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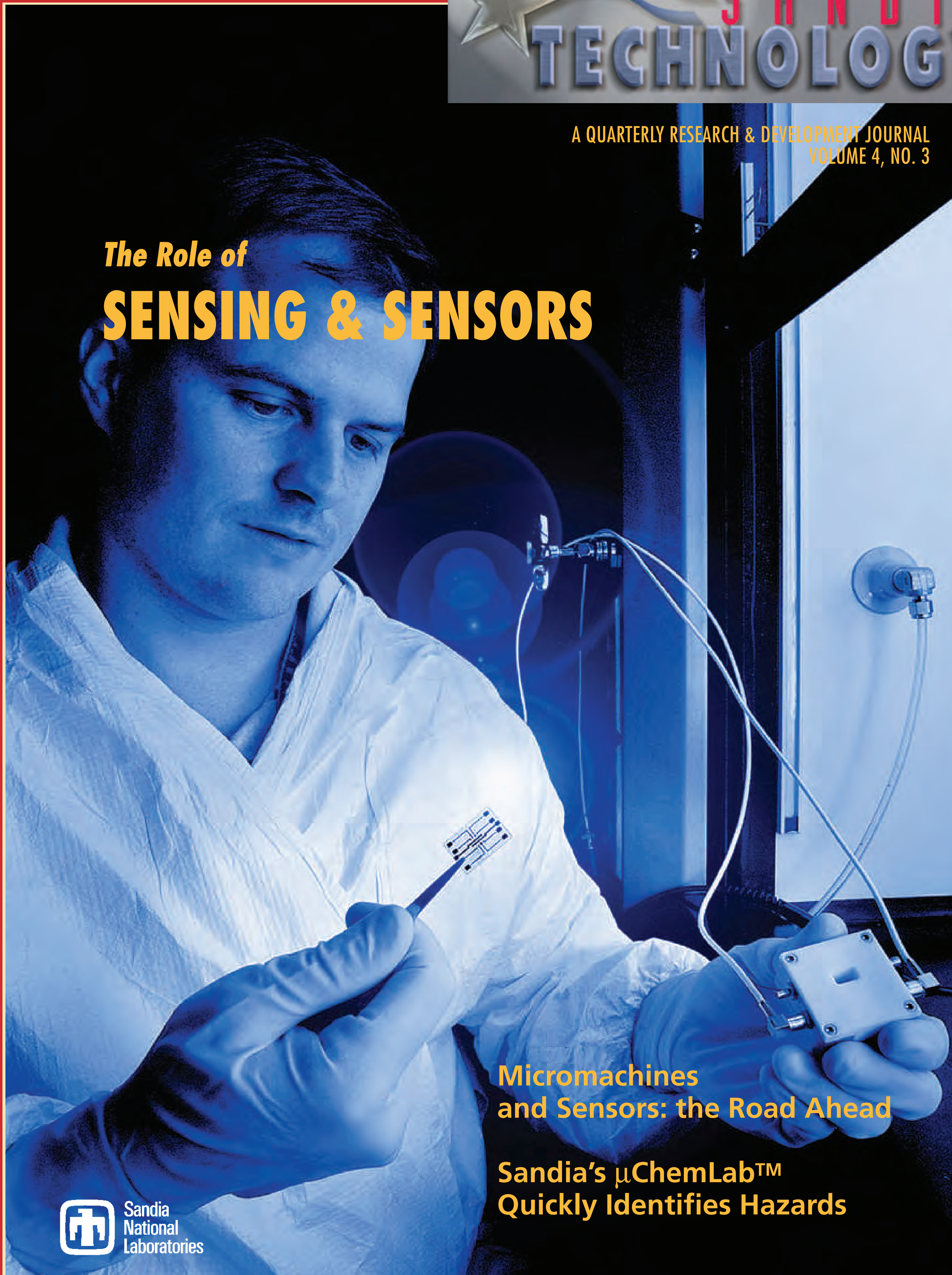

The Role of
SENSING & SENSORS

Micromachines and Sensors: the Road Ahead

Sandia's μChemLab™ Quickly Identifies Hazards

Sandia National Laboratories

ON THE COVER: Sandia Researcher Darren Branch conducts an experiment with the lipid bilayer biosensor, a device with the promise of rapidly detecting a variety of biological agents, including viruses, anthrax and other bacteria.

Photo: Randy J. Montoya
Design: Doug Prout

Sandia Technology is a quarterly journal published by Sandia National Laboratories. Sandia is a multiprogram engineering and science laboratory operated by Sandia Corporation, a Lockheed Martin company, for the Department of Energy. With main facilities in Albuquerque, New Mexico, and Livermore, California, Sandia has broad-based research and development responsibilities for nuclear weapons, arms control, energy, the environment, economic competitiveness, and other areas of importance to the needs of the nation. The Laboratories' principal mission is to support national defense policies, by ensuring that the nuclear weapon stockpile meets the highest standards of safety, reliability, security, use control, and military performance. For more information on Sandia, see our Web site at *http://www.sandia.gov.*

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FROM THE *Editor*

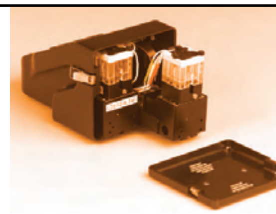
Dear Readers:

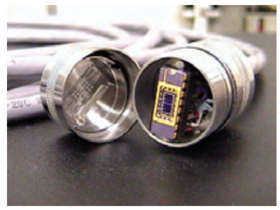
If you get the impression from this issue that "Sensors R Us," we at Sandia won't be disappointed. Sandia has shown leadership in a number of areas involving sensor development and we've tried to showcase some of them here. We owe a special thanks for this issue to our subject-matter champion, Marion Scott, who helped us by spinning off a number of fruitful article topics and followed up by being a key reviewer. As Director of Sandia's Microsystems Science and Technology, and Components Center, Marion was already too busy, but his help and that of his staff have been invaluable.

Nigel Hey, retired Senior Administrator and former Manager at Sandia, was also an important contributor. He did the tough work of outlining an approach to the sensor topic, which pervades many organizations within the Labs. His overview essay, which begins on page 2, helps provide perspective for other work under way.

Making sensors tiny, giving them capabilities to be more pervasive, and extending the reach of their potential uses will be continuing activities at the Labs. The stories here represent only a portion of an expanding area of expertise for Sandia researchers.

Will Keener
Editor





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The Role of Sensing and Sensors

Sensors. They're everywhere, all around us and even inside us, offering an enormous amount of information. By converting information about our environment into impulses that can be read by a machine, sensors can function as our eyes, nose, ears and sense of touch.

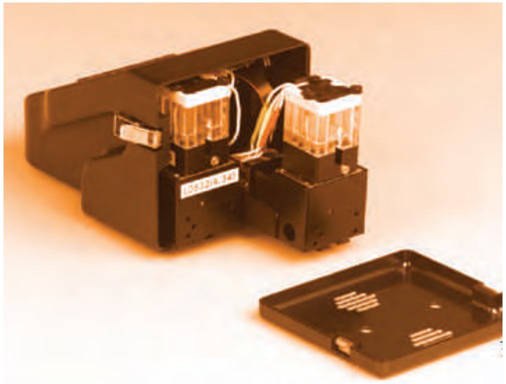
by Nigel Hey

At Sandia, sensor technology pervades much of what we do. Need a sensor to measure the temperature of glass during its manufacture? To detect pollutants in groundwater? To analyze smokestack emissions? To sniff out biotoxins in subway stations? To trigger an alarm when hydrogen leaks from a booster rocket engine? Sandia has devised all of these and more.

This issue outlines some of the accomplishments and attempts to provide a sense of where this research is going. Mostly, it is going smaller and cheaper. To more broadly disperse sensors, they must be smaller and more easily manufactured. To succeed in this area, Sandia draws from a host of core competencies — in particular, silicon semiconductor technology, compound semiconductor technology, micromachining, and integrated circuit design. These competencies, translated into a diversity of sensor devices, serve a variety of Labs' missions, says Marion Scott, Sandia's Director for Microsystems Science, Technology and Components. Among them are protection of the public health, safe and secure weapons, and non-proliferation.

A single sensor is almost never sufficient in itself. More often, the solution to a problem lies in precise calibration, careful packaging, and the addition of electronics that will gauge an electrical current, equate it with a given indicator — and then sound

Complex, miniaturized integration of sensor-based systems is exemplified by Sandia's µChemLab™. This field-portable device moves a sample through a maze of micromachined tubes, pumps and valves to identify it. Two modules fit in the back of the device (inset) for easy access.



"Continuing technological innovation is the lifeblood of this nation. It must keep moving if we are to stay ahead of our competitors and our foes."

an alarm, while generating a set of numbers that can be read and understood at a moment's notice.

Add electronics to a sensor, then build in an alarm and a readout, and you've integrated a system that is more complex and more useful than the sensor alone. For decades, systems integration has been one of Sandia's best-known trademarks.

"Our job at Sandia is to present policy makers with a set of tools," says Scott. Complex, miniaturized integration of sensor-based systems is epitomized by the µChemLab™, a program that began as a "Grand Challenge" Laboratory Directed Research and Development effort and has grown to include several external customers. The basic device — presented as the µChemLab™ – contains two sets of sample concentrators, separators, and detectors, through which a sample material moves via a complex of micromachined tubes, pumps, and valves. The whole system, including power supply and readouts, can be held easily in the hand, and will deliver a sample analysis in 30-60 seconds. This gas-phase apparatus detects and identifies chemical species. A liquid-phase version also has been developed to detect and identify biological compounds.

Other examples are portal technologies for use at US borders. Devices are under development that won't slow crossings, but will sense chemical and radiological components and report them to proper authorities.

"The kind of technological creativity that goes into the design of smart sensors is a dynamic force that will help maintain U.S. primacy in national security, as well as its leadership in commercial markets," says Sandia President C. Paul Robinson. "I stress the word 'dynamic.' Continuing technological innovation is the lifeblood of this nation. It must keep moving if we are to stay ahead of our competitors and our foes. Just as importantly, we must match our technologies with the organizational genius that enables ever more complex systems integration, in order to ensure that we use those technologies to the best possible advantage."

Protecting our Precious Water Supplies

America's water supply faces two key challenges in the 21st Century — one from terrorism and the other from pollution. A continuous water monitoring system, now being developed at Sandia, may provide a key tool in efforts to protect this national resource.

Micro-chemical sensors now under development at Sandia will reduce the need for labor-intensive manual sampling for protection of public health and the environment by establishing a system that constantly monitors for contaminants in soils and water. Sandia researcher Cliff Ho is helping to develop this new system that checks for various toxins and gives continuous readings to help individuals determine if there are significant changes in the condition of soils or groundwater.

Ho describes the device that he, Sandia colleague Bob Hughes, and others have built as a robust package that can be put directly underground — in water or in soils where the humidity reaches nearly 100 percent — to detect toxic chemicals and transmit information about them. "It has the capability of detecting undesirable chemicals *in situ* and in real time," Ho says.

The system could be used to monitor a variety of sites, including underground storage tanks, chemical spills, and waste dumps without taking samples to an offsite laboratory. There are thousands of these sites requiring monitoring for protection of resources and to help determine what cleanup measures might be required.

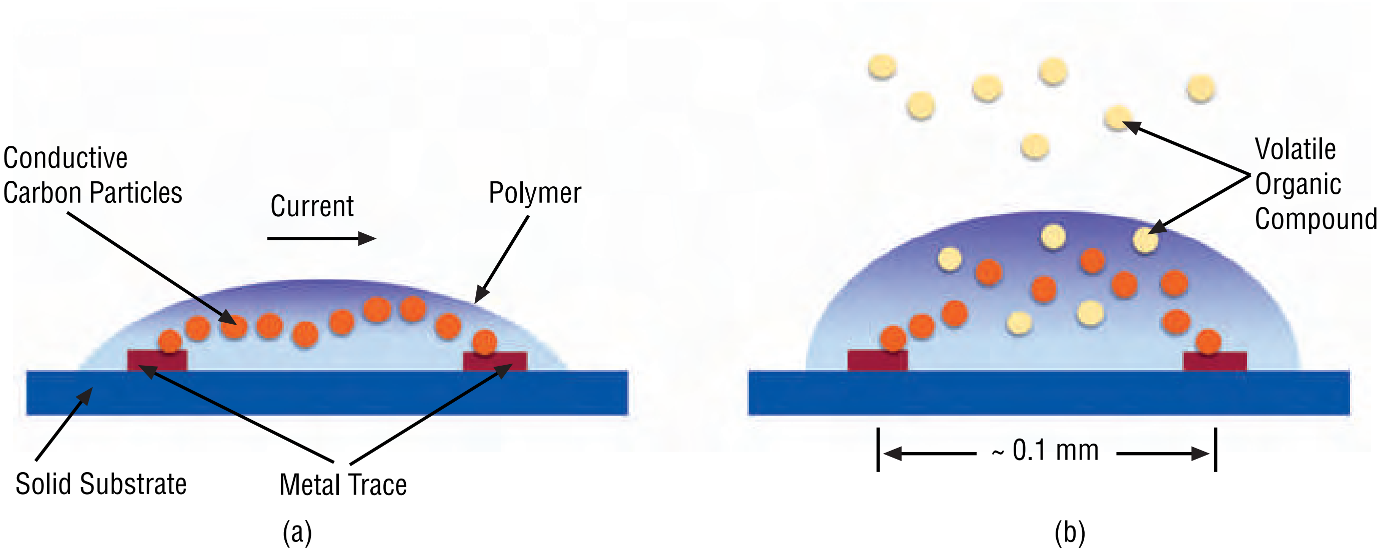
Traditional sampling methods involve physically collecting water, gas, or soil samples, documenting them and taking them to a laboratory for analysis. This process can become expensive, with each sample analysis alone costing from $100 up to $1,000.

Sensor package with cable, showing white GoreTex® membrane in center.

The "sniffer" approach is designed to leave sensors at the site. The system transmits information about specific contaminants and their concentrations to a data collection station. Information can be downloaded and analyzed to determine if follow-up is needed.

Chemiresistor Arrays

The heart of the system is an array of tiny sensors that can detect different volatile organic compounds. These compounds, called VOCs, comprise a family of contaminants including solvents, degreasers,



VOC detection by a thin-film chemiresistor: (a) Electrical current flows across a conductive thin-film carbon-loaded polymer deposited on a micro-fabricated electrode; (b) VOCs absorb into the polymer, causing it to swell (reversibly) and break some of the conductive pathways, which increases the electrical resistance.

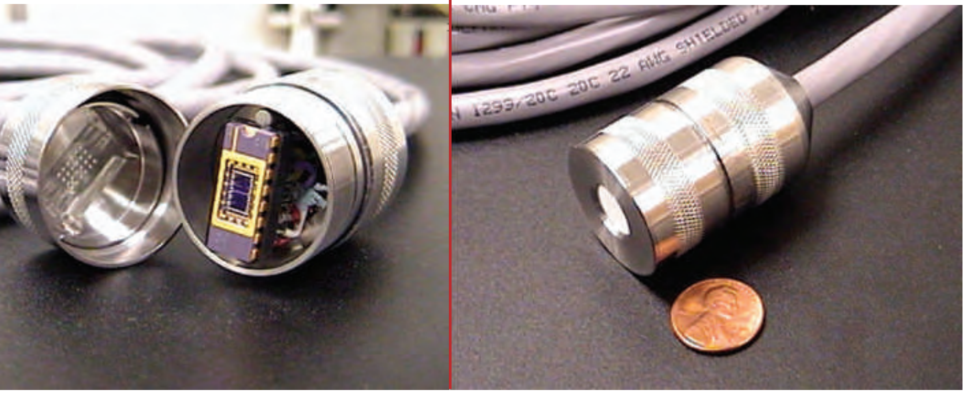
In contaminated water, VOCs will move across the membrane into gas phase, where they are detected by the chemiresistors.

hydrocarbons, and alcohols. Because of past commercial use, they are often found as contaminants in groundwater.

Each sensor, called a chemiresistor, is a polymer-absorption device fabricated by dissolving commercial polymers in a solvent with conductive carbon particles. The ink-like fluid is deposited and dried on wire-like electrodes on a specially designed microcircuit. When contaminants, such as VOCs, are present, they absorb into the polymers. This causes polymer swelling, which changes the electrical resistance of the material. These resistance changes can be measured and recorded. They can be used to calculate the concentration of a contaminant in the vapor that is in contact with the polymer.

The polymers shrink if the chemical or contaminant of interest is removed, causing the material to revert to its original state and electrical resistance.

An array of different sensors can be used to identify various VOCs by comparing resulting chemical signatures with those from known samples. “By using four different kinds of polymers — one for each sensor — we think we can detect and identify all solvents of interest,” says Hughes, who developed the sensors for the project.

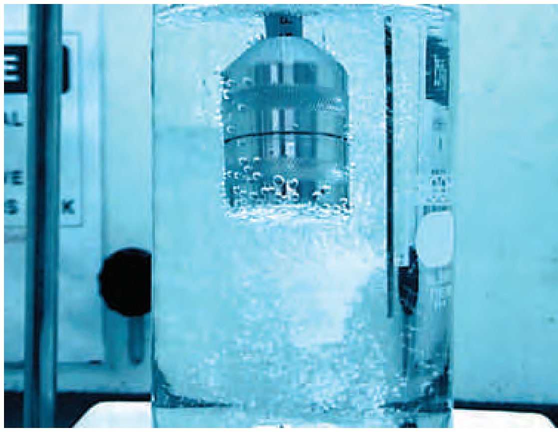


Left: Sensor package taken apart, exposing chemiresistor sensor chip inside.
Right: Sensor package with penny for scale.

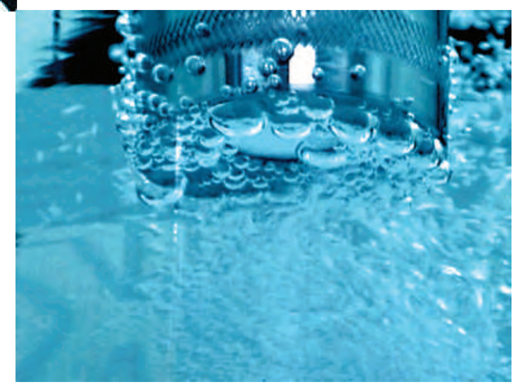
Waterproof Housing

To allow the array to get to a place where it is needed, Ho and his colleagues designed a tough package that can be used in water or underground. The package is small — just an inch in diameter — but allows the chemiresistors to be exposed to contaminants in both gas and liquid phases. A small space within the package allows liquid phase to

The electronic sniffer approach began at Sandia with internal Laboratory Directed Research and Development funding. Now, Ho and Hughes see the next step as partnering with a company to work on manufacturing and quality control issues.



Sensor package being tested underwater during air sparging, a remediation method to strip contaminants from the water by injecting air into the water.



Bubbles accumulating on Gore-Tex® membrane during underwater sparging. Bubbles dissolve as the gas partitions through membrane.

pass into gas phase across a GORE-TEX® membrane. Like clothing made with GORE-TEX®, the material repels liquids but allows vapors to "breathe" or diffuse across the membrane. In contaminated water, VOCs will move across the membrane into gas phase, where they are detected by the chemiresistors.

"The package is modular, like a small, water-tight flashlight, and is fitted with o-rings, so it can be unscrewed, allowing for easy exchange of components," Ho explains. "We needed a rugged housing and this one has worked out in our lab and field testing."

Inside the package the chemiresistor array chip is placed on a 16-pin dual inline package connected to a long weatherproof cable. The cable, in turn, can be connected to a data logger. Measurements are made with DC voltages, allowing the cables to be almost any length.

Durability Testing

Data was logged for several months at a remote Sandia chemical waste landfill to test the robustness of the sensor package. Later tests were also conducted at the DOE's Nevada Test Site, north of Las Vegas, using controlled exposures to a VOC.

"At this stage, the system isn't going to replicate EPA sampling method quality," says Ho. "But it has the potential to reach the reliability and quality that would do that."

Current challenges include learning and responding to how sensors will react to humidity, temperature, and barometric pressure changes. Researchers must also learn how the various polymers in the chemiresistors will react to unknown chemicals.

The electronic sniffer approach began at Sandia with internal Laboratory Directed Research and Development funding. Now, Ho and Hughes see the next step as partnering with a company to work on manufacturing and quality control issues. "An interested company could commercialize the technology by working with Sandia," Ho says.

Palm-top µChemLab™ Quickly Identifies Hazards

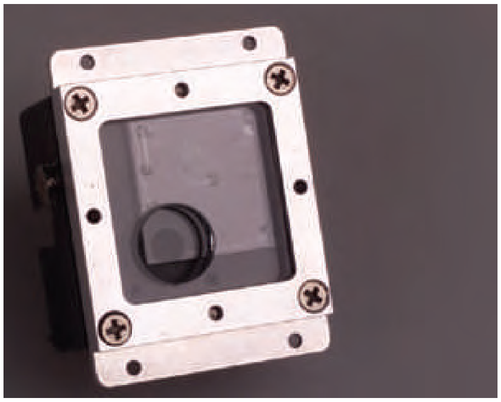
by Nancy Garcia

Like the unique whirls and ridges of fingerprints lifted by an evidence technician to identify a suspect, chemical and biological agents tip their presence through distinctive signatures.

Thanks to Sandia research — begun by the largest Department of Energy (DOE) investment of its kind —a growing list of hazards can now be quickly detected for the first time with a palm-top device . The µChemLab™ invention places the capability of a fully staffed chemistry lab at the fingertips of a trained operator.

Initiated in 1996 through Sandia's first "Grand Challenge" Laboratory-Directed Research and Development project, the multi-million µChemLab™ research effort shrinks and speeds standard chemical analysis equipment that has occupied lab benches as far back as the 1950s.

The capability to rapidly detect suspected agents was a key feature of antiterrorism briefings that Homeland Security Director Tom Ridge received after the September 11, 2001 attack. "It's that kind of creative genius that I think we can count on in making our homeland more secure," Ridge said. Rather than waiting hours for confirmation from a distant lab, emergency responders should soon test prototypes of µChemLab™ to sniff out danger in minutes.



This view of the sensor shows the microfluidic chip (seen from the bottom up) where the detection-system laser shines on the separation channel. The laser light is a slightly shorter wavelength than that used for DVD players.

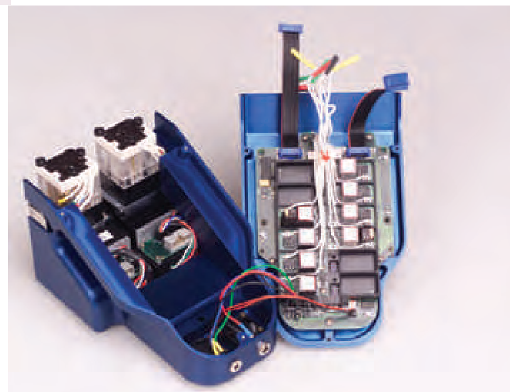
Sandia's John Vitko, Terry Michalske and Al Sylwester led the Grand Challenge that merged Sandia California and New Mexico proposals. "It's a tremendous example of what Sandia does best, which is systems integration," John said. "We had 40 to 80 people on the project, and making it work involved not just one miracle but many. It's a prime example of what can be done with microelectromechanical systems (MEMS) to create a fully integrated hybrid device. (See related story on page 10.)

"It's proved to be a tremendous success. We're really just beginning to take off. It's ready for commercialization in its own right, with applications to water quality, medical research and biotechnology."

With a market study to guide investment decisions, DOE funders soon saw the value of devoting "critical mass" to such a project, said Laboratory Directed Research &

The gas-phase μChemLab™ has been field-tested at the U.S. Army's Chemical and Biological Center in Edgewood, Maryland and with simulated contaminants (mixed with concrete dust) at the Nevada Test Site.

Both speed and sensitivity are enhanced by analyzing small sample quantities; here a module is shown next to a 25-cent piece for scale.



Two modules fit in the back of the sensor, where they are easily accessible to the user.

Development program manager Chuck Meyers. An external review panel also gave high-level credibility and exposure to the work.

Researchers first demonstrated detection of chemical warfare agents on a system that analyzes gases. In liquid analysis, the team spotted biotoxins (poisons from plants or microbes) and traces of explosives (important for environmental restoration). Next may come evidence of disease-causing viruses in liquids, while the gas-phase application is also being broadened to detect toxic industrial chemicals.

"That's probably the bigger threat," said Richard Kottenstette, one of the investigators with the gas-phase detection team centered in New Mexico, "and if it's not just for chemical warfare agents, first responders will be more likely to use it, keep it calibrated and keep the batteries fresh."

The gas-phase μChemLab™ has been field-tested at the U.S. Army's Chemical and Biological Center in Edgewood, Maryland and with simulated contaminants (mixed with concrete dust) at the Nevada Test Site. "We tracked the plume as it drifted over the instrument trailer," Kottenstette said.

A prototype (in temperature-enclosed housing) was installed this summer in an airport air-handling system. This preceded trials in a subway setting, complicated by iron track-dust and heat and humidity swings.

The compact, simple gas chromatograph identifies about a dozen agents. Their tell-tale mass is measured when they impinge on a quartz crystal bearing a coated surface acoustic wave detector. When the coating absorbs the compound, a wave traveling the surface changes frequency, much like a drum will change tone if a hand is placed on the vibrating surface. "It's like a little mass balance that ultimately becomes an electronic signal," Kottenstette said.

The chip's mass detection snugly employs on-chip application-specific integrated circuits created by Sandia. It also compresses

The sensor system is field-portable.

A second-generation prototype to separate proteins in liquids, released in June, runs eight hours on lithium camera batteries. Its redesigned light-tight optical detection system boosted sensitivity about 10 times; a molecule as dilute as one in a million can be spotted.

an 86 cm-long separation column into a coil about 1 cm per side. The column, just 400x100 microns wide, has a chemical lining that essentially sifts mixtures into homogenous clumps that emerge over time. Time of appearance and mass indicate their identity.

"Tuning" especially enhances the micro-device's efficiency. A pre-concentrator retains potential chemical agents and excludes volatile organics. The concentrated sample is released into the column, where separations need no special carrier gas. "It's very, very sensitive," says program manager Duane Lindner. Research and development partnerships for the gas-phase system are already under way in both the petroleum and pharmaceutical industries, while aspects of the liquid-phase work are also subject to partnership agreements.

As he negotiated a memorandum of understanding last fall between the DOE and Britain's Ministry of Defence, Gen. John Gordon (then National Nuclear Security administrator) walked through the Defence Science and Technology Laboratory at Porton Down, England and shook hands with Julie Fruetel, who led a field trial detecting ricin strains there. Fruetel heads a 20-member team on the liquid-phase separation work in California. "It's a flexible research platform," Fruetel said.

A second-generation prototype to separate proteins in liquids, released in June, runs eight hours on lithium camera batteries. Its redesigned light-tight optical detection system boosted sensitivity about 10 times; a molecule as dilute as one in a million can be spotted. The new system carries two separations modules in which proteins tagged with a green dye are separated in just a few minutes, then illuminated by an ultraviolet laser diode and visualized through a green filter. A variety of electrophoresis schemes quickly sort on the basis of charge and size to identify protein toxins. Employing more than one scheme at the same time is a unique feature that increases reliability and specificity. The group plans next to focus on identifying viruses. When pre-concentration is added, sensitivity should increase up to 500 times.

"You'd like to see a thousand times less than the hazardous limit, to detect well below lethal concentrations," said Art Pontau, Microfluidics department manager. Developed in parallel, the gas and liquid-phase systems will be combined into one tool by 2008 – possibly as soon as 2005.

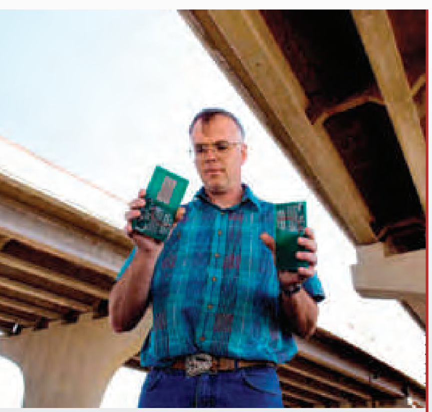
Sensor-MEMS work shrinking µChemLab™

An important example of microsensor and microelectromechanical systems (MEMS) cooperation at Sandia is recent successful work on miniaturization of the µChemLab™. A collaboration between several researchers and groups at Sandia has produced a hand-held analysis tool constructed with integrated, micro-fabricated devices built in cooperation with two different micro-fabrication laboratories. In the case of the µChemLab™ , a sampling device (called a preconcentrator), a gas chromatograph column and two sensors (called flexural plate wave sensors) needed to be fabricated at the micron scale.

The ongoing work combines the three elements into a single monolithic crystalline device. "We use technologies adapted from integrated circuit manufacturing to create these devices," explains Ron Manginell, of the Labs Micro Analytical Systems department. The performance of MEMs for handling tasks at the micro-scale has made the sensors very sensitive, he says. After preconcentration of the sample, gas molecules selectively adhere to coatings on the surface of the chromatograph column and then release. Testing of the flexural plate wave sensors shows good performance so far.

The current version involved a cooperative processing approach using both Sandia's Microelectronics Development Laboratory and the nearby Compound Semi-conductor Research Laboratory. This combined approach is important technologically and because of the cross-lab coordination it demonstrates, Manginell explains. While testing is still under way on many aspects of this micro-scale version, the potential for uses of the µChemLab™ is even greater as its size and manufacturing costs are reduced.

Available Power for Remote Uses



As remote applications become more and more feasible in terms of sensor capability, the problem of powering sensors in faraway and difficult locations is gaining more attention from Sandia researchers.

Two recent innovations illustrate progress in this area:

- Sensors that use natural vibrations from the buildings and bridges they are located in to make electrical power, and
- Glucose-powered micro fuel cells, which convert sugar in plants or even human skin into low-level power.

Sensors aren't the only potential uses for these new power sources, but they are an important possibility.

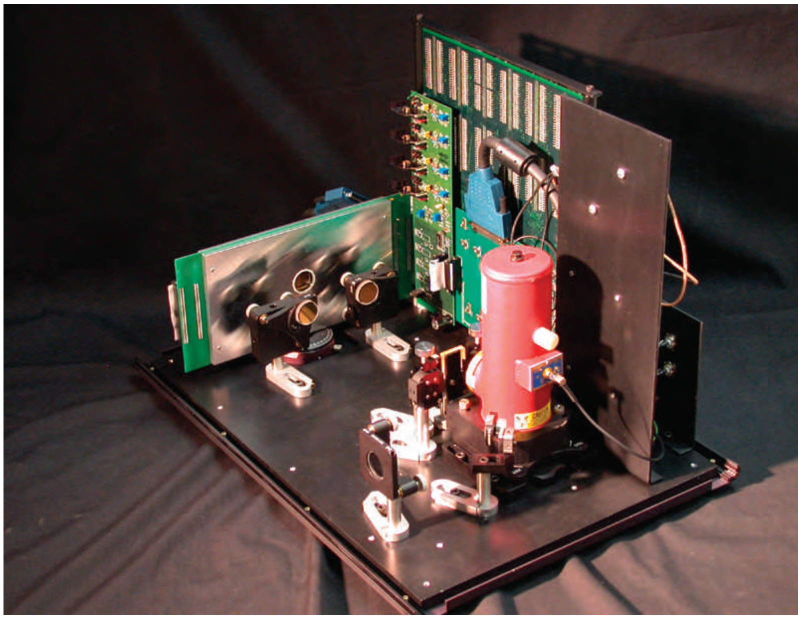
A Sandia team led by Kent Pfeiffer (photo at left) has designed and demonstrated the concept of a wireless, battery-free sensor and data-storage device, powered by structural vibrations. The device uses piezoelectric materials attached to the structure to generate current. These materials change crystalline alignment under stress and produce an electrical charge.

With his Sandia colleagues, Pfeifer created the device in cooperation with Sandia's Architectural Surety™ Program. Microsensors could be used to measure stresses, strains, temperature changes, and other data on beams, buttresses and other key building features to check the structure's overall health, says Pfeifer, who works in the Labs' Microsensor Science and Technology department. Work on integrating and testing a complete self-powered microsensor system is planned.

As part of a Laboratories Directed Research and Development "Grand Challenge," Sandia researchers are also working to demonstrate an integrated glucose-fueled micropower system by the end of 2004. To date, the program team, led by Doug Loy of Sandia's Chemical and Biological Technologies department and Kent Schubert, of the Labs' Microdevice Technologies group, has demonstrated the feasibility of converting glucose to electricity. Researchers from the Labs' Microsensors Research and Development, Biosystems Research, and Integrated Micro-systems departments are involved in the project.

The team has created a polymer electrolyte membrane that has particular promise for silicon-based micro fuel cells, and even conventional large-scale fuel cells. Work is under way to develop a fuel harvesting interface and enzyme catalysts to replace conventional precious-metal catalysts. In its final form, the system is expected to be only the size of a matchbox.

Analyzing Hazards From a Distance



Scientists at Sandia, Honeywell, and Massachusetts Institute of Technology are moving ahead on a sophisticated device, called a Polychromator, which combines optical and micro-electromechanical systems (MEMS) to identify plumes of hazardous chemicals safely from a distance.

An environmental engineer assays the types of gases escaping from an industrial smokestack. A soldier eyes a cloud of battlefield smoke to determine if chemical weapons are in use. A firefighter checks the black cloud pouring out of a blazing industrial warehouse to see if it is safe to enter. Hazardous materials responders analyze vapors from a railcar spill to determine if harmful chemicals are present.

With a device now under development by a team from Honeywell, Massachusetts Institute of Technology, and several Sandia organizations, these determinations will be made safely from afar — possibly miles away. The device, which can remotely analyze and identify a gas in a matter of seconds, is now feasible in a highly portable form.

And scientists at the three institutions are moving ahead jointly on an even more sophisticated version, called a Polychromator, which combines optical and microelectro-mechanical systems (MEMS) to expand the number of possible gases and speed the identification.

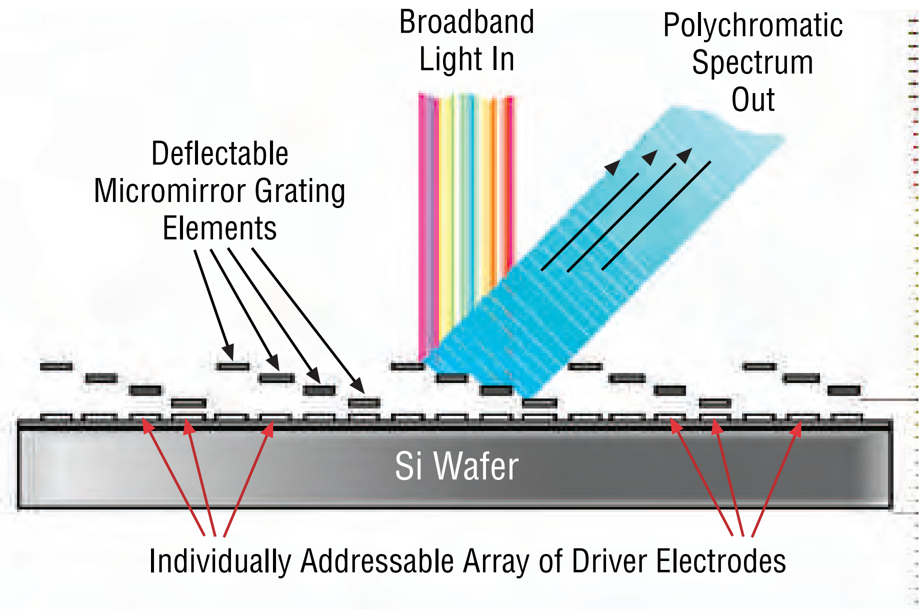
The Polychromator is at a critical time in development, explains Mike Sinclair, of the Labs' Microsystem Materials, Tribology and Technology department. Funding from the Defense Advance Research Projects Agency has wrapped up and Sandia with its partners are concluding work on three working prototype devices (photo above). Laboratory testing comes next.

"Our goal is to show that chemical sensing with the Polychromator is useful and worth doing," says Sinclair. "We've characterized the chip, the electronics and the optics individually, but now we've put them together and we need to test their ability to see different gases."

Infrared Analysis

The concept of remotely identifying various gases is based on a process where infrared light passes through a gas sample. Each gas creates a distinct pattern of colors in the light that can be used to identify it. "The idea to use infrared signatures to detect chemical species has been around for years," explains Sinclair. When he and a colleague started thinking about the remote detection concept in 1994, Sinclair worked out a computer program to link these known patterns with a series of microscopic reflective ribbons, called diffraction gratings, deposited on a silicon chip.

One gas analysis technique involves carefully reading each wavelength and intensity in a spectrum and consulting known values to identify it. A faster approach is to compare the



The system works when the light from a gas plume or sample is gathered by an optical system — such as a binocular set — to strike a chip.

patterns without the detailed wavelength information and simply determine if there is a match. "With this approach you can look at dozens of gases in seconds and it scales down to a smaller size more easily," says Steve Casalnuovo, manager of Sandia's Microsensors Science and Technology department.

The system works when the light from a gas plume or sample is gathered by an optical system — such as a binocular set — to strike a chip. The research team first proved that by etching patterns, or gratings, for a specific gas type on a silicon chip, gases could be identified. Thus, using a series of chips and a moving wheel or similar device, an operator could quickly compare light from a gas in the field with a dozen or so known patterns. This short-term solution could be brought forward toward market now, Casalnuovo believes.

Moveable Gratings Approach

In a more sophisticated Polychromator version, a microprocessor within a chip manipulates movable gratings (diagram above) through a series of configurations. This processing, accomplished by changing the heights of each ribbon, makes the identification faster than a configuration with individual chips for each comparison, Sinclair explains.

"It should be sensitive and able to discern quickly between chemicals with similar infrared spectra." Microelectromechanical systems, or MEMS, made possible the concept of up-and-down moving gratings, allowing multiple configurations. The chips are manufactured with standard microlithography techniques of masking and etching used in integrated circuit manufacturing.

An extensive effort by Honeywell resulted in a chip about the size of a dime with more than a thousand MEMS gratings, each about 10 microns wide and one centimeter long. Quality has improved with each new batch, Sinclair says.

Sandia took the chip and surrounded it with a design for the optics system assembly tasks and will be responsible for testing, along with other potential customers.

These tasks are posing a number of challenges. For example, the electronic configuration, used to control voltage of each of the 1024 gratings, is presently much larger than the chip. While the electronics are more difficult to scale down, Sandia is currently working on approaches to make the electronics-MEMS interface compatible during chip manufacture, explains Kent Pfeiffer, also of Sandia's Microsensors Science and Technology department. He worked with Honeywell on the massive job of electronically bonding each of the gratings during the prototype construction.

Researchers generally agree that integrated optics and electronic miniaturization is achievable in the future with a development effort. Once the feasibility of the system is demonstrated, Sinclair believes, funding and interest will follow for the third phase of the project — miniaturization and increasing the product's ruggedness.

Micromachines and Sensors: the Road Ahead

Using micromachines that can handle samples, separate chemicals, switch electrical and optical signals, and conduct other tasks in combination with sensors, is providing greater versatility and surprising new applications in increasingly smaller packages.

The combination of microelectromechanical (MEMS) structures, or micromachines, with other sensing devices is opening up a variety of possibilities, says Jay Jakubczak, deputy director for Microsystems Applications at Sandia. Using MEMS — in the form of tiny machines that handle samples, separate chemicals, switch signals, and do other tasks — provides greater versatility in increasingly smaller packages, Jakubczak notes.

In addition to Sandia's work with its micro-chemistry lab, or µChemLab™, (see page 7) and the Polychromator (page 11), the examples here show some ways Sandia is bringing MEMS and sensor technologies together to address customer needs.

Analyzing modes of failure in critical warfighting components

There's a reason Bob Cranwell's office at Sandia in Albuquerque is filled with models and photos of F-16s, the new Joint Strike Fighter, and Apache attack helicopters. Cranwell and his staff in the Systems Sustainment Program department are helping to keep these birds in the sky.

As manager of a team of mathematicians, statisticians, modelers and simulation experts, Cranwell is far from the flight-line, but at the forefront of an innovative approach to aircraft maintenance, called Prognostics and Health Management, or PHM. "This is the next step in preventative maintenance," says Cranwell, "instead of waiting for things to fail."

One key to this approach is the use of miniature sensors to provide the PHM data. "The idea is to use sensor technology on critical components or parts of a system to determine if things are out of the ordinary, like vibrations, fluid quality, oil contaminants, electromagnetic fields," says Cranwell. "You want miniaturization so as not to add cost and weight."

Cranwell's team uses sensor data to determine abnormal performance, and then goes to the next step. "The sensor provides the diagnostic information. We take the data and do a prognosis to provide an estimate of remaining useful life. We say, given a certain mission profile, here is the optimal maintenance strategy. That's the health management part of the work."

For an example, consider the F-16 accessory drive gearbox. Located directly in front of the engine, this complex system literally keeps the F-16 from dropping out of the sky. It operates a variety of wing and tail surface controls and provides an engine starter, among other things. Similar gearboxes

The PHM team develops mathematical formulas to manipulate sensor data to answer the question "What is the health of this component and what is the best thing to do?"

can be found in other high performance military aircraft, including the Joint Strike Fighter, now in development.

Presently the gearbox manufacturer recommends the equipment be replaced after a certain amount of flight time. But the experience of Air Force maintenance personnel shows that some gearboxes fail earlier than the recommended time change interval and many others look almost new at changeout. "We need to get smarter and put in sensors to determine vibration, hydraulic contamination and other factors to get a longer life out of these parts and save money," says Cranwell. "To replace a gearbox, you have to pull the engine. It's a big expense."

The PHM team develops mathematical formulas to manipulate sensor data to answer the question "What is the health of this component and what is the best thing to do?" in a variety of situations. Consider a hypothetical situation where data from refueling and re-arming an F-16 shows the gearbox is likely to fail in ten hours. Maintenance workers can look at the mission profile and make a determination. Is it a one-hour sortie without any "high g" maneuvers? Is evasive action likely that will put stress on the plane's systems? "A maintenance team can run the simulation in a wartime scenario and make a determination about the safety of the aircraft."

Researchers have begun work on the PHM concept by attaching microsensors to shop instruments in Albuquerque and at a DOE facility in Kansas City and have used the data to develop life prediction algorithms. Applications extend in many directions, Cranwell notes. Naval aircraft carrier designers are interested in the PHM approach as a way of improving safety and reducing personnel.

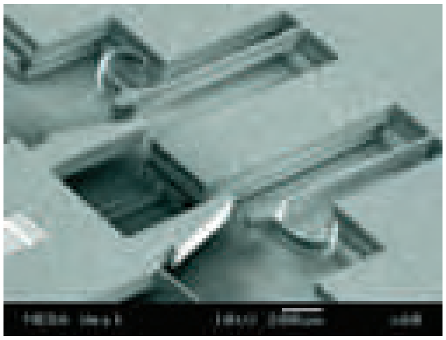
Arming conventional weapons in an unconventional way

For America's conventional weapons stockpile, the term "safe, arm, fuze and fire" bespeaks technology designed to keep a weapon safe until it's readied for detonation. Now Sandia is working to make these devices more robust and at the same time micro-sized.

Darren Hoke, project manager for this effort, carefully spills a small handful of parts across his desk. They comprise the safe, arm, fuze and firing mechanism for a mortar shell. They easily fit into an egg-sized dome atop the shell. Components like these are manufactured by a small and declining number of vendors, he explains. They are assembled by hand. Dissimilar materials used for different parts of the mechanism create worry in terms of the device's shelf life.

Next, Hoke, from Sandia's Electromechanical Engineering department, picks up a quarter-inch cube. "We want to replace these parts with this," he says. The cube is the first generation of what researchers are calling MicroFuze — a MEMS safety and arming device.

The cube has three silicon wafer layers etched or treated using techniques adapted



MEMS Safe and Arm Device fabricated at the Compound Semiconductor Research Laboratory

from the manufacture of integrated circuitry. "The device has to react to the acceleration of being shot out of a gun barrel, which is very different from being dropped on the floor or other shocks," Hoke explains. This acceleration releases a bar, unlocking a sliding plate. "The device also has to sense the spin created by the rifling in the barrel and react to it." Spin forces slide the plate until it snaps into a new location, which aligns fuzing and firing mini-explosives.

In addition to these aspects of weapon control in a high-gravity (1000g's), high spin (2000 rpms) environment, the US military now is looking for smarter weapons as well. "We learned in Desert Storm that we need weapons that will go to very deeply buried targets," says Hoke. Reaching these targets means even higher acceleration levels. "One of the things in favor of MEMS technology is that the smaller the mass of an object the higher its tolerance."

"The device has to react to the acceleration of being shot out of a gun barrel, which is very different from being dropped on the floor or other shocks."

Weapons that can sense where they are in a building or structure are a new goal for designers. Existing accelerometers help with this awareness, but have limitations. Researchers are looking at a way to replace these accelerometers with un-powered MEMS sensors. The sensors would use a sliding mechanism, similar to the MicroFuze, to sense shocks. Multiple sensors could work together to determine where in a target environment the weapon is.

Processing these MEMS devices is far from routine, says Hoke. "Getting the mechanical structure to do things in a certain way was very difficult." A second problem area involves starting a series of successively larger blasts beginning with a hole on the order of several hundred microns in diameter filled with explosives. "We are pushing the size and control boundaries for materials in microprocessing," says Hoke.

While many laboratories are looking at MEMS solutions to these weapon issues, Sandia's Microsystems expertise gives it an edge. "We hope to prove the MicroFuze principle by 2003 and test it at the systems level at one of the Department of Defense fuze laboratories," Hoke explains. By using artillery shells for proof of principle, a huge database on device reliability can be built more quickly. "These shells are manufactured by the tens of thousands," Hoke notes. "Then we can move to other weapons."

Micro-sizing a proven intelligence-gathering device

The value of synthetic aperture radar (SAR) has literally soared in recent years. With Sandia's development of the Lynx system in 1999, the 120-pound radar was fitted to both manned and unmanned aerial vehicles (UAVs). From these platforms it provides photographic-like images through clouds, in rain or fog, and in day or night conditions. The real-time SAR system produces fine resolution images at ranges of up to 50 miles.

"SAR has proven its value for intelligence and reconnaissance," says George Sloan, a researcher in Sandia's SAR program. "We've done some good things in terms of fielding these instruments and making contributions to soldiers in the field."

But the pressure is on, Sloan explains, to make a new generation of SAR that's

"SAR has proven its value for intelligence and reconnaissance. We've done some good things in terms of fielding these instruments and making contributions to soldiers in the field."

smaller and lighter. The smaller version is being called mini-SAR. "Our customers need systems that are smaller without sacrificing quality," says Sloan. Customers want to use SAR in guided weapons, tactical (smaller) UAVs, or as part of multiple sensor platforms that are getting more and more crowded.

Working toward goals of a 30-pound system and eventually a 20-pound version, Sloan believes that microwave frequency MEMS may offer attractive enhancements to next-generation SAR subsystems.

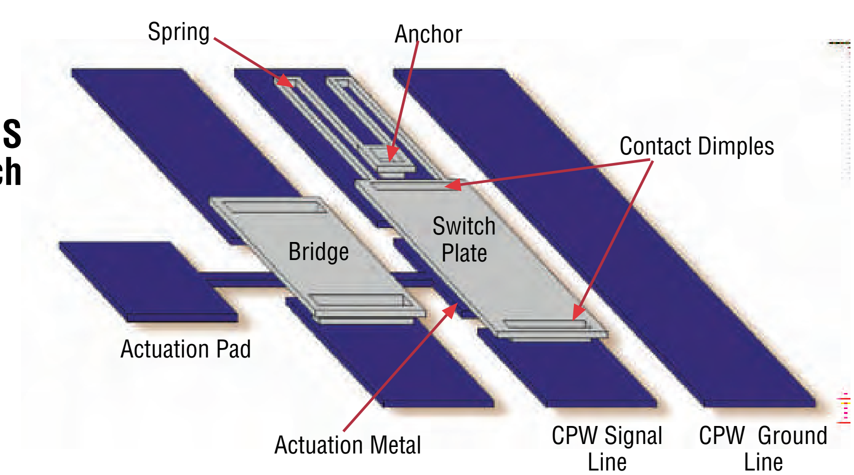
"There are several technologies that may help reduce size and weight to enhance mini-SAR," says Charles Sullivan, who manages Sandia's Radio Frequency (RF) Microsystems Technology department. One is an RF switching device, using MEMS, that can create phase shifts or time delays along an array of antennas. These phase shifters have the affect of "tilting" the phase, which alters the direction of the array's beam, Sullivan explains. Unlike current dish antennas with mechanical gimbals that direct it, the active phased array does not require actual movement of the antenna, only programming of the switches to change the phase tilt, or direction.

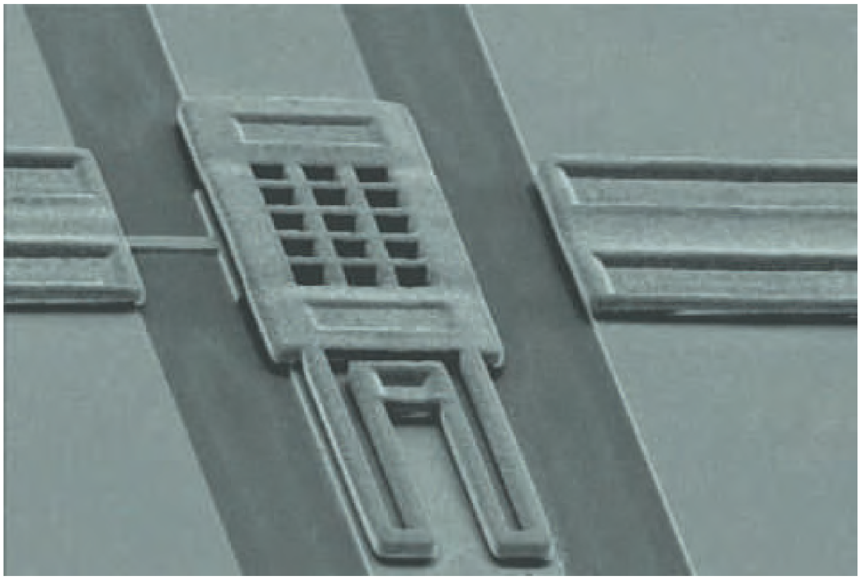
Among the many advantages of this approach are the facts that the phased array can be put in a smaller space, even a curved space, and it does not require a "front-end" location on a platform. Also, it offers the potential for novel radar modes, since the beam can be steered much quicker than standard gimbaled versions. "We have more freedom to put it where we want and reduce the size of the overall system," Sullivan says. RF MEMS offers the potential for a substantial reduction in microwave loss with wide bandwidth, compared to conventional approaches used today in phase shifters.

Also being studied are solid-state power amplifiers built with materials, such as gallium nitride (GaN). The goal of these devices is to realize high output microwave power at high efficiency to replace the vacuum tubes and modules currently used. This should also reduce the size of the radar. MEMS technology approaches, such as micro-channel heat-pipes, are being looked at to help manage the heat spread from these solid-state devices.

Sullivan's group is now using micro-fabrication techniques at Sandia's Compound Semiconductor Research Laboratory to

MEMS RF Switch





The perspective view (facing page) along with the process diagram (below) illustrate the complexity of creating microswitches like the one shown at left.

> *"There are several technologies that may help reduce size and weight to enhance mini-SAR."*

develop MEMS RF switches and power amplifiers to provide micro-system replacements and enhancements for existing SAR components. "These are in the early stages right now. We are still asking what can be done, how do you do it, what are the problems and how do you fix them? While laboratory demonstrations have been very encouraging, a product in the field may be years away," Sullivan notes.

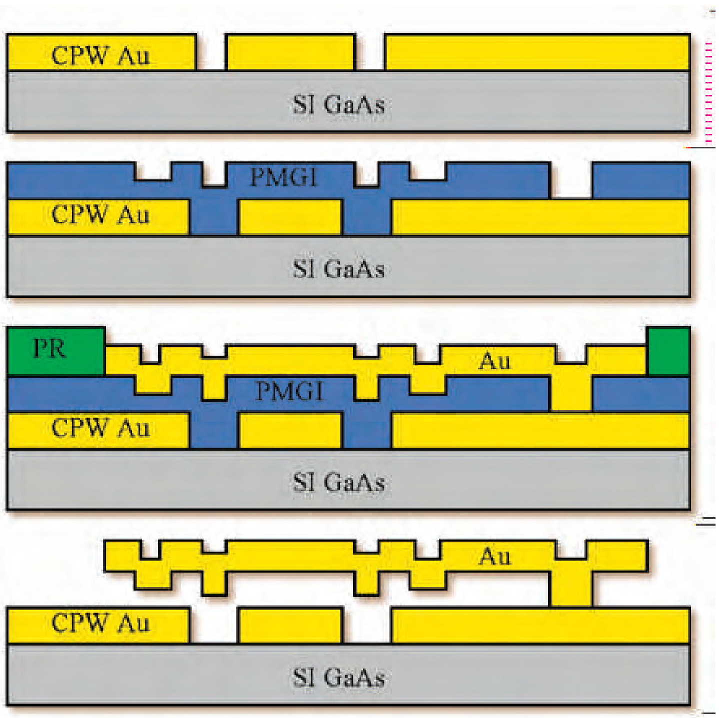
The first version of mini-SAR is expected within the next 18 months. As RF MEMS and GaN technologies become available, they will be integrated into even smaller versions of Sandia SARs.

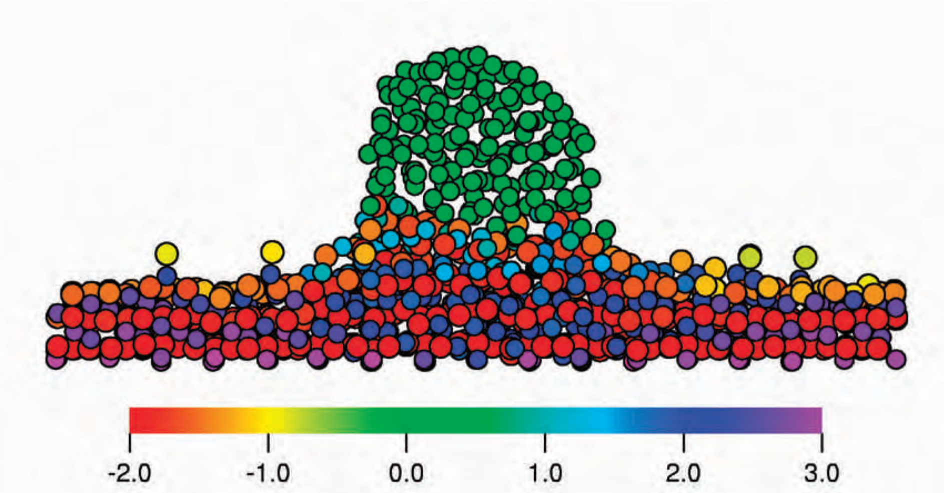
Bringing new technology from the lab to the field

As Sandia researchers move ahead with applications for microsystems combining MEMS and sensor technologies, a major unresolved issue looms over the work. "Will these devices work in the field twenty years from now and work on demand?" asks Duane Dimos, deputy director for operations and planning in Sandia's Materials and Process Sciences Center. "We are concerned that these systems are as reliable as they need to be, and how do we determine that?"

Sandia must address microsystem reliability if this technology is to be adapted by weapons users and designers for the Labs' primary mission. Microsystem reliability is also a concern in industries and applications such as space and conventional munitions. "So this is an opportunity to work with industry on problems generically important to all of us. We think there are some real contributions Sandia can make to move forward toward confidence in microsystem reliability."

With encouragement from Marion Scott, director for the Labs' Microsystems Science, Technology and Components Center, several key managers and staff got together to





This molecular dynamics simulation of an interaction of aluminum on alumina is an example of how Sandia scientists are working to understand aging and reliability issues in microsystems.

"We brought together experts from a lot of organizations with different backgrounds — design, modeling, microsystem technology, manufacturing — to determine the key questions that need to be studied and resolved."

develop a program to understand reliability issues. "We brought together experts from a lot of organizations with different backgrounds — design, modeling, microsystem technology, manufacturing — to determine the key questions that need to be studied and resolved," Dimos says.

The result is an effort that has been put together with funding from multiple Laboratory Directed Research and Development projects and pieces of the Nuclear Weapons Science & Technology program, to create a coherent approach to the science and engineering issues.

"We already had some prototype devices, so our thought was why don't we take lessons from what has been previously done with larger systems and isolate microsystem components within controlled environments so we can protect against some environmental variations they might encounter," explains Fred Sexton, manager of Sandia's Reliability and Radiation Physics department. "This would be a much quicker path to proving reliability for national security applications."

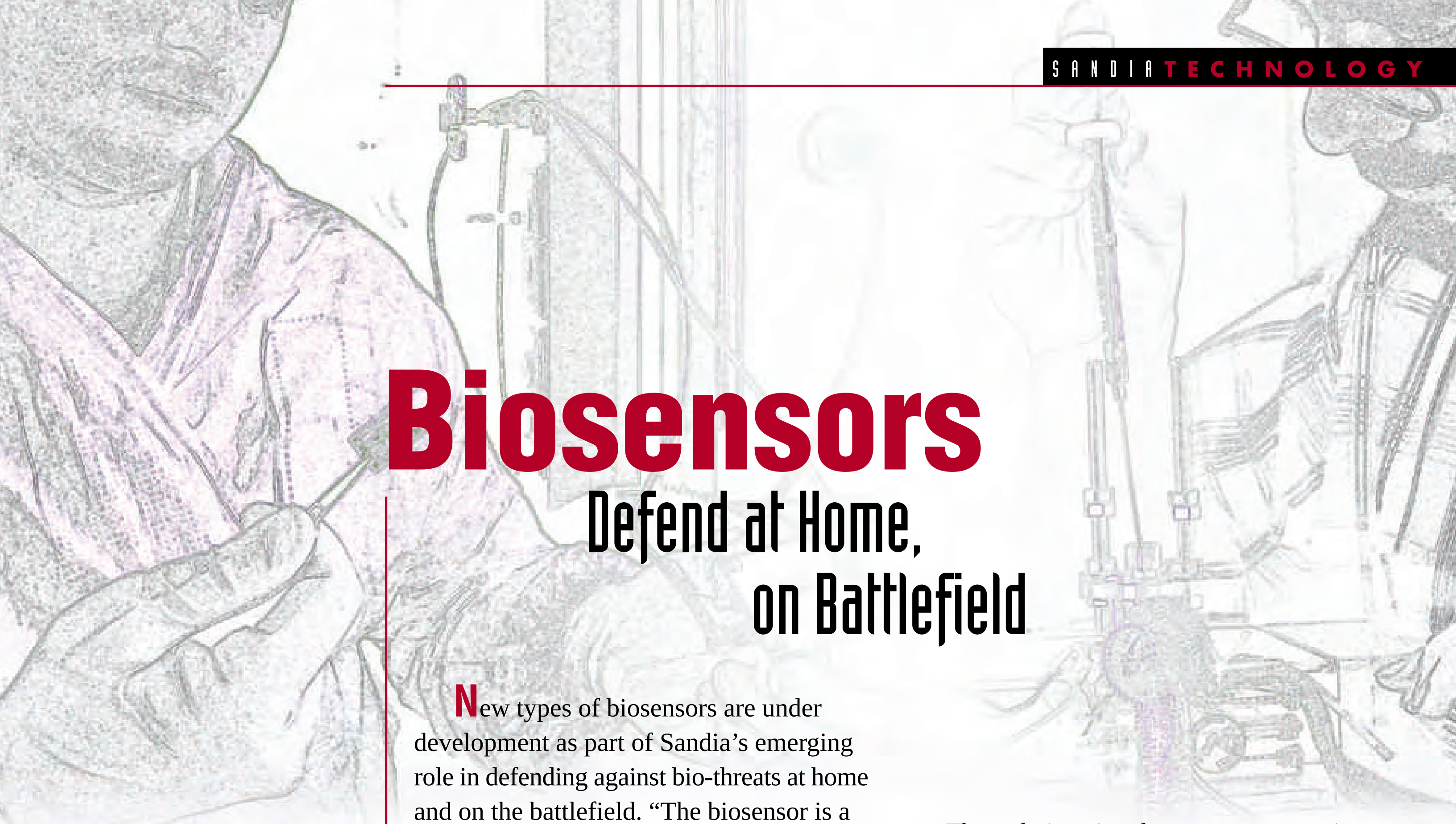
"If a chip will only see a certain temperature range or shock profile, instead of the entire range of possibilities, it will be much easier to qualify a new technology faster and cheaper. Right now qualification cycles can be in the multi-year range," adds Jay Jakubczak, deputy director in the Microsystems center. This "micro-packaging" could even allow device designers to use commercial technologies in some cases, instead of developing custom components, he notes.

"We're not starting from scratch. A lot has already been done to understand the physics of failure in microsystems at the component level, but now we need to understand reliability issues at the assembly level," says Sexton. In some cases, up to five years of reliability data is already available. Sexton outlines a four-part attack on reliability:

- Develop a controlled environment for microdevice packaging, using active and passive methods;
- Work to gain a better scientific understanding of device aging and reliability issues;
- Find ways to measure internal microsystem environments and surfaces to better describe and resolve reliability problems; and
- Develop test structures to test at the micro-fabricated chip level, after micro-packaging, and in field-ready devices.

"We cannot just test, test, test," says Sexton. "We need a scientific approach to understand how to test and what to test and how to develop and validate models."

"In the next three to five years, we have to figure out if these systems are going to have the kind of reliability that is demanded," says Dimos. Maybe we won't have complete answers, but we need to develop answers that will allow our system designers and engineers to move microsystem technologies forward for use in critical applications."



Biosensors

Defend at Home, on Battlefield

Biological agents — viruses, anthrax and other bacteria — have become the targets of several sensors now under development at Sandia.

New types of biosensors are under development as part of Sandia's emerging role in defending against bio-threats at home and on the battlefield. "The biosensor is a part of our anti-terrorist strategy," says Al Romig, vice president for Science Technology and Partnerships at Sandia. "One aspect of this strategy is prompt and accurate detection of a biological threat."

Sandia's unique contribution will be in the integration of physics, engineering, and chemistry with biology by way of applying materials science, microsystems and information technology to the problem, Romig believes. Here are some examples of current Sandia approaches.

Burning Bacon – the pyrolization approach

Curtis Mowry, of Sandia's Micro-Analytical Systems department, is leading an effort to develop an anthrax detector using microfabricated components that can recognize the deadly biotoxin in only a few minutes. Identification of anthrax in five minutes, rather than the hours currently needed, is a critical step in alerting building occupants to flee the deadly threat.

The technique involves pre-concentrating airborne particles on a tiny heating element that vaporizes fatty acids within the anthrax cell walls to derive fatty acid methyl esters, or FAMEs, for analysis. FAMEs provide a unique fingerprint for bacteria, Mowry explains. Like burning bacon to the human nose, FAMEs contain gases from the heating element that are distinctive to a detector, he says. A computer program compares the mass of each FAME in the gas at a particular time to known data indicative on anthrax or other pathogens, seeking a match.

Fatty acids are found in all living organisms with cell membranes. Gases derived from these acids have been used to identify a number of pathogens.

Efforts are now under way, using Laboratory Directed Research and Development funds, to miniaturize the process using micro-fabrication techniques. "The focus is on increasing the speed of analysis in the micro-fabricated systems, while retaining enough information to distinguish between microorganisms," Mowry says.

"Many tools for diagnosis now get results after treatment has started, or even after the death of a victim. This is not acceptable. Our goal is to develop sample handling capabilities appropriate for pre-clinical diagnosis of disease."

"Right now we are shooting for a prototype the size of about two footballs —one for the sample collection and the other to do the analysis," Mowry says.

Sample Handling – a key to success

Although Mowry's team is presently looking at a commercial sample collection approach, other Sandia researchers, such as Mark Derzon, of the MESA Microfabrication department and Eric Cummings of the Microfluidics department, are working on this important aspect of the bio-detection problem.

"Often pathogens are very low in concentration and we need to concentrate a sample to identify them to take actions," Derzon explains. "You need to rapidly separate pathogens from a raw sample to enhance the signal and reduce the noise. Many tools for diagnosis now get results after treatment has started, or even after the death of a victim. This is not acceptable. Our goal is to develop sample handling capabilities appropriate for pre-clinical diagnosis of disease."

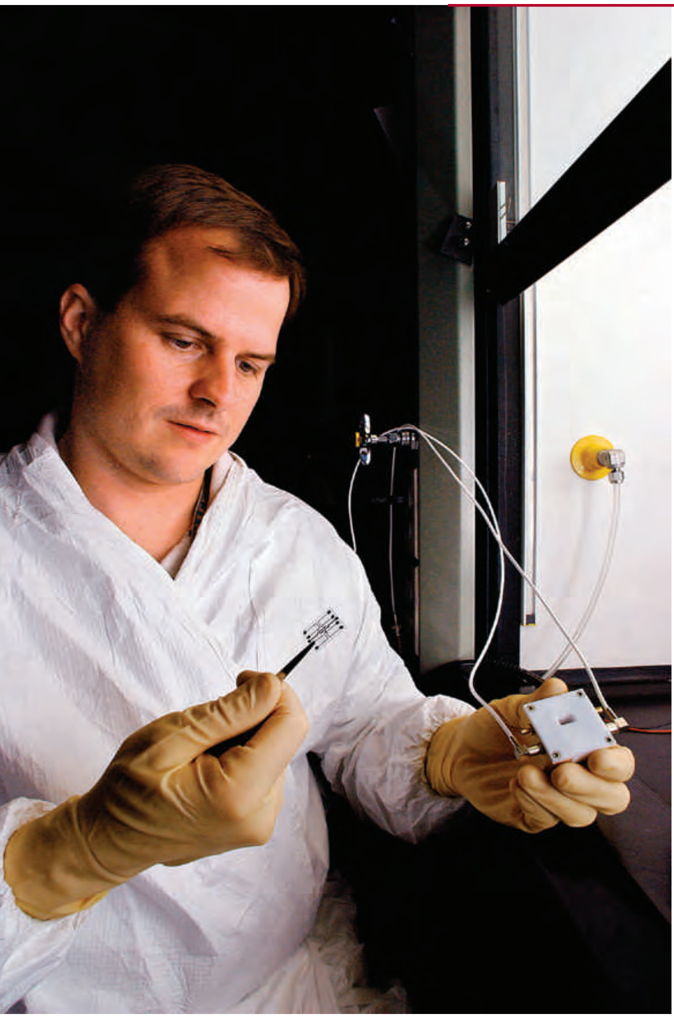
Derzon and Cummings's approach is unique in its use of high flow rates to enhance the analysis. Electrodynamic and hydrodynamic forces cause different reactions and are used to concentrate and separate different types of particles from a fluid. "Our goal is to add a component to concentrate and separate target pathogens at the front end of the analysis to make it more effective," he explains.

Curt Mowry deposits bio-materials to be rapidly analyzed.

Lipid biosensor in a dime-sized device

Another Sandia approach to detection makes use of ultra-thin double layers of fat molecules, which resemble and act much like soap bubbles. This dime-sized sensor under development by Bob Hughes, of the Labs' Microsensor Science and Technology department, and a team of researchers has the potential to identify a number of viruses and bacteria.

Hughes is adapting electrical impedance detection technology, which he has used successfully in chemical sensors to biological sensing. "Developing biosensors is a natural outgrowth of Sandia's chemiresistor program," Hughes says. "They couple sensitivity and selectivity of biological



Darren Branch conducts an experiment with lipid bylayers.

systems to the simple measurement of change in electrical resistance."

Chemiresistors have a base of wire-like electrodes on a specially designed microfabricated circuit. In the case of detecting volatile organic compounds (see page 4), Hughes deposited thin polymer films to detect specific compounds by absorbing them, which in turn changed the electrical resistance of the film. Instead of using polymers as sensing materials, the new sensor uses organic lipid bilayers, described as self-assembled, soap-bubble-like fat molecules.

"Now we have to show we can detect different biological agents. This last step may be our most difficult work yet."

"Scientists have studied these molecules for many years and understand their characteristics," Hughes says. But working with the lipids is still tricky because of their fragile nature. "We had to come up with a way to make them rugged enough to last through experiments and for eventual use in the field."

Researchers used sol-gel, a durable glass-like film, in one approach to this problem. Darren Branch, of the Microsensors Science and Technology department, found another solution using a hybrid material that attaches a lipid layer to the metal of an electrode to provide support.

To date, the researchers have been able to build rugged lipid bilayers that last up to three weeks, Hughes reports. Others on the team are creating "ion channels," or voids in the lipid bilayers that open and close in response to the presence of a specific biological agent. This reaction of the target agent with the ion channels causes a change in the bilayer's electrical properties.

"Now we have to show we can detect different biological agents," says Hughes. This last step, involving making the ion channels receptive to specific bio-agents and then measuring the electrical change, "may be our most difficult work yet," he says.

Other sensor platforms – and beyond

Yet other bio-sensing work at Sandia is proceeding using acoustic wave sensors and photonic sensor platforms. In the case of the acoustic sensors, a thin layer of material that selects specific target agents is painted on a piezoelectric substrate. Acoustic waves are generated in this substrate when it is excited electrically. The selective binding of microorganisms to the thin layer of material creates changes in wave properties, which can be measured and used to determine the type and concentration of the agent present.

A Tale of Two Companies

Two sensor-related businesses working with Sandia offer examples of how the Labs partner with the private sector. This partnering brings technologies to the marketplace, improves US economic competitiveness and stimulates more research and development at the Labs.

Two companies, geographically separated but closely intertwined with Sandia technology, have suffered ups and downs in a difficult economy but continue to make headway. The following is the story of how they work with the Labs and how Sandia works with them.

Sensor Synergy Inc.

Jamie Wiczer left Sandia and Albuquerque eight years ago to join an on-going software concern. After five years of custom software development work, he was presented with an exciting sensor-related startup opportunity that better utilized his skills. Wiczer's interests in the sensor field have evolved and his company, Sensor Synergy Inc., based in the Chicago suburb of Buffalo Grove, Illinois, now focuses on smart sensor networking. "Smart is one of those words, like 'lite' or 'professional,' that describes a product and gives certain expectations," explains Wiczer, who founded Sensor Synergy and is Chief Executive Officer. "It's the product everyone wants, a smart washer or a smart toaster. But in the case of sensors it isn't enough to have a smart sensor product. You need to have a smart sensor that will interface to your systems without requiring a difficult and expensive custom effort. You need to have industry-wide standards that accommodate many diverse needs but allow the use of a common hardware and software interface technology."

Wiczer's work with the Institute of Electrical and Electronics Engineers to develop standards is focused on "common ways to talk to sensors and ways to create self-documenting devices." This activity attracted the attention of former colleagues at Sandia who invited him to present these ideas at a seminar. Follow-up discussions

Dr. Jamie Wiczer

with several Sandians ultimately resulted in a new collaboration. Many sensor concepts at Sandia and elsewhere involve grids of sensors, explains Wiczer. They may be used in airports, factories, or environmental settings. "My company is developing the technology to implement these concepts." Sensor Synergy offers custom and off-the-shelf products with smart sensor interfaces for these types of networking situations.

Wiczer credits his work at Sandia in helping to prepare him for his current position. "I gained a vast amount of knowledge about microsensors, automation and key technologies underlying these fields, which helped me recognize needs and potential solutions for industry," he says. His contacts at Sandia continue to express great interest in understanding the private sector and the trials and tribulations of an entrepreneurial venture. Wiczer in turn shares his views about the private sector with Labs colleagues.

"As a Sandia employee coming directly from the university, I didn't fully appreciate the special environment at Sandia," says Wiczer. "The Labs' concentration of the very best scientists and engineers in the world with

Dr. Mike Butler

Butler and his colleagues chose to adapt an electrically programmable diffraction grating technology used at Sandia for remote chemical sensing for the optical communications field.

a can-do attitude and a willingness to collaborate – has no parallel in industry today."

Sandia has recently purchased a license from Sensor Synergy for use of a company software product. "These software programs were developed exclusively with private funding at an estimated cost of $1.6 million," explains Wiczer. "Sandia will use it in smart sensor work for only a fraction of those development costs."

Polychromix

For Mike Butler, taking the step from Sandia researcher to entrepreneur began at a dinner in 2000 at an Albuquerque restaurant. Dining with colleagues, including Steve Senturia, of the Massachusetts Institute of Technology (MIT), the discussion turned from the current application of a technology for the Defense Advanced Research Projects Agency to other possible applications in private industry.

Senturia, who recently retired from MIT, took the lead in setting up a company to pursue other applications. He negotiated a licensing agreement with Sandia for the technology and soon Butler found himself living in Woburn, Massachusetts as the key product developer for Polychromix, an optical telecommunications equipment company.

"We started out in a room we sublet from a dot com company in the process of rapidly downsizing," says Butler. Now his company has prototype devices that are in testing and has grown from three to 15 employees.

Butler and his colleagues chose to adapt an electrically programmable diffraction grating technology used at Sandia for remote chemical sensing (see Polychromator, page 11) for the optical communications field. The choice was good but the timing presented a challenge, Butler explains. An economic slump in optical telecommunications, made fund-raising more difficult, but it also provided the small company an extended time window for its product development work.

"When you put light signals in an optical fiber cable you want to get as much information in as you can. You use different wavelengths, or colors, to carry different signals. The Polychromix technology lets us manage data streams on a wavelength basis, by changing power levels, blocking, or switching them." Polychromix builds subsystems for large system manufacturers, who in turn serve Internet providers, phone companies or institutions wanting to establish optical communication systems.

"Sandia has been very supportive of commercializing technologies like this. My management was very supportive of my going ahead. We also have a Work-for-Others agreement with Sandia that allows us to access expertise at Sandia and to help us develop products. From our viewpoint, it's been very helpful," says Butler.

In return Polychromix offers a pathway for commercialization to Sandia. "We are focused on optical telecommunications right now, but if Sandia is interested in commercializing a remote chemical sensor in the future, for first responders or for the defense department, we will have the knowledge, capabilities and resources to build that kind of product."

For more information about these companies:

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Working with Industry

Typically, industrial partners can obtain exclusive rights within a specified field of use for technologies developed under a Cooperative Research and Development Agreement.

"Collaborative research and development with industry contributes to strong Labs development programs, with benefits to industry and to Sandia and the Department of Energy (DOE)," says Kevin Murphy, of Sandia's Licensing and Intellectual Property Management group. "Our objective at Sandia is to help the line advance its technology for the benefit of Sandia's business units and the DOE's mission."

Sandia has a number of tools available to help with industry interactions, including work-for-others and user facilities agreements. The standard approach, however, is the Cooperative Research and Development Agreement, or CRADA. "We work with a potential partner to determine if there is an overlap of technology and business interests, which usually leads to a scope of work description for a CRADA."

Typically, industrial partners can obtain exclusive rights within a specified field of use for technologies developed under a CRADA, Murphy explains. This leads to negotiations about the market scope of the technology application and financial considerations that may be paid as upfront fees, annual minimum fees or royalties rates, or some combination.

In licensing technologies, Sandia typically offers non-exclusive rights to its "background" intellectual properties so that the Labs can partner with different companies using the same technology, but in different application areas. Obviously, negotiating skills are important in forging these agreements and Sandia currently employs five licensing and intellectual property management staff members, with help and advice of the Labs' legal staff and others in technical fields.

Royalties at Sandia are used in accordance with federal laws and regulations with the objectives of rewarding researchers and providing investment for further success, such as maturing immature technology to the point where industry can see a future application, Murphy explains.

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Jeff Brinker Wins E.O. Lawrence Award

Brinker was honored for innovations in materials science that created nanostructured materials with applications in energy, manufacturing, defense and medicine.

Sandia's C. Jeffrey Brinker was awarded the Department of Energy's E.O. Lawrence Award in a ceremony in October in Washington, D.C. He was one of seven scientists to receive the award — considered one of the highest honors bestowed upon researchers by the DOE.

Brinker is a senior scientist at Sandia and professor of chemical and nuclear engineering and chemistry at the University of New Mexico. He was honored for innovations in materials science that created nanostructured materials with applications in energy, manufacturing, defense and medicine.

The award, established in 1959, is named in memory of physicist Ernest Orlando Lawrence, who invented the cyclotron — a particle accelerator — and received the Nobel Prize in physics in 1939.

"In addition to his pioneering work in sol-gel technology, which made possible the lowest-density structures ever created, Brinker's leadership in mastering nature's secrets are extraordinary," said C. Paul Robinson, Sandia president. "His development of materials that mimic the structure of abalone seashells makes it possible to build tough, lightweight structures or coatings that, because of their inherent microstructures, can resist cracking."

Brinker's first work at Sandia involved sol-gels — gelatin-like solutions heated at relatively low temperatures until they solidify into material similar to glass. This early work culminated in 1990 with the publication of a book he co-authored that remains the most highly cited reference in the field.

In the 1990s, Brinker moved from creating sol-gels into creating aerogels — materials extremely light because of extensive cave-like tunnels. He devised room-temperature techniques that were simple and inexpensive. Done in collaboration with UNM researchers, the work overcame the 60-year-old barrier to commercial aerogel production and enabled the first preparation of aerogels as thin films.

In addition to an inexpensive aerogels, Brinker wanted better control over the size of its interior chambers, or pores. In the mid-1990s, he devised techniques to cheaply, easily, and precisely control pore size of films for use as membranes, adsorbents, concentrators, and electrically insulating materials called dielectrics. He used simple evaporative methods to organize two-sided detergent-like molecules into intricate patterns as regular as the knitting on a blanket (only more so). This pattern served as a mold around which silica solidified. Removal of the detergents then created a predictable series of holes.

Brinker extended his techniques to organic materials. He created nanocomposites that mimic the hard and soft laminated construction of natural materials like sea shells, with hardness, toughness, and strength advantages for materials design and construction.

Next he set out to control the overall architecture of these materials. The starting point was a solution or colloidal suspension like that used to form films. Evaporation of aerosolized droplets (like those formed using a simple humidifier) causes self-assembly to proceed inwardly. Any additives introduced into the solution are inevitably incorporated within the self-assembling droplet, enabling "ship-in-the-bottle" type constructions. This approach has implications in a diverse range of technologies including drug delivery, cosmetics, chromatography, and custom-designed pigments.

Brinker demonstrated the direct writing of functional self-assembled nanostructures applied through computer-driven pens and ink-jet printers. This approach, dubbed "intelligent ink," formed functional organized structures in seconds and established the first link between computer-aided design and self-assembled nanostructures. He followed this with work on photosensitive films with ultraviolet-sensitive molecules within the nanostructures. By varying the intensity of ultraviolet light shone upon the material, researchers are able to control wetting behavior, pore volume, pore size, and refractive index. This capability should enable standard lithographic methods to be used to pattern and define the structure and function of nanomaterials.

Brinker and his colleagues most recently turned attention to encapsulating organic, electron-transmitting molecules within self-assembled nanostructures.

"The kind of technological creativity that goes into the design of smart sensors is a dynamic force that will help maintain U.S. primacy in national security, as well as its leadership in commerical markets. I stress the word 'dynamic.'"

C. Paul Robinson
President
Sandia National Laboratories

Sandia National Laboratories

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