and determine the symmetry of the Cooper pairs.

The most recent scanning SQUID microscopes can image room-temperature samples. Wellstood's systems allow a high-T_c SQUID to be brought within 25 μm of a room-temperature object, separated by a small vacuum space and a thin sapphire window. Clarke's group has constructed a high-temperature scanning SQUID microscope for examining samples at room temperature within a distance of 15 μm. Neocera (Beltsville, MD) also is developing a prototype high-T_c SQUID-based microscope, based on Wellstood's design, for imaging samples at room temperature. The microscope will become commercially available this year.

One of the earliest commercial uses for SQUID magnetometers came in oil exploration, where a technique known as magnetotellurics was used to determine the electrical resistivity of the Earth's crust by measuring its electric and magnetic fields. The technique is also useful for mapping earthquake faults. Although the need to use liquid helium in the past and the current low price of oil has diminished oil-company interest in using SQUIDs for geophysical exploration, a solid niche market exists for laboratory instruments, according to Bill Goree, who heads 2G (Mountain View, CA), a maker of low-T_c SQUID systems for geophysical research. The company specializes in magnetometers that measure magnetic properties of rock. "There's not much growth in this market, but it does support a small given research segment," Goree says. At Jülich, portable and economical small high-T_c SQUID magnetometer systems are being developed for field use, in collaboration with Metronix GmbH, a manufacturer of geophysical field equipment.

Of course, SQUIDs still find applications in basic research. For example, Clarke's team uses SQUIDs as sensitive transducers for detecting nuclear magnetic resonance and NQR, which are important for studying chemical structure on a molecular scale. More exotic is the use of low-T_c SQUIDs as transducers on gravitational-wave antennae, as well as the use of SQUID sensors to detect axions, one of the candidates for the dark matter believed to comprise most of the universe's mass.

In the area of biological physics, Clarke studies magnetotactic bacteria, which contain a permanent magnetic dipole that can be tracked and measured with high-T_c SQUID microscopes to yield important information on the bacteria's dynamics. The next step is to study these bacteria carrying out bioremediation. "One hopes to use bacteria to eat contaminants like oil in the environment," Clarke says. "But then you are placing the organisms in an opaque porous medium where they can't be seen. We can track them magnetically with SQUIDs."

Future challenges

Despite the growing number of successful laboratory applications of both low-T_c and high-T_c SQUIDs, major technical and commercial challenges remain. First and foremost, says Clarke, is the cooling requirement, an added inconvenience and expense for many potential markets. From a manufacturing perspective, the production of state-of-the-art high-T_c Josephson junctions is not as well developed as the process for low-T_c devices, which increases the sensor cost and may limit the commercialization of high-T_c SQUID systems.

Furthermore, because SQUIDs are so sensitive, any noise from ambient magnetic fields can affect measurements. For certain applications, such as geophysics, the measurement of this ambient-field fluctuation is a primary purpose of fielding magnetometers. Biomedical measurements, however, have been conventionally carried out in costly magnetically shielded environments. CTF's multichannel systems reduce noise by way of synthetic gradiometers that act as spatial filters. "They make instruments essentially near-sighted," says Vrba. "They reject magnetic fields that come from a distance, and they are sensitive to magnetic fields nearby." In eddy-current testing for locating cracks in structures, Braginski avoids this problem by employing very narrow frequency bands, so that noise at most other frequencies is automatically eliminated. But for many applications, ambient noise remains a troublesome issue.

Despite the technological advances achieved in recent years, several former leaders are exiting the SQUID market. IBM, formerly a major innovator in SQUID technology, no longer makes the devices, and even internal R&D on SQUIDs is dwindling, according to Koch. Conductus (San Diego, CA), the company that introduced the first high-T_c electronics product, is also exiting the business. "The technology is far enough along so that we can make very high-quality SQUIDs," says Bruce Hegstad, president of Neocera. "However, the key is to get commercial applications with some volume. The SQUID business is a series of $2 to $3 million products, and I don't see that changing in the short term."

The key, says John Rowell, a New Jersey-based consultant who spent many years with Conductus, is to develop novel systems in cooperation with the potential customers of SQUID products. This is something that is emphasized more in Europe and Japan than in the United States. Jülich SQUID applications are being developed in conjunction with targeted customers and small industrial partners. Japan's SSL was founded by the Japanese Technology Center with support from 10 private companies, including such industry giants as Toshiba Corp., Hitachi Ltd., Seiko Instruments, Inc., and Sumitomo. SSL's prototype low-T_c multichannel systems have been installed at university medical facilities for joint research. "The work at Jülich is an example of how to collaborate with potential customers in the development of a number of high-T_c SQUID-system applications," Rowell says. "The U.S. companies, with one or two notable exceptions, have not shown the same imagination and marketing skills."

Even Braginski is realistic about the obstacles to broad commercialization of SQUID technology, despite his group's success with licensing its prototypes. SQUIDs, he maintains, will only penetrate specific, high-value markets where the economic tradeoffs gained from improved sensitivity justify the additional expense. "The customer must feel that the SQUID brings him something that he otherwise cannot achieve, making the extra inconvenience of dealing with the cooling requirements worthwhile," he says. "If you can do it any other way, you shouldn't use a SQUID."

Clarke points out, however, that SQUIDs are still the most sensitive detectors of magnetic flux over a frequency range that spans 13 decades, from 10^{-4} Hz (geophysics) to 10^{9} Hz (axion detectors). Says Clarke, "There is a lot of scope left for innovative and money-making ideas." ■