April 2006

Science & Technology Review

National Nuclear Security Administration's
Lawrence Livermore National Laboratory

Flexible Stress Sensing

Also in this issue:

- Transparent Ceramics Advance Laser Technology
- New Insight into Crystal Deformation
- Livermore and Los Alamos Collaborate on Accelerator Tests

About the Cover

As the article beginning on p. 4 describes, the Laboratory is developing sensor technologies for measuring and retaining information about the physical and environmental phenomena that a weapon experiences during its lifecycle. The micrometer-size stress sensors measure contact loads by converting applied pressure, or contact stress, between objects to a recorded change in electrical resistance. Contact measurements are important for numerous applications, from automotive brakes to orthopedic devices to weapons diagnostics. Livermore scientists have also designed silicon arrays of more than 1,000 sensors that can bend and flex to map the load distribution over a surface area. On the cover, freestanding conductive gold wires connect a flexible, springlike array of stress sensors (the edge of a penny is shown for scale).

Cover design: Kitty Madison; Photography: Marcia Johnson

About the Review

Lawrence Livermore National Laboratory is operated by the University of California for the Department of Energy's National Nuclear Security Administration. At Livermore, we focus science and technology on ensuring our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published 10 times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

Please address any correspondence (including name and address changes) to *S&TR*, Mail Stop L-664, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94551, or telephone (925) 423-3432. Our e-mail address is str-mail@llnl.gov. *S&TR* is available on the World Wide Web at www.llnl.gov/str.

Prepared by LLNL under Contract No. W-7405-Eng-48

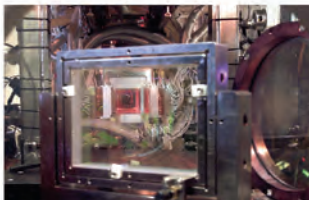
Science & Technology REVIEW

April 2006

Lawrence Livermore National Laboratory

Contents

Features



Research Highlights

Departments

S&TR Staff

Scientific Editor
Maurice B. Aufderheide III

Managing Editor
Ray Marazzi

Publication Editor
Pamela MacGregor

Writers
Arnie Heller, Ann Parker, Gabriele Rennie, and Maurina S. Sherman

Art Director and Designer
Kitty Madison

Compositor
Louisa Cardoza

Photographers
Michael Anthony, Marcia Johnson, and Joseph Martinez

Proofreader
Carolin Middleton

S&TR, a Director's Office publication, is produced by the Technical Information Department under the direction of the Office of Policy, Planning, and Special Studies.

S&TR is available on the Web at www.llnl.gov/str.

Printed in the United States of America

Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

UCRL-TR-52000-06-4
Distribution Category UC-99
April 2006

Astronomers detect echoes from ancient supernovae

A team of international astronomers has found faint visible "echoes" of three ancient supernovae by detecting centuries-old light reflected from interstellar dust clouds. Just as a sound echo can occur when sound waves bounce off a distant surface and reflect back toward the listener, a light echo can be seen when light waves traveling through space are reflected toward the viewer.

Livermore astronomer Kem Cook, a coauthor of the paper that appeared in the December 22, 2005, edition of *Nature*, says, "We are carrying out a large wide-field, time-domain survey looking for the signature of dark matter, and, as a bonus, we are discovering the unexpected such as these light echoes." The light echoes were discovered by comparing images of the Large Magellanic Cloud taken years apart. By precisely subtracting the common elements in each image and analyzing which variable objects remain, the team looks for evidence of dark matter that might distort the light of stars in a transitory way.

Astronomer Armin Rest of the National Optical Astronomy Observatory, lead author of the paper, says, "Without the geometry of the light echo, we had no way of knowing just how old these supernovae were. Some relatively simple mathematics can help us answer one of the most vexing questions that astronomers ask—exactly how old is this extraterrestrial object?" Astronomers also can use supernova light echoes to measure the structure and nature of the interstellar medium. Dust and gas between the stars are invisible unless illuminated by a light source such as a supernova blast.

Contact: Kem Cook (925) 423-4634 (cook12@llnl.gov).

Cosmic dust could help uncover the origins of life

The National Aeronautics and Space Administration's (NASA's) Stardust spacecraft returned from a 7-year mission on January 15, 2006, bringing back cometary and interplanetary dust particles that may be able to tell the story of our solar system's beginnings and possibly the origins of life. By tailing a comet called Wild 2 that was shooting material into space at 6.1 kilometers a second, the spacecraft captured dust particles in a collector made up of aerogel—a material consisting of 99.8 percent air.

After landing, the capsule was flown to NASA's Johnson Space Center (JSC) in Houston and opened. Researchers from Livermore's Institute of Geophysics and Planetary Physics (IGPP) performed some of the first extractions at JSC using ultrasonic diamond-microblade technology, which was developed at Livermore by postdoctoral researcher Hope Ishii. The first few days were devoted to optical scanning of the aerogel tiles. Extractions of particles from aerogel cells began the next week, after which samples were distributed to Livermore and other research laboratories around the world. Livermore researchers are now using the Laboratory's transmission electron microscope—the world's most powerful electron microscope—and the nano secondary-ion mass spectrometer to analyze the mineralogy, chemical, and isotopic composition of the dust particles.

The detailed and precise process involves carving dust tracks from the aerogel with ultrasonic diamond blades. Scientists then use microscopic needles to extract the dust from the tracks. According to John Bradley, director of Livermore's IGPP, the actual tracks of cometary dust within the aerogel are visible to the naked eye. The particles themselves can be seen as white specks under a microscope.

Stardust is part of NASA's series of Discovery missions and is managed by the Jet Propulsion Laboratory. Other collaborators in the project include the University of Washington, Lockheed Martin Space Systems, the Boeing Company, the Max Planck Institute for Extraterrestrial Physics, NASA Ames Research Center, and the University of Chicago.

Contact: John Bradley (925) 423-0666 (bradley33@llnl.gov).

Researchers find new way to produce coherent light

A team of researchers from Lawrence Livermore and the Massachusetts Institute of Technology found a new source of coherent optical radiation when they performed molecular dynamics simulations of shock waves propagating through crystalline sodium chloride. "To our knowledge, coherent light has never been observed from shock waves propagating through crystals because a shocked crystal is not an obvious source to look for coherent radiation," says Evan Reed, an E. O. Lawrence postdoctoral fellow at Livermore and lead author of a paper published on January 13, 2006, in *Physical Review Letters*.

The simulations solved the classical equations of motion for atoms that are subject to interaction, thermal effects, and deformation of the crystal lattice. The intensive computer simulations were made possible using Livermore's Thunder supercomputer. Researchers expected to see only incoherent photons and sparks from the shocked crystal, but they observed weak yet measurable coherent light emerging from the crystal in the range of 1 to 100 terahertz.

Applications for these research results are numerous. For example, the coherent light produced in the crystal can serve as a diagnostic for understanding shock waves, specifically providing information about shock speed and the degree of crystallinity.

Contact: Evan Reed (925) 424-4080 (reed23@llnl.gov).

Continued on p. 23

Commentary by Steven R. Patterson

Bridging the Gap between Scientific Discovery and Solutions to National Needs

BRIDGING the gap between scientific discovery and solutions to national security needs is a profoundly creative process. It requires multidisciplinary teams that can achieve an intimate understanding of extraordinary problems. They must have a command of the enabling science and possess the engineering ingenuity and discipline to create deployable technology solutions.

As national security needs evolve, we are presented with increasing challenges for which no "off-the-shelf" solutions exist. Multidisciplinary research combined with technology innovation and rigorous engineering makes for compelling contributions to our overarching national security missions. This approach has helped us to develop and test nuclear weapons that are safe, secure, and reliable. It has also led to extraordinary capabilities to capture experimental results through high-speed diagnostics systems, groundbreaking biodetection devices for national security, modeling and simulations that extend the boundaries of our knowledge, and unprecedented high-power laser systems. A systems engineering approach to current and future challenges ensures that we engage all the elements required for success—from concept to reality to deployment.

Today, in support of the National Nuclear Security Administration's strategic nuclear stockpile strategy, we are faced with the challenge of ensuring the safety, security, and reliability of our current weapons stockpile without nuclear testing. Extraordinary scientific and technical objectives are associated with this mission. As the article beginning on p. 4 describes, one of these objectives is to develop reliable new sensor technologies for measuring and retaining information about the physical and environmental phenomena that a weapon experiences during its life cycle.

This work is being carried out by coupling innovative concepts with Laboratory capabilities in micromachining, materials engineering, and rapid prototyping. Recent developments in micro- and nanotechnology at Livermore, and elsewhere, are being used to manipulate and control materials at the nanometer scale. Livermore scientists and engineers from diverse disciplines, including engineering, chemistry, biology, physics, materials science, and computer science, are making rapid advancements in device development, systems integration, and platform technology in support of multiple missions.

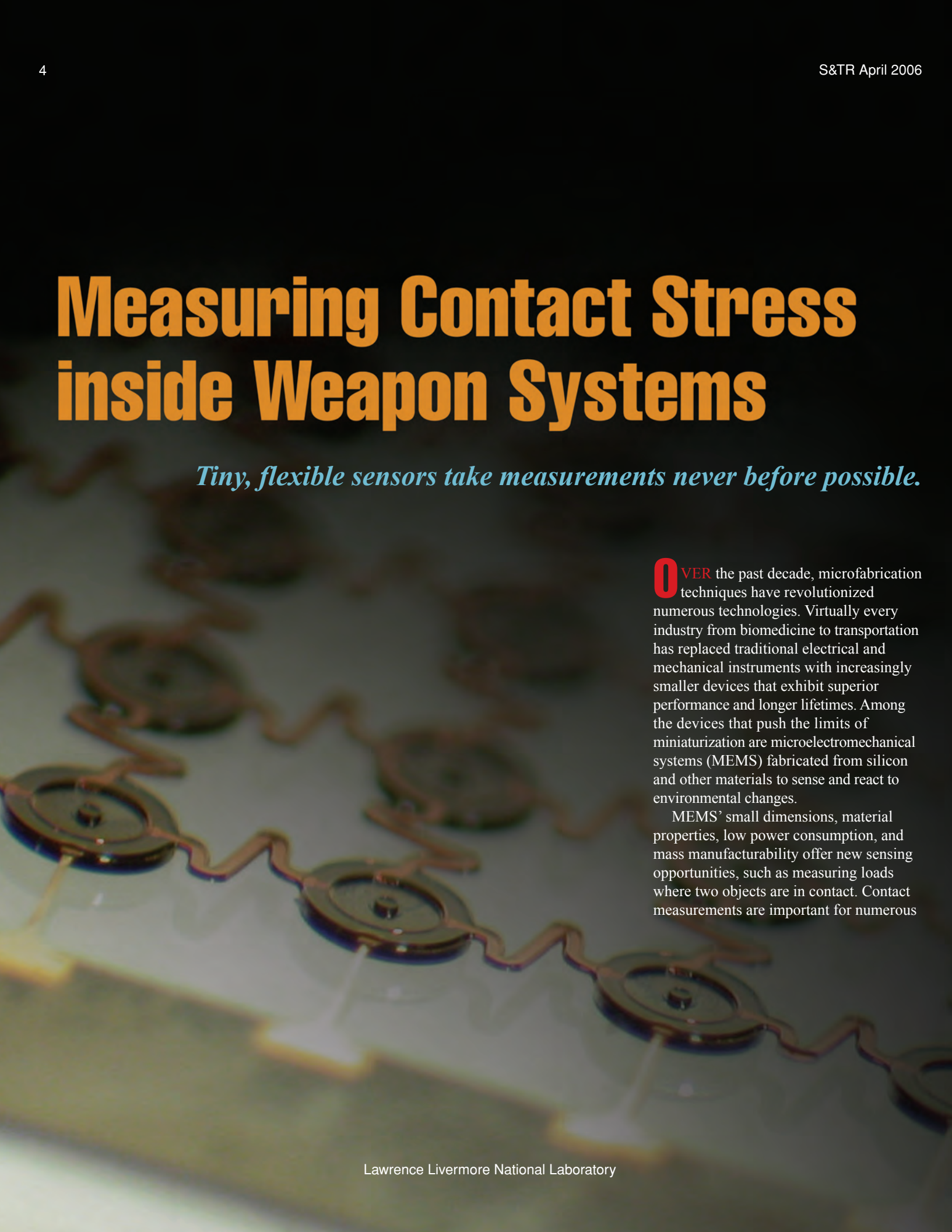
These multidisciplinary collaborations at the forefront of research and development (R&D) have led to novel capabilities such as highly integrated biomicrosystems for sensors and medical devices, photonic microsystems for high-speed signal and data acquisition, microelectromechanical systems for advanced sensing and actuation, and scalable power systems for powering micro- and mesoscale devices. The combination of a talented workforce and unique fabrication facilities has led to highly innovative, full-system solutions to technology needs in stockpile monitoring and stewardship, homeland security, and intelligence programs.

The nuclear stockpile sensor technologies described herein represent a case in point. Unique, microfabricated sensors have been developed that, for the first time, can take repeated measurements of changing loads perpendicular to a surface in a weapon system. The technology stems from earlier work on medical applications and highlights the benefits derived from the Laboratory's multidisciplinary, multimission environment. These microfabricated sensor technologies are providing the breakthroughs in reliability, longevity, and functionality that are required to develop new measurement systems to carry out our stockpile monitoring and stewardship mission.

■ Steven R. Patterson is associate director of Engineering.

Measuring Contact Stress inside Weapon Systems

Tiny, flexible sensors take measurements never before possible.



OVER the past decade, microfabrication techniques have revolutionized numerous technologies. Virtually every industry from biomedicine to transportation has replaced traditional electrical and mechanical instruments with increasingly smaller devices that exhibit superior performance and longer lifetimes. Among the devices that push the limits of miniaturization are microelectromechanical systems (MEMS) fabricated from silicon and other materials to sense and react to environmental changes.

MEMS' small dimensions, material properties, low power consumption, and mass manufacturability offer new sensing opportunities, such as measuring loads where two objects are in contact. Contact measurements are important for numerous

applications, from gaskets, seals, brakes, and air bags in the automotive industry to artificial limbs, knee orthopedics, and hip replacements in medicine. Some of the Laboratory's work in stockpile stewardship would benefit from the ability to accurately characterize loads in a weapon over its long lifetime using onboard diagnostics. MEMS offer an approach for introducing stress sensors for the first time into these applications and many others.

Stress sensors measure contact loads by converting applied pressure, or contact stress, between objects to a recorded change in electrical resistance. To measure loads at an interface, such as in the human knee, a sensor must be extremely thin and flexible so the sensor's presence doesn't alter the stress it is measuring. Because of this size requirement, the application of existing sensing technologies to many research efforts and commercial products has been limited. In weapons diagnostics, meeting the longevity, accuracy, and geometry constraints of contact stress measurements poses additional challenges. The demands of monitoring weapons in the stockpile require unusually thin and flexible devices.

Measuring Stress in Weapons

The Department of Energy's (DOE's) National Nuclear Security Administration (NNSA) is responsible for ensuring the safety and reliability of the nation's nuclear weapons stockpile through its Stockpile Stewardship Program. To audit the health of the stockpile, DOE established a program that includes using representative test units for each stockpile weapon, called Joint Test Assemblies (JTAs), to obtain diagnostic measurements. Tests involving JTAs are conducted annually by Lawrence Livermore, Los Alamos, and Sandia national laboratories.

The annual assessment includes flight and ground tests of the units and, at times, the dismantlement of randomly selected weapons for inspection. Although these activities are effective at determining information about physical performance characteristics, they do not reveal valuable data on the mechanical history of a weapon.

Mechanical engineer Jack Kotovsky says, "It's difficult, if not impossible, to predict load distribution. Direct measurements using stress sensors are the only way to accurately determine the contact mechanics inside a complex assembly." Commercial stress sensors that can meet the demands of weapons diagnostics and enable researchers to obtain these valuable data do not exist.

Through funding from NNSA, Kotovsky leads a team that has designed the first MEMS contact stress sensor to meet the demanding requirements. The single sensor silicon device is the only contact stress sensor that can repeatedly measure changing loads perpendicular to a surface within a weapon system. The device is 4 millimeters square and 50 micrometers thick (for comparison, a human hair is 100 micrometers thick) and is embedded in a polyimide film package. A completely packaged device measures 100 micrometers thick.

The effort is a result of a collaboration formed in 1999 between Livermore's Defense and Nuclear Technologies and Engineering directorates to develop a new family of sensors that could be used for integrated diagnostics in JTAs. The design for Livermore's stress sensor originated from Kotovsky's interest in developing a

One stress sensor measures just 4 millimeters square and 50 micrometers thick.

sensor used as an orthopedic tool for knee-joint contact studies. When he was a graduate student at the University of California at Davis, Kotovsky contacted Livermore's Center for Meso, Micro, and Nanotechnologies, because it had the equipment he needed to complete the research for his dissertation. The center's MEMS fabrication facility is used to develop smaller, more reliable device technologies for the Laboratory's national security missions.

Assembling Microsensor Parts

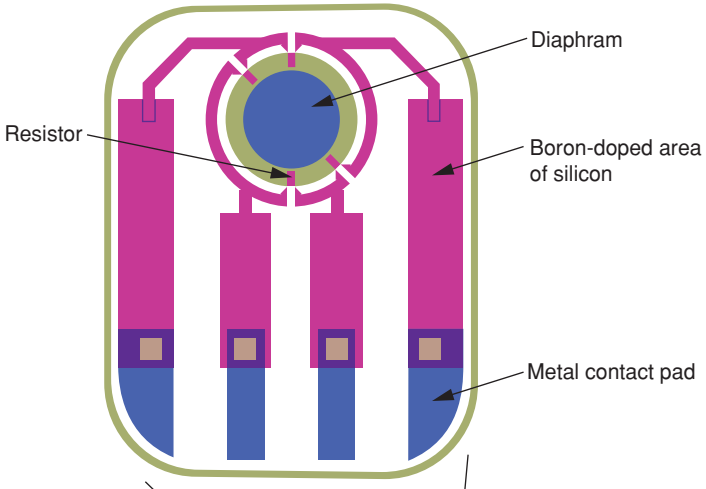
Fabricating stress sensors is a time-intensive process. Holly Petersen, a key member of Kotovsky's team and one of the center's technicians, begins the process with a 102-millimeter-diameter, 500-micrometer-thick wafer of silicon that is bonded to a 15-micrometer-thick wafer. A 200-nanometer-thick silicon oxide layer acts as a glue to bond them. Silicon is often chosen as the substrate material for MEMS sensors because of its consistent response to deformation under changing pressure. When a certain amount of pressure is exerted on a sensor's silicon diaphragm, it will deflect and spring back, repeatedly, to its original position when the pressure is removed. (See the box on p. 7.)

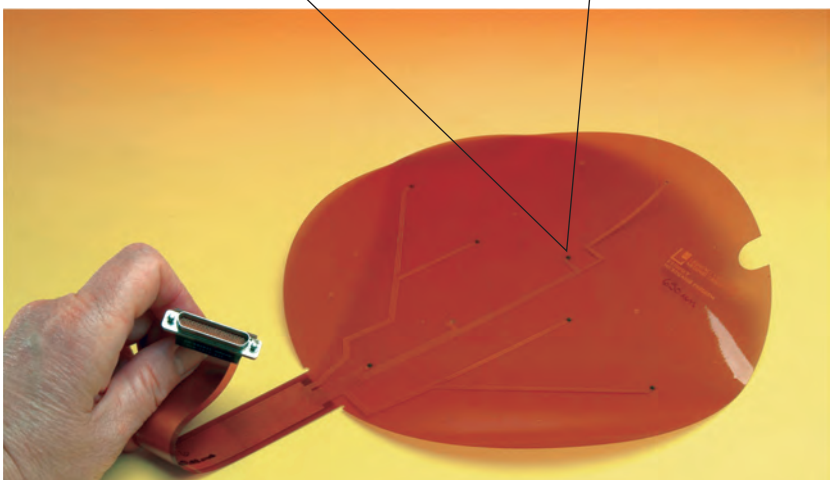
Once the silicon layers are prepared, a thin layer of photosensitive material, called photoresist, is coated on the silicon wafer and baked. Ultraviolet light rays are then sent through a series of seven computer-generated masks. Each mask is dedicated to a layer on which a pattern is transferred by a process called photolithography.

In one of the processing steps, a silicon wafer is placed in a chamber that implants boron ions in specified areas, creating conductive traces. Adding boron allows the silicon to respond with significant changes in electrical conductivity as atoms in the crystal lattice stretch and spring back with applied pressure. One of the masks defines a pattern for a diaphragm on the silicon that will serve to measure contact stress applied to the device. Applied loads will cause the diaphragm to deflect, thereby causing stress on the silicon. The boron-doped traces register the amount of change in the resistance. A photolithographic step is also used to define the copper traces on the polyimide film package that will connect the embedded MEMS devices to external electronics.

Silicon's resistivity depends on both temperature and pressure. Temperature changes in the surrounding environment cause silicon to register resistance change in the same way as if pressure were applied. To compensate for this effect and ensure that only contact load is being measured, Kotovsky designed the device with four resistive boron traces. All four respond to temperature, but only two respond to pressure. The difference between the two sets of measurements isolates the response due to load.

The Livermore design is the first in which the circuitry is embedded within layers of polyimide using generic, flexible circuit processing. "Flexible circuit technology is a good packaging choice for MEMS sensors because it's strong, mechanically and thermally stable, and inexpensive," says Kotovsky.





(top) Four boron-doped resistors register the change in resistance as pressure is exerted on the stress sensor's diaphragm. (bottom) A polyimide film encases microelectromechanical sensors in the sensor package. The copper traces are routed to external electronics.

Designing Sensor Arrays

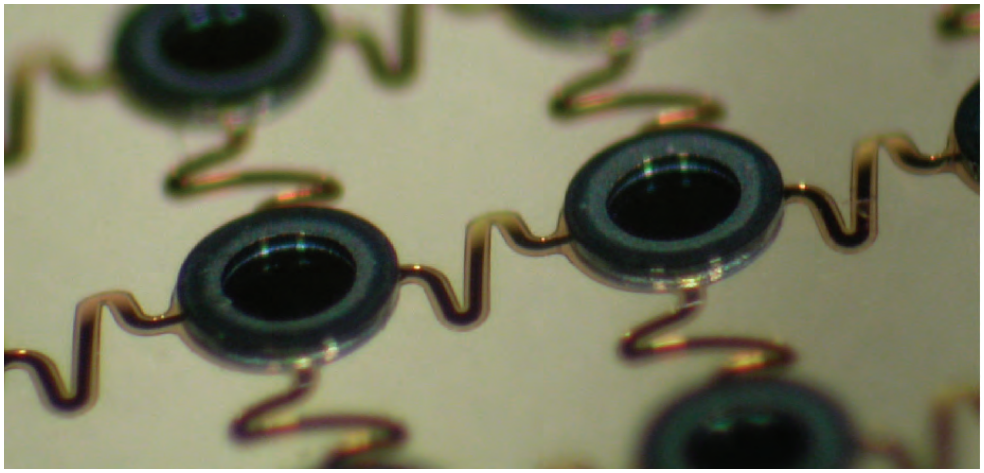
The MEMS sensor was initially designed to perform repeatedly under loads at one location on a surface. However, in many

instances, measurements are needed for loads distributed over an area. Expanding the single sensor design to an array of sensors has been difficult, in part because silicon is brittle and does not conform to complex curvatures.

Kotovsky has developed designs for large arrays of contact stress sensors that can bend, flex, and stretch to conform to surfaces of any curvature. “The sensor arrays are interconnected in such a way that they behave similar to a fabric, allowing complex-curvature conformity,” says Kotovsky. The Livermore team has demonstrated designs for continuous silicon arrays of more than 1,000 sensors that bend and flex. A unique feature of their array designs is the use of independent “islands” of silicon that each contain a sensor and are interconnected by freestanding or polymer-backed conductive springs. “Arrays of independent silicon devices allow enormous flexibility, which is useful for a variety of applications,” says Kotovsky.

To assist with the fabrication challenges for the array, Kotovsky enlisted Adam Mednick, a graduate student from California Polytechnic State University in San Luis Obispo. In one Livermore array design, serpentine gold wires interconnect islands of silicon. Mednick found a fabrication solution in which each of the gold wires is encased in polyimide to provide mechanical and electrical protection to the wires.

Increasing the number of sensors for an array also meant finding a method to address the effect of temperature. Duplicating the approach for the single sensor would be impractical for an array with hundreds of sensors. As an alternative, Kotovsky designed an array in which the sensors are interrogated in a grid. A sensor in the corner of the grid does not have a stress-sensing diaphragm and only registers temperature. Resistance changes due to temperature can be determined by comparing results from a resistor with a diaphragm and one without a diaphragm.



Freestanding conductive gold wires connect a flexible, springlike array of stress sensors.

Fabricating Microsensors and Actuators

Research on microelectromechanical systems (MEMS) sensors dates from the late 1960s. Most MEMS devices can be classified as either sensors or actuators. Sensors convert a form of energy produced by a phenomenon being measured to a signal that represents a change. For example, the mercury in a thermometer will expand as a result of a rise in temperature. Actuators move or manipulate phenomena based on energetic input. For example, when electricity is applied to a motor, the motor will spin or activate.

MEMS sensors and actuators are fabricated using techniques similar to those used by the electronics industry. Structures are assembled in layers of materials, typically semiconductors, dielectrics, metals, and polymers. The microfabrication processes commonly used are surface micromachining and bulk micromachining. These processes include photolithography, chemical vapor deposition, ion implantation, chemical etching, metal evaporation, sputtering, and plasma etching to produce mechanical and electronic structures. The most common method used to transfer design geometries is photolithography, or patterning a design into photosensitive materials. In photolithography, a photosensitive but chemically resistant (photoresist) masking material is applied onto the substrate material in a particular pattern. The structural layer is then etched, implanted, or metallized, according to the photoresist pattern, and the photoresist is removed. This process is repeated until all the desired layers have been patterned.

In some applications, microsensors are embedded into structures and have no physical connection to outside the device. Therefore, the development of MEMS requires micropower supplies to be integrated into the microsensor system. A power supply on the same scale as the MEMS device permits a stand-alone integrated system that can be fully functional within its environment.

Miniaturized devices can provide numerous performance advantages, including simple installation and maintenance and lower power consumption. The most important quality for sensors is that they are compatible with the environment in which they operate, so they can provide accurate measurements.

The stress sensors will provide researchers involved in the JTAs with the ability to obtain important data on weapons in the stockpile. “These sensors will enable us to take measurements in a weapon that were never before possible. We can take measurements in situ and transmit the collected data without dismantling the weapon,” says Tony Lavietes, who leads Livermore’s Microsensors Program. Sandia is currently preparing to manufacture the single-sensor device that will be used in JTAs. NNSA’s Kansas City Plant is manufacturing the polyimide package. The design for both the single sensor and the array are available for licensing.

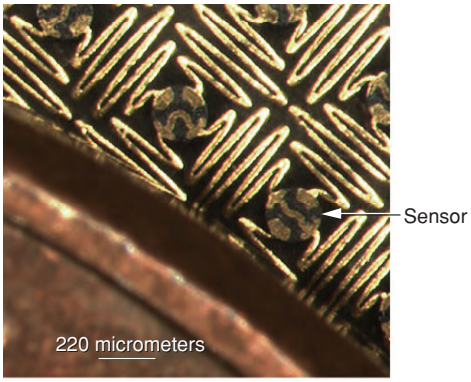
Optical Sensor Technologies

Livermore researchers are also studying possible sensors that could replace electronic systems, which are not compatible with some components of weapon systems. One possibility is the use of optical technologies. The data gleaned from nonnuclear JTAs have shown researchers there would be value in developing enhanced diagnostics for the explosives package in a nuclear weapon. Sensors used in diagnostic systems for the nuclear explosives package are not intended to be powered electrically, because of the remote possibility of contact with energetic materials such as high explosives. Optical sensors are intrinsically safe and are ideal for use in harsh environments that include radioactive and energetic materials.

Engineer Mike Pocha, also with the Center for Meso, Micro, and Nanotechnologies, led a team that developed a miniaturized signal-processing system for a Fabry–Perot optical sensor. This sensor is an interferometer in which changes in the phase of light are measured to determine the behavior of the property being studied. A collimated light-emitting diode broadband source is sent through an optical fiber to an optical sensor. The object of interest interacts with the sensor, changing the phase of the reflected light. The reflected light is transmitted back along the same pathway. The processor measures the phase modulation and sends the processed signal to an external instrument.

One limitation of commercial optical systems is that the signal processors are too large to be used in many applications, including weapons diagnostics. The Livermore-designed signal processor is enclosed in a 2- by 8-centimeter package, and the team is hoping to shrink it further to the size of a sugar cube. Still, the current design is several times smaller than commercial processors. Its small size would allow it to be connected to an optical fiber sensor for use in applications where minimal sensor size is critical. Pocha says, “Commercial optical fiber sensors have been available for about 10 years. They can measure a limited set of parameters such as temperature, pressure, and strain. However, for many Laboratory missions, we are developing optical sensors that measure additional properties such as force, gas composition, and acceleration.”

A flexible sensor array is designed to bend and stretch over any curvature.



Serpentine gold wires, each encased in polyimide, connect “islands” of silicon stress sensors.

Reliability over the Long Term

Researchers in the Microsensors Program have designed several optical sensors that are compatible with Pocha’s processing system, including an optical gap gauge and force probe designed by Kotovsky and Billy Wood. Another member of the team, Steve Swierkowski (now retired), has developed an optical accelerometer, which is available for licensing.

Single electronic MEMS sensors, sensor arrays, and optical sensors will all benefit future JTAs. Lavietes says, “The idea is to provide a portfolio of sensors to conduct diagnostics on weapon performance. Those conducting the tests could then pick what type of sensor is best suited for the job. For a replacement weapon that might be developed, these onboard, integrated diagnostics would be a valuable component. Today, in order to perform a comprehensive assessment, researchers must disassemble a sampling of weapons over time. In addition to this being extremely expensive, the costs in transporting and securing a weapon are also significant, especially when it’s a nuclear weapon.”

Another cost savings from integrating sensors would be a reduction in the number

of weapons needed. Traditionally, the number manufactured includes some that will be pulled from the stockpile over the weapon system's lifetime and disassembled for testing. Integrated diagnostic systems could provide the information currently obtained from disassembly activities, and the overproduction to accommodate these surveillance requirements could be greatly reduced or eliminated.

The primary requirement for sensors is reliability. "The device is going to be in the weapon for 20 to 50 years," says Lavietes. Reliability and inherent safety over a long lifetime are critical requirements for many Laboratory efforts. Anantha Krishnan, director for research and development at the Center for Meso, Micro, and Nanotechnologies, says, "A big difference between the technologies developed at Livermore and those of commercial industries is that the commercial sector plans on a technology being obsolete in as few as 2 years. In contrast, we often need technologies that last a long time. Developers of electronic games, who are driving new technology today, don't have to plan for a product to be safe and reliable for 30 years. Our goal is to use the best technology possible and still provide the longevity and safety we need." The materials in the Livermore stress sensor—silicon, copper, and polyimide—are chemically stable and have characteristically long lifetimes.

Jack Kotovsky characterizes the processing of a MEMS sensor array on a scanning electron microscope.

Advancing Biomechanics Research

Kotovsky plans to design a three-axis sensor, one that can measure normal loads and shear loads, or forces from two additional sides. He also hopes to continue work on stress sensors for orthopedics. "About 10 percent of annual visits to orthopedic surgeons are related to knee injuries, and about 40 percent of those visits are directly related to meniscal injuries," says Kotovsky.

Originally assumed to be nonfunctional, the meniscus plays an important role in transmitting force between the femur and the tibia. In the past, orthopedic surgeons removed the entire meniscus when it was damaged. It was later discovered that removing the entire meniscus causes progressive degeneration of the cartilage in the knee. Eventually, this condition leads to osteoarthritis because of increased contact pressures and the alteration of load distribution on the joint. In recent years, efforts have been made to preserve, repair, and replace the damaged meniscus, but significant work remains to improve these procedures. Eventually, the Livermore-designed sensor could provide biomechanists with the precise measurements they need to improve surgeries.

Some studies have suggested that a meniscus from a cadaver could be used to replace a damaged meniscus. If so, the stress sensor could help orthopedic surgeons determine the shape and size of the meniscus and the best method to transplant one into a patient. "However," says Kotovsky, "until transplanting a meniscus is shown to be effective at preserving healthy cartilage stress distribution in the knee, surgeons will not be inclined to adopt this difficult operation."

Livermore's Center for Meso, Micro, and Nanotechnologies has accomplished critical milestones in novel techniques for photolithography, wafer handling, silicon etching, and sensor design. "The Holy Grail," says Krishnan, "would be to have an integrated platform of sensor, processor, and actuator operating in an autonomous mode. In the last several years, tremendous progress has been made in processing information from sensors. Linking this information to the decision-making processes that exist in an architecture such as that of the human brain so that actuators can respond with the appropriate solution would truly be remarkable."

—Gabriele Rennie

Key Words: Joint Test Assemblies (JTAs), microelectromechanical systems (MEMS), optical sensor, polyimide, stress sensor.

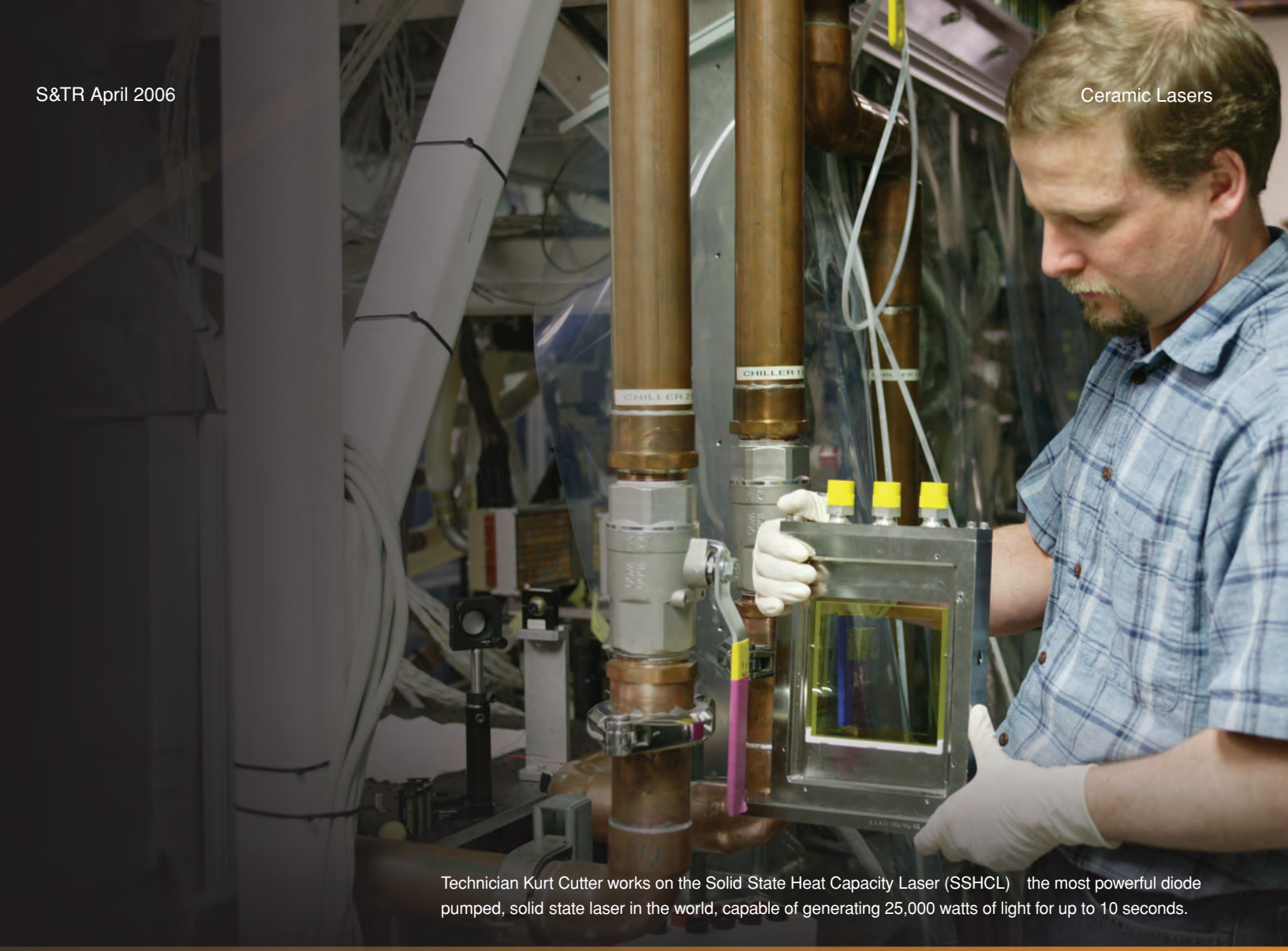
For further information contact Jack Kotovsky (925) 424-3298 (kotovsky1@llnl.gov).

Transparent Ceramics Spark Laser Advances

Livermore's Solid-State Heat Capacity Laser is a showcase for transparent ceramics that offer clear advantages over traditional crystals.

HARD, brittle, and heat- and corrosion-resistant, ceramics have served society for thousands of years. Ceramics are made by shaping and then firing a nonmetallic material, such as clay, at a high temperature. The earliest ceramic products were pots and bricks prepared by forming a wet clay mixture and then drying and firing it in an open hearth. The result was a hardened substance that was impervious to heat, resistant to wear, and opaque—perfect for baking, cooking, and building.

Today, because of their formability, electrical insulating quality, heat resistance, and robustness, modern ceramic parts are ubiquitous in the aerospace, electrical, and automotive industries. They are used not only



Technician Kurt Cutter works on the Solid State Heat Capacity Laser (SSHCL) the most powerful diode pumped, solid state laser in the world, capable of generating 25,000 watts of light for up to 10 seconds.

for bricks and pottery but also for products ranging from golf clubs to rocket nozzles. Even the medical industry has embraced ceramics as prostheses for bones and teeth.

In the 1960s, scientists at General Electric (GE) discovered that under the right manufacturing conditions, some ceramics, especially aluminum oxide (sometimes known as alumina or sapphire), could be made translucent. These translucent materials were transparent enough to be used for containing the electrical plasma generated in high-pressure sodium street lamps. During the past two decades, additional types of transparent ceramics have been developed for applications such as nose cones for heat-seeking missiles, windows for fighter aircraft, and scintillation counters for computed tomography scanners.

In the early 1970s, during the first part of a 33-year career at GE, Livermore physical chemist Thomas Soules pioneered computer modeling of light transmission through translucent ceramic alumina. His model showed that microscopic pores in ceramic, mainly trapped at the junctions of microcrystalline grains, caused light to scatter and prevented true transparency. The volume fraction of these microscopic pores had to be less than 10^{-5} for high-quality optical transmission; in other words, the density had to be 99.99 percent of the theoretical perfect crystal density. "Although achieving this density is a tall order," says Soules, "the model showed no intrinsic reason preventing someone from making a truly transparent ceramic."

Recently, Japanese scientists have developed techniques to produce ceramic parts that rival the transparency of traditional crystals (grown from a single seed) and exceed a single crystal's fracture resistance and robustness of manufacturability. In particular, scientists at the Japanese firm Konoshima Ltd., a producer of ceramic construction materials and industrial chemicals, have been looking for markets for their transparent ceramics.

Livermore researchers realized that these ceramics might greatly benefit

high-powered lasers used in the National Ignition Facility (NIF) Programs Directorate. In particular, a Livermore research team began to acquire advanced transparent ceramics from Konoshima to determine if they could meet the optical requirements needed for Livermore's Solid-State Heat Capacity Laser (SSHCL). (See *S&TR*, April 2002, pp. 19–21; October 2004, pp. 8–9.) Researchers have also been looking at and testing possible applications of these remarkable materials for use in other Livermore lasers. Potential applications include scalable components and advanced drivers for laser-driven fusion power plants.

The transparent ceramics furnished by Konoshima are well suited to amplify the laser light of the SSHCL, the most powerful diode-pumped, solid-state laser in the world. As in other solid-state lasers, the heart of the SSHCL is a solid, transparent insulator "doped" with a small amount of an optically active ion, in this case, neodymium ions. The insulator's neodymium ions are "pumped," that is, raised to an excited state either by gas-filled flashlamps or, in the case of the SSHCL, arrays of high-power laser diodes. Some of the energy stored in the excited neodymium ions is released when the laser beam passes through the insulator. In this way, the insulator amplifies the input pulse to the required power and energy while maintaining the original beam's spectral and temporal characteristics. In its current configuration, the SSHCL has four transparent ceramic insulators, called amplifier slabs, measuring 10 by 10 by 2 centimeters that are pumped by 16 arrays of battery-powered laser diode bars.

Ceramics Fill Critical Need

The SSHCL's amplifier slabs were originally made of crystalline gadolinium–gallium–garnet doped with neodymium ions (Nd:GGG). However, obtaining the large boules has proved difficult. The vendor that formerly supplied the slabs was no longer able to manufacture the required size.

"Growing large boules of highly refractive single-seed crystals is difficult," says Soules. "Although it is being done on a regular basis for some materials, such as sapphire, it is still as much an art as a science." Ceramic neodymium-doped yttrium–aluminum–garnet (Nd:YAG) seemed an ideal solution to the production problems associated with crystals and also offered several advantages. "We wanted to exploit the power of ceramics to advance our laser programs as well as produce amplifiers to replace the unavailable crystal amplifiers," says Soules.

Researchers working with the transparent ceramics include Soules, electronics engineers Mark Rotter and Scott Fochs, laser technicians Balbir Bhachu and Kurt Cutter, mechanical technician Charles Parks, and mechanical engineer and SSHCL project leader Bob Yamamoto. The Livermore researchers worked with Konoshima to obtain ceramic slabs for the SSHCL. "Konoshima developed a process to produce amplifier slabs of unprecedented size and thickness," says Yamamoto.

The SSHCL requires slabs that are 2 centimeters thick, but the original production method used by Konoshima, called slip casting, is only effective for slabs 1 centimeter thick and smaller. The solution developed at Konoshima entails firing two 1-centimeter-thick slabs at a lower temperature and then vacuum sintering and bonding the two pieces using hot isostatic pressing (HIP). In this process, the two slabs are heated to high temperatures in a furnace under a pressure of several hundred megapascals of argon gas. (See the box on p. 16.) The result is the world's largest laser-quality transparent ceramic Nd:YAG slabs. When viewed from a certain angle, the bond joining the two pieces is barely visible and does not cause any loss of transmission.

The SSHCL uses the world's largest laser-quality transparent ceramic amplifier slabs, which measure 10 by 10 by 2 centimeters.

The ceramic slabs are sent from Konoshima to Baikowski-Japan for polishing. Once at the Laboratory, the slabs are covered with a two-layer coating developed at Livermore, which reduces surface reflection of both the laser beam and the laser diode-pump light to very low amounts.

"Transparent ceramics allow us to scale the SSHCL in a simple manner," says Yamamoto. He explains that other laser systems increase power by adding laser beams. However, the SSHCL remains a single-aperture system regardless of power. "We can increase laser output power linearly in one of three ways: add more amplifier slabs, increase the cross-sectional area of the amplifier slab, or run diodes at 20-percent duty cycle (the percentage of time the laser operates) instead of 10-percent duty cycle. Adding slabs is the easiest way. It's similar to going from a four-cylinder engine to six to eight."

With the transparent ceramic slabs in place, the SSHCL can generate 25,000 watts of light for up to 10 seconds at 10-percent duty cycle. The SSHCL is pulsed, turning on and off 200 times per second to generate a beam that can penetrate a 2.5-centimeter-thick piece of steel in 2 to 7 seconds depending on the beam size at the target. The system recently achieved 67,000 watts of average power with five ceramic slabs for short fire durations. The laser, which is powered by batteries, was conceived as part of the U.S. Army's program to develop directed-energy technologies to defend against missiles, mortar shells, and artillery. Unlike chemical lasers designed for the same purpose, an SSHCL is small enough to be installed on a transport vehicle or helicopter.

An SSHCL can also be used to clear land mines. Its pulses can dig through several centimeters of dirt to expose and neutralize a mine. The SSHCL team received a 2004 R&D 100 Award from *R&D Magazine* for developing this concept. (See *S&TR,* October 2004, pp. 8–9.)

Suppressing Unwanted Light

The transparent ceramics are also being used to suppress amplified spontaneous emission (ASE), which is light emitted spontaneously in all directions by the excited neodymium ions. The presence of ASE degrades laser performance. The method used to remove ASE from the Nd:GGG slabs entailed diffusion-bonding sections of cobalt-doped GGG to the edges of the crystal slab. This process was expensive, time-consuming, often unreliable, and not possible for ceramic Nd:YAG. The SSHCL team worked with Steve Letts in Livermore's Chemistry and Materials Science (CMS) Directorate to bond ASE-absorbing materials to the ceramic slabs with specialized epoxies.

The most promising approach for suppressing ASE is to partially sinter four separate ceramic pieces of YAG doped with samarium (Sm:YAG) and then co-sinter them to the ceramic Nd:YAG in a manner similar to that used to create the thick amplifier slab. The continuous piece that is formed frames the edges of the ceramic Nd:YAG slab with ceramic Sm:YAG. The team worked with Konoshima to design the Sm:YAG pieces and develop this method. (See the figure on p. 14.)

The ceramic Sm:YAG edge-cladded slab has been installed in the SSHCL and has been shown to be effective in reducing ASE. What's more, the edge cladding does not absorb any diode-pump light, which helps limit wavefront distortion by minimizing heating.

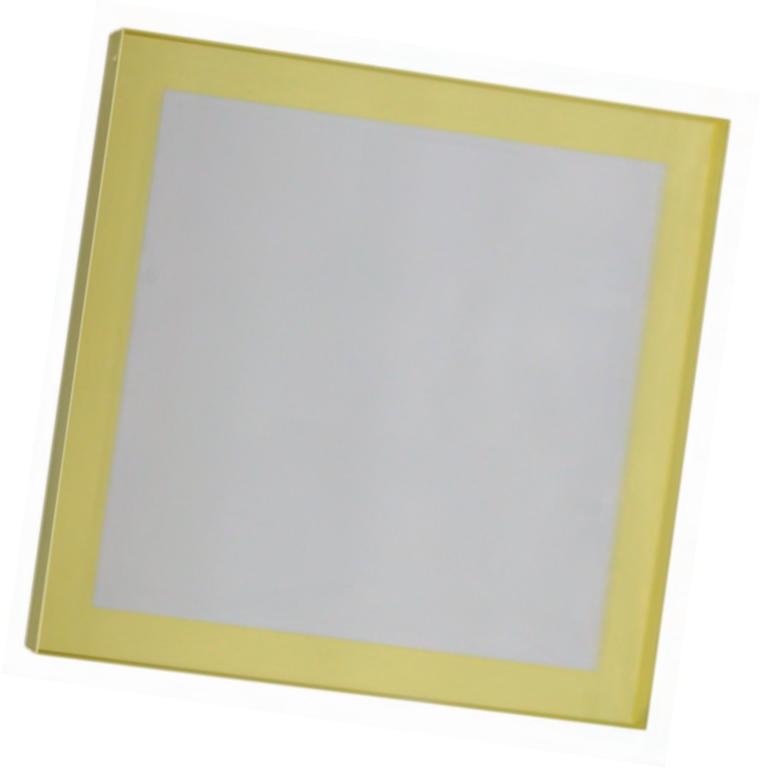
"Making ASE suppression an integral part of the slab and having it be transparent to the pump light had not been done before," says Soules. "Our design also eliminates a lot of manufacturing and reliability problems we encountered with previous approaches and opens up design

The SSHCL can penetrate a 2.5-centimeter-thick piece of steel in 2 to 7 seconds. In the sample shown, the time span of the entire shot was just 10 seconds.

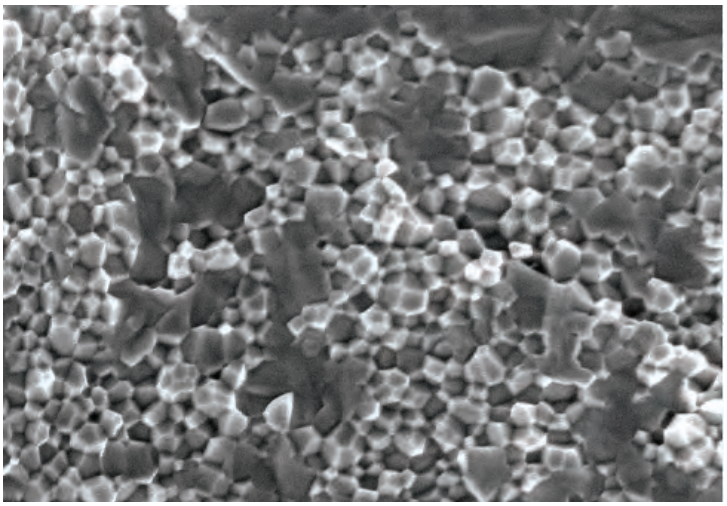
possibilities such as scaling to larger apertures by incorporating ASE suppression into the amplifier slab."

Clear Advantages

Tests show that the transparent ceramics exceed specifications. The amount of scattered light, for example, is similar to that measured from single crystals of Nd:GGG or Nd:YAG. The ceramic slab contains tens of thousands of boundaries between microcrystallites, or "grain boundaries," in the path of the laser light. However, the laser light passing through doesn't "see" the many grain boundaries that measure less than 1 nanometer wide. "The performance of transparent ceramic slabs in the SSHCL is astounding, easily meeting or surpassing the performance of the crystal Nd:GGG slabs," says Soules.



The most promising approach for suppressing amplified spontaneous emission entails co-sintering four separate ceramic pieces of yttrium–aluminum–garnet (YAG) doped with samarium to the amplifier slab of neodymium-doped YAG, forming one continuous piece.



This image taken with a scanning electron microscope shows the three-dimensional grain structure of a Livermore transparent yttrium–aluminum–garnet ceramic sample.

50 micrometers

In what Soules describes as the "acid test" for optical quality, a laser beam is passed back and forth through the ceramic slabs, and any distortions in the wavefront are measured. The ceramic slabs have passed this test with no more wavefront distortion than that expected from polishing.

The Livermore team has found that amplifier slabs made from transparent ceramics offer several advantages over those produced from crystals. Perhaps most important is that these slabs can be obtained regularly, on time, and without unexpected additional costs. Ceramic materials are also more easily fabricated into large sizes for greater power, and ceramics can be made any size and shape. "We're only limited by the size of the sintering furnace," says Soules. The time required to produce the slabs from start to finish is much shorter than the time to grow crystal boules—days instead of weeks. In addition, multiple samples can be fired in one furnace at the same time.

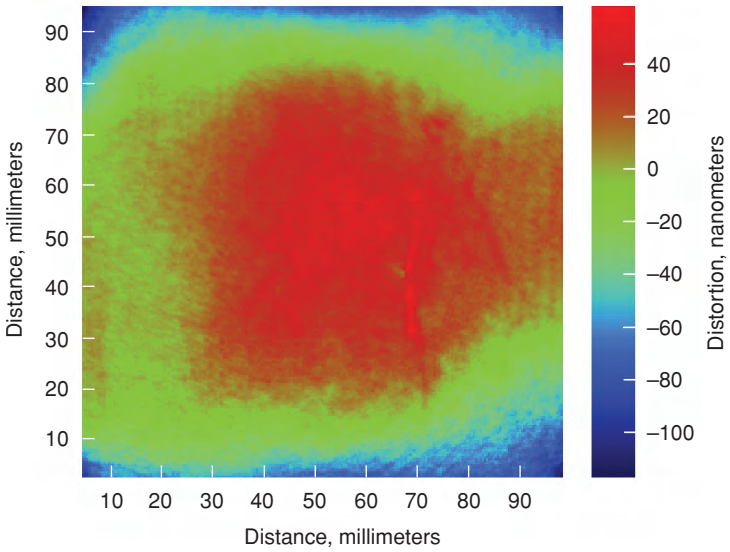
Ceramic slabs are also tougher than single-seed crystal slabs and much less apt to undergo a catastrophic fracture. When a crystal slab fractures, the fracture can "run," extending some distance from the original crack and often branching or making a random turn into the center of the crystal to relieve stress. Because cracks are impeded by grain boundaries, ceramic fractures don't run as easily or randomly. Ceramics also measure lower residual stress, which is stress that resides in a material after it has been manufactured. Significant residual stress distorts the laser beam and can make the material more susceptible to cracking.

Ceramics can accommodate higher concentrations of dopants (rare-earth ions such as neodymium), which could permit pumping at wavelengths that might

otherwise be impractical. Dopant concentrations are highly homogeneous in ceramics and can be controlled precisely. In crystals, dopants tend to segregate toward the bottom of the growing boule.

Ceramics also offer the possibility of novel composite structures. For example, a single slab could have an "active" layer of YAG doped with neodymium ions and another layer composed of YAG doped with chromium ions. Such a design is called a passive Q-switch, which turns on the laser after saturation. The different materials would be co-sintered to produce a single integral structure in the same way that the team co-sinters the Sm:YAG ASE suppressors. Another possible approach is to embed different powders with the same host before sintering the slab to create a gradation of neodymium ions or incorporate the passive Q-switch.

"We're making tremendous progress in understanding, using, and manufacturing transparent ceramics," Yamamoto says. "We need slabs that are very pure because contaminants absorb heat and become hot spots. The quality we're seeing is outstanding."



Wavefront distortion through the Konoshima ceramic is extremely low, as seen in the test results from passing a laser beam back and forth through the ceramic amplfier slab. The distortion at the edges is caused by polishing.

Livermore researchers have produced 15-millimeter-diameter samples of transparent ceramic yttrium–aluminum–garnet. A sample exhibits excellent optical qualities after hot isostatic pressing (right).

On Their Own

Soules is also working on a Laboratory Directed Research and Development–funded project with Joshua Kuntz, Alex Gash, and Richard Landingham from CMS and Kathleen Schaffers from NIF. The researchers are making small samples of transparent ceramics to better understand the key process variables involved. "We don't plan to produce large transparent ceramic slabs for lasers, but we want to understand the critical parameters that affect transparency and then extend the technology to other materials," says Soules.

The team has produced 15-millimeter-diameter samples of transparent Nd:YAG and determined the most important parameters that affect their quality. In making these pieces, the team largely followed the Japanese production methods and used an in-house furnace to vacuum sinter nanopowders. The pieces were then sent out for HIP. Finally, the pieces were returned to Livermore for coating and testing. "It's not an easy process, but once optimized, it's a repeatable process," says Soules. The samples have shown excellent optical qualities.

The team is also exploring new ways to make the initial nanopowders. Borrowing on expertise developed in CMS over the past 5 years, the team is making nanopowders based on aerogel and solgel processing and then sintering them. Another technique being tested uses a combustion process to generate the powders by burning an organic solid containing yttrium, aluminum, and neodynium and then collecting the smoke, which consists of spherical nanoparticles.

In addition, the team is using manufacturing techniques, including Livermore-developed extruding techniques, that allow the transparent ceramic parts to have complicated shapes,

such as shells and tubes, for improved coupling to the pump light and for transferring heat more efficiently. Different materials can be co-extruded and then sintered into a single transparent piece. For example, an amplifier slab can be made so that part of the structure acts as a light guide to focus pump light from laser diodes into regions with a high concentration of neodymium ions located in the smaller, central region of the slab.

In collaboration with the University of California at Davis and Stanford University, the team is investigating other ceramic materials for lasers. These include other oxides and fluorides. The team also wants to identify new commercial sources of ceramic Nd:YAG and determine their viability for Livermore lasers. “If laser scientists have a need for a different material, we will try to determine if it is

Making Transparent Ceramics

Transparent ceramics are produced by forming a nanopowder of ingredients into the desired shape, then sintering (heating below the melting point) in a vacuum to form an aggregate of microcrystals that exhibit optical and thermal qualities almost identical to those of a single-seed crystal.

Livermore researchers are experimenting with several methods to make transparent ceramics. Following a recipe similar to that used by Japanese scientists, they begin with a solution of yttrium, neodymium, and aluminum salts and add a solution of ammonium hydrogen carbonate. The precipitate is then filtered, washed, and dried. At this point, the co-precipitated amorphous carbonate is made up of agglomerates of particles measuring about 10 nanometers in diameter. The particles are heated to about 1,100°C to decompose the carbonates and obtain particles of neodymium-doped yttrium–aluminum–garnet (Nd:YAG) measuring about 100 nanometers in size. Highly agglomerated, the particles are treated ultrasonically, and then the large particles are removed to obtain a uniform small size.

In a process called slip casting, a suspension of the fine powder is poured into a plaster of paris mold and allowed to settle. Excess water is poured off, and the mold is set aside to absorb most of the remaining water and dry. The result is a porous structure called a preform structure, which is removed from the mold. The preform still contains many pores and is only about 40 to 45 percent dense.

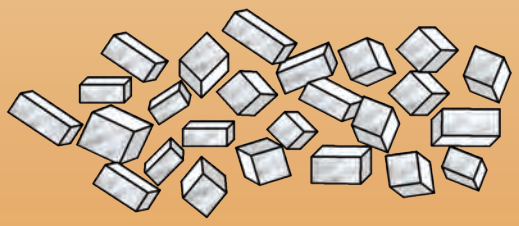
The preform structure is then fired in a vacuum at high temperature for many hours. This sintering process involves surface atom diffusion, resulting in the particles fusing together and decreasing the total surface energy. Some of the pores are squeezed out, and the structure shrinks but still retains its overall shape. Additionally, many physical and thermal properties undergo dramatic improvements during sintering.

Under a microscope, the structure begins to resemble a three-dimensional mosaic of small, irregularly shaped, and densely packed grains fused together with channels running along grain edges and in regions where the grains do not fit together well. Finally, the channels become narrower and break up into small spherical pores that are usually trapped at corners where more than two grains meet.

Because the sintering process still leaves a few trapped pores, the ceramic parts are sent to a vendor for a 1- to 2-hour treatment in a hot isostatic press. The press drives out the last pores by heating the sample to high temperatures under enormous pressure (several hundred megapascals). Provided that no impurities exist, the remaining trapped pores collapse, and the finished part achieves the greater than 99.99 percent theoretical density required for nearly perfect transparency.

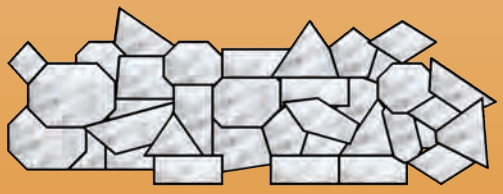
Before sintering

Powder



After sintering

Transparent ceramic



Transparent ceramics are produced by forming a nanopowder of a desired shape, then sintering the sample in a vacuum to form an aggregate of microcrystals.

feasible," says Soules. "We will share technology we develop with industry." He notes that several companies are "jumping in" to provide ceramics for lasers. "We want to work with domestic suppliers as well as maintain strong relationships with our Japanese suppliers."

Looking Ahead

Yamamoto and colleagues are designing a megawatt-class, solid-state ceramic laser that builds on the success of the ceramics in the SSHCL. The new design features 16 ceramic laser slabs measuring 20 by 20 by 4 centimeters.

Transparent ceramics promise to greatly expand the availability of low-cost, high-quality components in much larger sizes than is possible with traditional crystals. For example, many classes of laser designs could benefit from ceramic-based laser structures such as amplifiers with built-in edge claddings. Also, ceramic amplifier slabs could provide more robust and compact designs for high-peak-power, fusion-class lasers for stockpile stewardship and high-average-power lasers for theatre missile defense. Scientists working at NIF, which houses the largest laser in the world, are interested in transparent ceramics because of their high thermal conductivity, high resistance to fracture, and potential damage resistance. Livermore scientists planning the Mercury laser, a large-aperture, high-average-power laser with a high repetition rate, are also interested in the team's work. Mercury is a compact version of a potential prototype for an inertial fusion energy power plant.

"For the first time, laser designers have available gain materials with all the desirable properties of crystals for scaling lasers to high average power," says Bruce Warner, principal deputy associate director for NIF Programs. "At the same time, transparent ceramics maintain all the desirable properties of high-quality laser glass such as that used in NIF—superb optical quality combined with the ability to scale to large apertures. These materials promise to transform the laser landscape and bring us one step closer to realizing laser drivers suitable for the production of energy in laser-driven fusion power plants."

With their optical quality, high thermal conductivity, and manufacturing savings, transparent ceramics are changing the way lasers are being designed and built. Scientists engineering the next generation of lasers have a new class of materials available to expand laser science.

—Arnie Heller

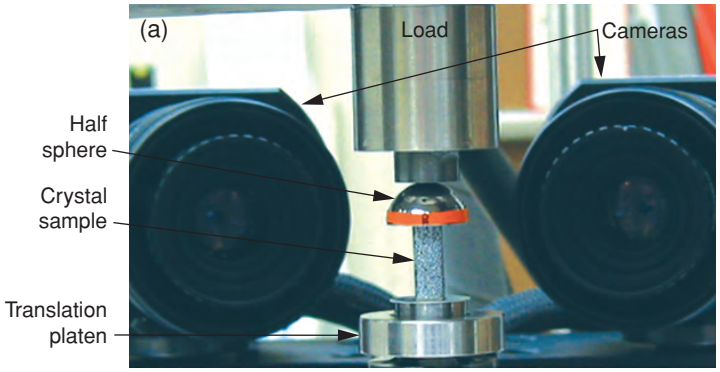
Key Words: hot isostatic press (HIP), laser diodes, neodymium-doped gadolinium–gallium–garnet (Nd:GGG), neodymium-doped yttrium–aluminum–garnet (Nd:YAG), passive Q-switch, samarium-doped yttrium–aluminum–garnet (Sm:YAG), sintering, Solid-State Heat Capacity Laser (SSHCL), transparent ceramics.

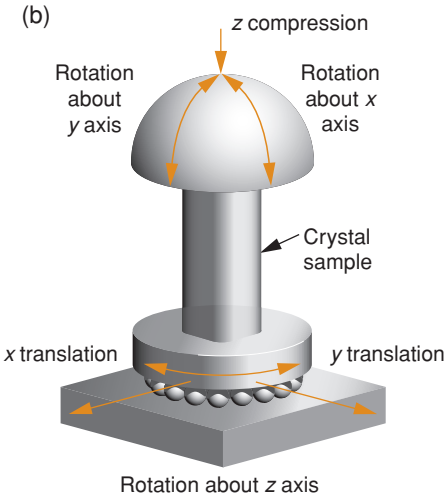
For further information contact Thomas Soules (925) 423-9260 (soules1@llnl.gov).

Studying the Behavior of Crystal Deformation

MOST of the seemingly static and unchanging metals we encounter in our daily lives are anything but unchanging. At the atomic level, metals are a highly complex and ordered arrangement of atoms that have the potential to rearrange themselves, especially when put under extreme strain and stress. Livermore researchers are working to gain a better understanding of how several metals achieve permanent, or plastic, deformation.

Most of the time, atoms self-organize into crystalline lattice structures. A single crystal is composed of millions of these lattices oriented in exactly the same direction. Single crystals are the building blocks of everyday materials, such as the steels used in automobiles, that are typically polycrystalline; that is, the lattice structures are stacked in many different orientations. Materials scientists at Livermore are using a three-dimensional (3D) image-correlation system and a novel mechanical test system to investigate how metallic single crystals behave under mechanical stress and strain. The researchers, funded by the Laboratory Directed Research and Development Program, are using a new method to look at an old problem. "We are closing in on a body of data that enable some new thinking on crystal plasticity," says David Lassila, a materials scientist in the Engineering Directorate.





(a) Livermore researchers use three-dimensional image correlation to measure full-field displacements and strains on a crystal sample. Two charge-coupled-device cameras focus on the experimental apparatus and capture images of the material before and after deformation caused by large strains. (b) The experimental apparatus allows the crystal to deform essentially unconstrained in six directions (orange arrows).

Livermore scientists investigate the structures and properties of various materials to better understand the limits of materials and how their properties may change under certain conditions. This work also enables researchers to design new materials that will have specific desirable properties.

Lassila's team includes materials scientist Jeff Florando and senior engineering associate Mary LeBlanc, also from Engineering. Their work contributes to Livermore's mission in support of the National Nuclear Security Administration's Stockpile Stewardship Program. Key to managing the nation's aging nuclear weapons stockpile is the development of material-strength models that are accurate under extreme conditions of high pressure, high strain rate, and large extents of strain.

Stepping into the Future

In the past, materials scientists have depended on traditional crystal plasticity theory, which was developed with data from 1D experiments during the 1920s and 1930s. Traditional plasticity theory—Schmid's Law—is based on the 1D response of thin wires, where only one slip system is active. The dislocation activity is idealized and not representative of real materials, where dislocation activity is much more complex. Lassila's team is finding traditional theory might lead to experimental results that are not very accurate. "We're collecting data with the 3D image-correlation system that's quite different from what we were inferring with traditional theory," says Florando.

The 3D image-correlation system includes two charge-coupled-device (CCD) cameras that focus on the experimental apparatus. Before the experiment, a single-crystal sample is painted with black dots on a white background, and a half sphere is centered over the sample. When a load is applied to the sample through the half sphere, the six-degrees-of-freedom (6DOF) apparatus allows for tilt

in two directions (two degrees), rotation about the compression axis (one degree), and compression in the *z* direction (one degree). Additionally, the bottom translation platen sits on ball bearings that allow full motion in the *x*–*y* plane, adding two more degrees of freedom. As the sample deforms, the two CCD cameras record the positions of the black dots by triangulation.

"We are deforming the lattice through load," says Florando. "This change is brought about by the atoms moving in a slip plane in response to the stress and strain of the load." Materials scientists call these atomistic disruptions "dislocations." In single crystals, slip planes are the preferred planes where dislocations move. The set of slip planes and slip directions in a crystal constitute the slip system. "Materials can slip in many ways," says Florando. "We're using the data from the image-correlation system to determine which slip systems are active." The recorded data are used to create strain maps with various colored bands displaying the inhomogeneities in the crystal deformation.

With the new experimental data, the researchers found that, in general, Schmid's Law is the exception and not the rule. Interestingly, the plasticity of crystals with different structures to be remarkably similar in their non-Schmid plastic response. The researchers hope to use Livermore's multiscale-modeling capabilities to understand non-Schmid behavior and establish a more fundamental understanding of the plastic response of metallic single crystals.

Multidirectional Measurements in Real Time

Although other optical techniques for measuring the deformation of materials are available, the team found that image correlation had a number of advantages in the study of single crystals. Image correlation allows researchers to measure larger, full-field strains while tracking the motion of the sample. It also allows them to measure the displacements and displacement gradients in three dimensions.

With a strain gauge, the traditional measuring device, calculations were attainable for only five independent slip systems. Image correlation, however, measures displacements rather than strain. "Using image correlation, we can accurately determine the slip activity for up to eight independent slip systems while the material is deforming," says Lassila. This additional knowledge leads to a better understanding of how materials fundamentally deform.

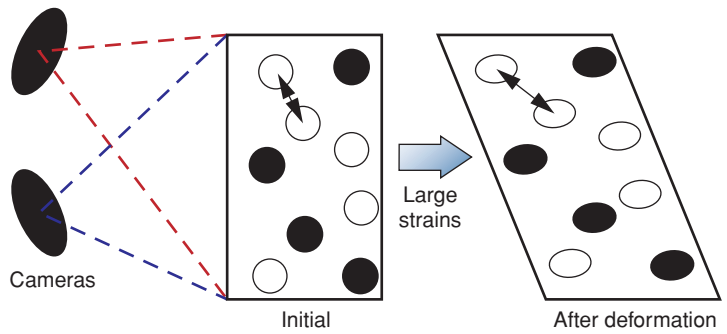
If a crystal is oriented such that the slip direction is parallel to a face of the sample, the slip activity for that system can be directly measured. Image-correlation techniques allow for the direct measurement of slip activity by rotating the axes to lie in the direction of the slip plane.

Experimental Insight

The deformation data being collected by the team is essential for direct comparisons and validation of dislocation dynamics simulations. (See *S&TR*, November 2005, pp. 4–11.) Currently, the large-strain deformation behavior of single crystals is not well understood. Because many materials of interest to scientists at Livermore are deformed to relatively large strains, new experimental techniques are needed for measuring the deformation behavior of single crystals under large extents of strain.

"Crystal plasticity models play a key role in multiscale modeling to predict the deformation response of complex materials under various loading conditions," says Florando. "Insight gained from large-strain experiments has the potential to advance crystal plasticity theory and predictive modeling capabilities."

—Maurina S. Sherman



In three-dimensional image-correlation experiments, the crystal sample is painted with black dots on a white background. As the sample deforms, the two charge-coupled-device cameras record the relative motion of the black dots, providing local displacement data.

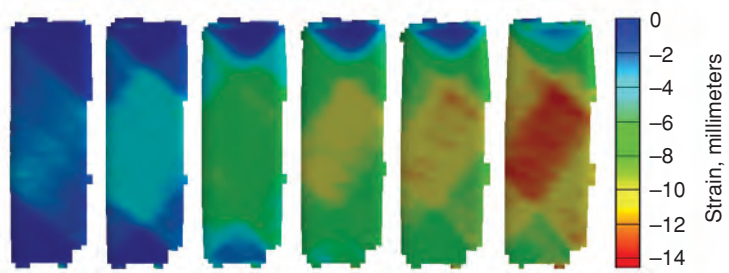


Image-analysis software processes data from three-dimensional image-correlation experiments to create strain maps. Maps from an experiment with a copper sample show axial strains at different stages. The areas represented by the red bands received the highest level of strain.

Key Words: crystal deformation, dislocation dynamics, metallic single crystals, six degrees of freedom (6DOF), slip systems, strain, stress, three-dimensional (3D) image correlation.

For further information contact David Lassila (925) 423-9537 (lassila1@llnl.gov) or Jeff Florando (925) 422-0698 (florando1@llnl.gov).

An Accelerated Collaboration Meets with Beaming Success

MAINTAINING a smaller, aging U.S. nuclear weapons stockpile without underground nuclear testing requires the capability to verify and validate the complex computer calculations on which stockpile confidence is based. This capability, in turn, requires nonnuclear hydrodynamic tests (hydrotests) that can x-ray stages of the implosion process, providing freeze-frame photos of materials imploding at speeds of more than 16,000 kilometers per hour. The images will yield important information on shapes and densities of metals and other materials under the extreme pressures and temperatures generated by the detonation of high explosives.

The Dual-Axis Radiographic Hydrodynamics Test (DARHT) Facility at Los Alamos National Laboratory is a two-arm x-ray imaging system that will provide such images, capturing the inner workings of a mock nuclear explosion with high resolution. Scientists compare the radiographic images with computer models, examine the differences, and refine the models to more accurately represent weapon behavior.

One of DARHT's arms (now called DARHT-II) recently got a "leg up" through a collaboration of Lawrence Livermore and Los Alamos scientists, using a Livermore accelerator to test its subsystems and codes.

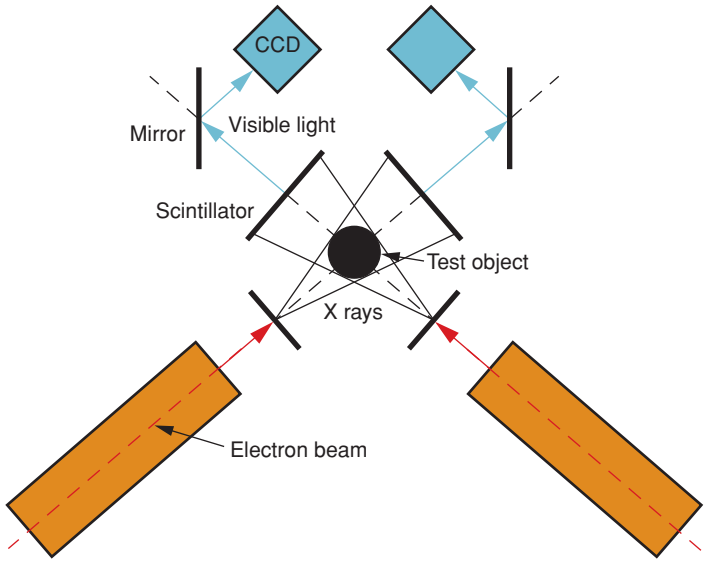
Imaging the Unseen

DARHT's two beamlines, set at right angles to one another, will generate two perpendicular images. These image pairs can be combined to yield quasi-three-dimensional pictures depicting the implosion process. The first-built arm of the DARHT Facility has an accelerator that generates a single 18-megaelectronvolt, 2-kiloampere pulse, lasting 60 nanoseconds. The second arm, DARHT-II, designed in a collaborative effort by Los Alamos, Lawrence Livermore,

An aerial view of the Dual Axis Radiographic Hydrodynamic Test (DARHT) Facility at Los Alamos National Laboratory shows the facility's two accelerators set at right angles to one another. (Image courtesy of Los Alamos.)

and Lawrence Berkeley national laboratories, generates a 20-megaelectronvolt, 2-kiloampere pulse that will last comparatively much longer—2 microseconds.

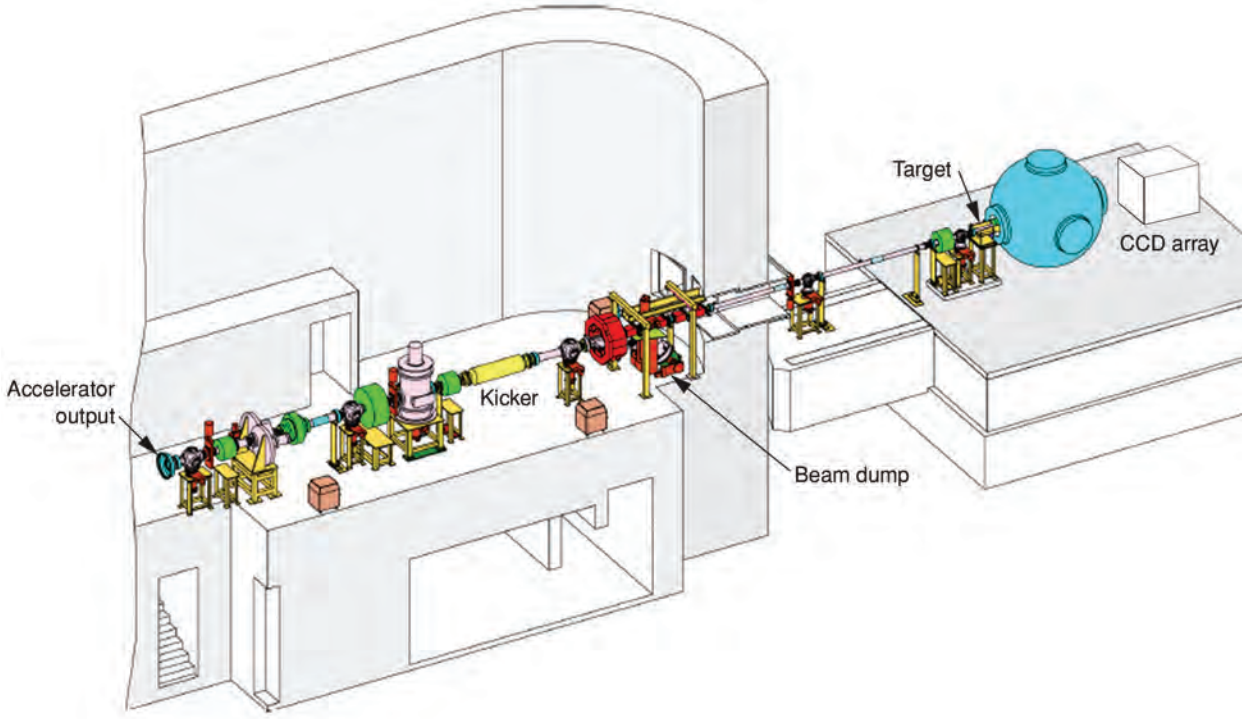
DARHT-II's electron beam is first accelerated to the proper energy for the experiment. A Livermore-developed "kicker" system then chops four shorter pulses of variable pulse-width and spacing from this longer, second-arm pulse. These shorter pulses will allow the system to produce time-resolved x-ray images. The chopped pulses are tightly focused onto a small x-ray target made of a high-atomic-number (high-*Z*) material such as tungsten. The target converts the high-energy electron beam into x rays, which emerge from the other side of the target. The x rays travel to and through the experimental object, which is being explosively compressed at velocities of many kilometers per second. The x rays are attenuated as they go through the object. For denser materials, fewer x rays will emerge from the other side. A segmented scintillator converts the remaining x rays to light, which is then lens-coupled onto a mosaic of large-area charge-coupled-device cameras.



X-ray images from the two accelerator arms will be combined to yield quasi-three-dimensional views of hydrodynamic experiments. The electron beams from the two accelerators will hit a metal target, which will produce x rays that will pass through a test object. A scintillator will covert the x rays to visible light, which will then be directed to charge-coupled-device (CCD) cameras.

Collaborating on the Line

While DARHT-II was undergoing refurbishment last year, Livermore scientists hosted Los Alamos personnel, so the visiting scientists could test its systems on Livermore's Experimental Test Accelerator-II (ETA-II). In particular, the beamline equipment and systems downstream from the electron accelerator were tested. The



This schematic shows the downstream transport of DARHT's second beamline, from the output of the accelerator to the CCD cameras.

Los Alamos–Livermore collaborators built a test bed on ETA-II, a high-repetition-rate accelerator designed to deliver high average power as well as high peak power.

"The tests proved very valuable," says physicist George Caporaso, who led the Livermore part of the collaboration. "They showed that the high currents required for long-pulse beam operation at Los Alamos could be successfully transported through the downstream beamline. The tests also allowed the teams to develop a predictive capability to tune the beamline, to establish the initial settings for future experiments, and to qualify hardware and software."

One initial question the teams had was whether the Los Alamos subsystems would "mesh" with the Livermore-built hardware. "We hooked everything up and checked to see how it all ran, including the beam diagnostics, and everything worked," says Caporaso. "Another question we had was, once we connected the Los Alamos diagnostic systems to ETA-II, would we be able to collect the data generated in the tests with this Los Alamos–Livermore combination of subsystems? Turns out, we could! The combined subsystems worked great."

The extensive dry runs provided assurance that DARHT-II's downstream beamline subsystems were ready for future experiments. The teams acquired information on the electron-beam parameters, such as current and energy, as the beam progressed through the downstream transport systems. They verified that the process for tuning the high-current electron beam, that is, getting just the right pulse shape and level, would work. "The DARHT Facility will be capable of generating 40 pulses a day for experiments; ETA-II generates 1 pulse per second. We were able to tune the current in real time with ETA-II," says Caporaso. The experiments also helped Los Alamos scientists perfect the computer algorithms that will be used to tune the beamline in the shortest number of shots.

Furthermore, the ETA-II test bed allowed Los Alamos scientists to operate the Livermore-designed kicker system and interface it to their data-acquisition system and diagnostics. The kicker uses electric and magnetic fields to manipulate the beam. When the kicker is turned off, the magnetic fields deflect the beam, and the beam is transported into a beam dump. Only when the kicker is turned on, will a short segment of beam travel onto the x-ray conversion target.

The DARHT collaborators addressed the challenge of how to focus the electron beam on a small area of the converter target in an optimum way. "A single beam pulse is normally powerful enough to blow a hole in the converter when it hits," says Caporaso. "With the second beamline operating, the target must survive long enough for four x-ray beams to emerge from the other side." The collaborators also worked on algorithms and schemes that would help them obtain the required spot shapes.

Preparing for What's Next

"The collaborative work on the downstream transport system was essential to help us prepare for long-pulse beam operation on DARHT-II at Los Alamos this summer," says Los Alamos's Ray Scarpetti, DARHT-II project director.

The teams from the two laboratories worked together to install the hardware, tune the magnets, model beam transport, and validate the codes. Los Alamos staff also had the opportunity to become familiar with the kicker system, including its controls and software, on an accelerator that allowed "real time" tweaking and fine-tuning. "The ETA-II test-bed effort was a successful technology transfer endeavor," says Caporaso. "Los Alamos people had an opportunity to become familiar with the Livermore-developed hardware and software, and the Livermore researchers had an opportunity to work with the Los Alamos equipment and codes. All in all, it was a successful exchange and collaboration for both labs."

—Ann Parker

Key Words: Dual-Axis Radiographic Hydrodynamics Test (DARHT) Facility, DARHT-II, Experimental Test Accelerator-II (ETA-II), stockpile stewardship, validation, x rays, x-ray imaging.

For further information contact George Caporaso (925) 422-7852 (caporaso1@llnl.gov).

Continued from p. 2

Superplastic carbon nanotubes

Researchers from Lawrence Livermore, Boston College, and the Massachusetts Institute of Technology have pioneered a new technique to stretch carbon nanotubes. A typical carbon nanotube can be stretched to 15 percent longer than its original length before it fails. In high-temperature experiments performed by the researchers, a nanotube heated to 2,000°C stretched to more than 280 percent of its original length before it broke. Carbon nanotubes are 10,000 times smaller than a human hair and are used in a variety of machines including computers, cellular phones, and personal handheld devices.

"This kind of intense stretching and reduction in diameter of a carbon nanotube is unprecedented," says Livermore's Yinmin (Morris) Wang, a coauthor of the paper that appeared in the January 19, 2006, edition of *Nature*. The superelongation is due to a full plastic deformation that occurs at high temperatures. Under such high temperatures, the nanotube appears to be completely pliable, resulting in a superplastic deformation that would otherwise be impossible at low temperatures.

"Our surprising discovery of superplasticity in nanotubes should encourage the investigation of their mechanical and electronic behavior at high temperatures," says Wang. "The tubes may find uses as reinforcement agents in ceramics or other nanocomposites for high-temperature applications."

Contact: Morris Wang (925) 422-6083 (wang35@llnl.gov).

Astronomers discover distant, Earth-like planet

Using a network of telescopes scattered across the globe, an international team of astronomers has discovered an extrasolar planet that is more Earth-like than any other planet found so far. The new planet—designated OGLE-2005-BLG-290 Lb—orbits a red dwarf star five times less massive than the Sun every 10 years. The discovery opens a new chapter in the search for planets that support life. The team's research appeared in the January 26, 2006, edition of *Nature*.

In most cases, new planets have been found by measuring the Doppler shift in light from the orbiting star. However, most of these planets have been giant gas planets. The team found the new rocky planet using a technique called microlensing. The planet is not directly "seen," nor is the star that it's orbiting, but its presence can be deduced from the effect of the planet's gravity on light from more distant stars. "There's a deviation of light when a planet is in the way," says Kem Cook, an astronomer at Lawrence Livermore who is also a member of PLANET (Probing Lensing Anomalies NETwork), a part of the group that made the discovery. "In this instance, there was a half-day brightening that was indicative of a planet."

Microlensing can show just how common planets are in distant parts of the galaxy and probe details of planetary formation that other techniques cannot. The discovery of the Earth-like planet is the joint effort of three independent microlensing campaigns: PLANET/RoboNet, the Optical Gravitational Lensing Experiment, and Microlensing Observations in Astrophysics. The effort involves 73 collaborators affiliated with 32 institutions in 12 countries.

Contact: Kem Cook (925) 423-4634 (cook12@llnl.gov).

A quantum leap in materials modeling

A Livermore team has determined the solid–liquid and solid–solid phase boundaries of carbon for pressures up to 20 million Earth atmospheres and more than 10,000 kelvins. "Results of computer simulations show a consistent description of elemental carbon in a broad range of temperatures and pressures," says Alfredo Correa, a University of California (UC) at Berkeley student who works in Livermore's Physics and Advanced Technologies Directorate under the Student Employee Graduate Research Fellowship Program. The physical properties of carbon are of great importance for devising models of Neptune, Uranus, white dwarf stars, and extrasolar carbon-rich planets.

In its elemental form, carbon is found in materials such as coal, graphite, diamond, bucky balls, and nanotubes. These materials have very different properties, but, at the microscopic level, they differ only in their carbon atoms' geometric arrangements. Experimental data on the phase boundaries and melting properties of elemental carbon are scarce because of difficulties in reaching megabar (one million atmospheres) pressures and temperature regimes of thousands of kelvins in the laboratory.

"Our simulation results call for a partial revision of current planetary models, especially for the description of their core regions," Correa said. "Our computational work also may help us interpret future experimental work." Correa is the lead author of a report published in the January 23–27, 2006, online edition of the *Proceedings of the National Academy of Sciences*. The research team is composed of Correa, Stanimir Bonev, and Giulia Galli, all of whom were at Livermore at the time the work began. Galli is now a professor at UC Davis, and Bonev is an assistant professor at Dalhousie University in Canada.

Contact: Alfredo Correa (925) 422-3520 (correatedesco1@llnl.gov).

Each month in this space, we report on the patents issued to and/or the awards received by Laboratory employees. Our goal is to showcase the distinguished scientific and technical achievements of our employees as well as to indicate the scale and scope of the work done at the Laboratory.

Patents

Compact Imaging Spectrometer Utilizing an Immersed Grating and Anamorphic Mirror
Scott A. Lerner
U.S. Patent 6,985,226 B2
January 10, 2006
The compact imaging spectrometer is composed of an entrance slit, an anamorphic mirror, a grating, and a detector array. The entrance slit directs light to the anamorphic mirror. The mirror receives the light and directs the light to the grating. The grating receives the light from the mirror and defracts the light back onto the mirror. The mirror focuses the light onto a detector array.

Method for Producing Nanostructured Metal-Oxides
Thomas M. Tillotson, Randall L. Simpson, Lawrence W. Hrubesh, Alexander Gash
U.S. Patent 6,986,818 B2
January 17, 2006
A synthetic route for producing nanostructure metal oxide–based materials using solgel processing. This procedure uses stable and inexpensive hydrated-metal inorganic salts and environment-friendly solvents such as water and ethanol. This synthesis involves the dissolution of the metal salt in a solvent followed by the addition of a proton scavenger, which induces gel formation in a timely manner. Both critical point (supercritical extraction) and atmospheric drying (low-temperature evaporation) may be used to produce monolithic aerogels and xerogels, respectively. With this method, metal oxide nanostructured materials have been synthesized using inorganic salts. Nanostructured metal oxides from the following elements of the periodic table can be made: groups 2 through 13, part of group 14 (germanium, tin, lead), part of group 15 (antimony, bismuth), part of group 16 (polonium), and the lanthanides and actinides. The solgel processing allows for the addition of insoluble materials (for example, metals or polymers) to the viscous sol, just before gelation, and produces uniformly distributed nanocomposites upon gelation. For example, energetic nanocomposites of an iron–oxygen gel with distributed aluminum are readily made. The compositions are stable, safe, and can be readily ignited to thermic reaction.

Metal-Oxide–Based Energetic Materials and Synthesis Thereof
Thomas M. Tillotson, Randall L. Simpson, Lawrence W. Hrubesh
U.S. Patent 6,986,819 B2
January 17, 2006
A method of preparing metal oxide–based energetic materials using solgel chemistry has been invented. The wet chemical solgel processing improves both safety and performance. Essentially, a metal oxide oxidizer skeletal structure is prepared from hydrolyzable metals (metal salts or metal alkoxides) with fuel added to the sol prior to gelation or synthesized within the porosity metal oxide gel matrix. With metal salt precursors, a proton scavenger is used to destabilize the sol and induce gelation. With metal alkoxide precursors, standard well-known solgel hydrolysis and condensation reactions are used. Drying is done by standard solgel practices, either by a slow evaporation of the liquid residing within the pores to produce a high-density solid nanocomposite or by supercritical extraction to produce a lower density, high-porous nanocomposite. Other ingredients may be added to this basic nanostructure to change physical and chemical properties, which include organic constituents for binders or gas generators during reactions, burn-rate modifiers, or spectral emitters.

Electronic Unit Integrated into a Flexible Polymer Body
Peter A. Krulevitch, Mariam N. Maghribi, William J. Benett, Julie K. Hamilton, Klint A. Rose, James Courtney Davidson, Mark S. Strauch
U.S. Patent 6,991,963 B2
January 31, 2006
A peel-and-stick electronic system is composed of a silicone body and at least one electronic unit operatively connected to the silicone body. The electronic system is produced by providing a silicone layer on a substrate, a metal layer on the silicone layer, and at least one electronic unit connected to the metal layer.

Awards

The American Physical Society (APS) has selected five Laboratory scientists as APS Fellows.

Vasily Bulatov of the Chemistry and Materials Science (CMS) Directorate was selected in the computational physics division "for outstanding contributions to computational materials sciences, particularly in the areas of dislocation dynamics and crystal plasticity."

Carlos Iglesias of the Physics and Advanced Technologies (PAT) Directorate was selected in the plasma physics division "for ground-breaking contributions to the study of the production and transport of radiation in astrophysical and laboratory plasmas, including the development of the OPAL opacity code."

John Moriarty, also of the PAT Directorate, was selected in the computational physics division "for his pioneering contributions to the first-principles quantum-based calculation of interatomic forces in d- and f-electron materials, with major impact on high-pressure physics, multiscale modeling and national security."

Harry Radousky of the University Relations Program was selected in the materials physics division "for his outstanding contributions and scientific leadership in experimental condensed matter and materials physics, with particular emphasis on innovative discoveries related to optical materials, superconductivity, and high-pressure research."

Joe Wong of the CMS Directorate was selected "for innovative and significant contributions to experimental materials physics, particularly for contributions to XAFS (X-ray Absorption of Fine Structure) and XANES (X-ray Absorption Near Edge Structure), and for the first measurements of phonon dispersion in plutonium."

Each year, no more than one-half of one percent of the current APS membership is elected to the status of Fellow. APS fellowship recognizes members who have made advances in knowledge through original research and publication or those who have made significant and innovative contributions in the application of physics to science and technology. APS Fellows also may have made significant contributions to the teaching of physics or service and participation in the activities of the society.

Abstracts

Measuring Contact Stress inside Weapon Systems

Advances in microfabrication techniques have allowed researchers to maximize the capabilities of numerous technologies using microelectromechanical systems (MEMS). Among the technologies benefiting from MEMS are stress sensors, which are used to measure loads at the contact interface between objects. Contact measurements are important for numerous applications, from automotive brakes to orthopedic devices to weapons diagnostics. The size and functionality of commercial stress sensors have prevented their use in some applications, including in weapons diagnostics. A Livermore team has designed the first silicon stress sensor that can repeatedly measure changing loads perpendicular to a surface in a weapon system. The sensor's small size—4 millimeters square and 50 micrometers thick—allows it to take measurements without altering the stress being measured. The team has also designed silicon arrays of more than 1,000 sensors that can bend and flex to map the load distribution over a surface area.

Contact:

Jack Kotovsky (925) 424-3298 (kotovsky1@llnl.gov).

Transparent Ceramics Spark Laser Advances

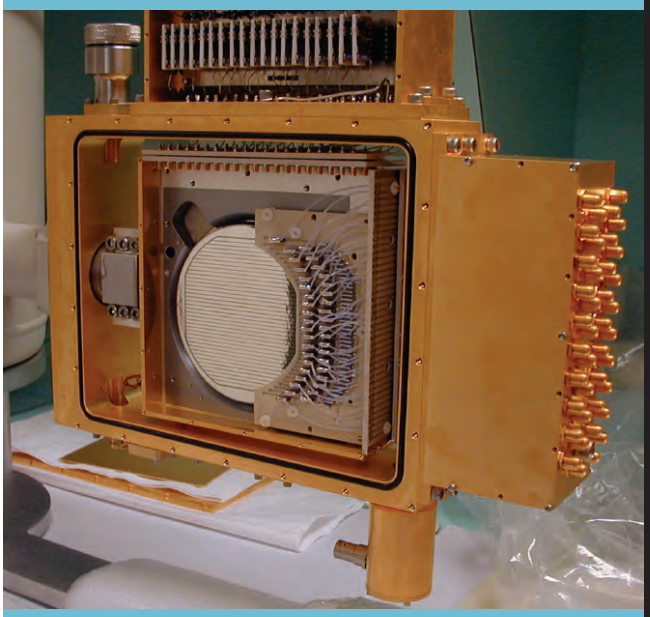
Building on work done in Japan, a team of Livermore researchers is acquiring transparent ceramics that can handle the high heat loads and optical requirements for high-power lasers, especially Livermore's Solid-State Heat Capacity Laser. Working with Konoshima Chemical Company, Ltd., the team has developed the world's largest laser-quality transparent ceramic slabs of neodymium-doped yttrium–aluminum–garnet measuring 10 by 10 by 2 centimeters. The production method entails forming a nanopowder of ingredients into the desired shape, then heating the sample to just below the melting point in a vacuum. This process forms an aggregate of microcrystals that exhibit optical and thermal qualities almost identical to those of a single-seed crystal but with important manufacturing savings and greater resistance to cracking. The team has developed new techniques to suppress amplified spontaneous emission, which is light emitted in all directions by excited neodymium ions. In addition, a small group within the Livermore team is funded by the Laboratory Directed Research and Development Program to produce its own transparent ceramics to better understand the keys to their manufacture.

Contact:

Thomas Soules (925) 423-9260 (soules1@llnl.gov).

U.S. Government Printing Office: 2006/570-077-10017

Improving Gamma-Ray Detection



Two gamma-ray imagers developed at Livermore are taking detection capabilities to unprecedented levels.

Also in May

- *A rapid test for foot-and-mouth disease and similar animal diseases will improve the nation's agricultural security.*
- *Livermore scientists are providing the best measurement yet of a correction to the quantum description of how atoms behave.*
- *Laboratory scientists have developed a highly accurate method for measuring the temperature of metal foils.*

Coming Next Month

University of California
Science & Technology Review
Lawrence Livermore National Laboratory
P.O. Box 808, L-664
Livermore, California 94551

NON-PROFIT ORG.
U.S. POSTAGE
PAID
LIVERMORE, CA
PERMIT NO. 154

Printed on recycled paper.