Replacing Silicon Dioxide Films With Thicker Alumina Films Deters Tunneling for Improved Reliability

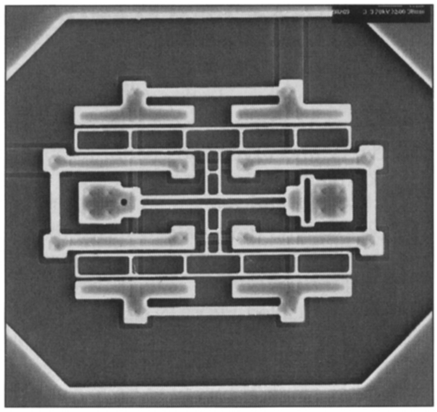
Researchers at the University of Delaware have developed a technique to produce alumina films offering an electrical storage capacity three times greater than silicon dioxide, the material most commonly used in existing transistors. James Kolodzey, professor of electrical engineering, said, "We've created alumina films demonstrating a...dielectric constant of around 12." Since the alumina stores more electrical charge than silicon dioxide, it can be made thicker, which helps deter electron tunneling.

According to the researchers' article published in the July 13 issue of *Journal of Electronic Materials*, the process involves indirectly or reactively sputtering aluminum onto a positively charged silicon substrate in the presence of nitrogen and argon gases, then exposing the material to air and heat. Graduate student Thomas N. Adam said that the silicon substrate is secured on a mounting device inside a vacuum chamber, along with argon and nitrogen gas and an aluminum target. When subjected to high-voltage electricity, he said, ions from the argon begin to bombard the negatively charged aluminum target. As ions pummel the target, aluminum atoms are dislodged, react with nitrogen, and then are drawn onto the silicon substrate. Then the aluminum nitride is oxidized, with nitrogen replaced by oxygen, creating alumina.

Kolodzey predicts that because alumina films store more electrical energy, they could be made thicker than silicon dioxide layers currently used in transistors.

MEMS Applied to a Timing Device May Replace Quartz Crystals

Researchers from Sandia National Laboratory and the University of California—Berkeley have built a microelectromechanical systems (MEMS) prototype that functions as a clock source, which they announced in June at the Solid State Sensor and Actuator Workshop in Hilton Head, South Carolina. Micromachines are made from polysilicon, the same material used in manufacturing integrated circuits. Because of this, the micromachines and integrated circuits can be constructed on one chip. According to the researcher, hundreds to thousands can be built on a single silicon wafer, whereas under current production methods, quartz crystal timing devices



A tuning fork-shaped microelectromechanical systems (MEMS) prototype, like the one shown here, may one day replace quartz crystals used in electronic timing devices.

and integrated circuits are manufactured separately and then assembled.

The micromachines are embedded in a shallow trench on a silicon wafer. These wafers are then used as the starting material for the conventional complementary metal oxide semiconductor (CMOS) manufacturing process of integrated circuits. The integrated circuits are built on the surface of the wafer, while the MEMS are sealed in the trench.

The MEMS timing device prototype consists of two tines, each 2 μm wide by 60 μm long and 2 μm thick, that are anchored in parallel to actuator frames. Voltage between 6.5 V and 7.5 V, set up in a continuous feedback loop (the oscillating effect), is applied through the actuator frames, causing the tines to rapidly vibrate, generating frequencies of about 1 MHz. Although this is a relatively low frequency for a system clock, the prototype oscillator is the first integrated oscillator that operates above the audio range. Despite the high frequencies, these micromachines produce very low noise, -88 dBc/Hz at a distance of 500 Hz from the carrier, primarily because of the integration of the mechanical structure with electronics and the design of the electronic circuit. The noise floor shows a 20-dBc/Hz improvement over previous MEMS tuning fork oscillators.

The frequencies provide the constant timing signals necessary for the digital electronics device to operate. Because of the low noise, the signals are constant and not disrupted, ensuring accuracy.

Jim Smith, manager of Sandia's Intelligent Micromachine Department, said that having the clock source on the same chip as other electronic circuitry is one of the building blocks toward developing complete MEMS in a single monolithic piece of silicon.

Ballistic Conductance Achieved in Carbon Nanotubes at Room Temperature

A team of scientists from the Georgia Institute of Technology reports in the June 12 issue of *Science* the observance of ballistic conductance at room temperature in arc-produced multiwalled carbon nanotubes (MWNTs) up to 5 μm long. The researchers attached an electrode to a bundle of nanotubes that had a single long tube protruding from one end. They mounted the bundle in place of the probe normally used in a scanning probe microscope and connected a battery to the electrode. They then used the microscope controls to raise and lower the single protruding nanotube into and out of a pool of mercury that served to complete the circuit back to the battery. The resistance they measured as the nanotube was raised and lowered into the mercury remained constant, changing only when a shorter tube protruding from the bundle made contact with the liquid metal.

The researchers measured the resistance of 20 nanotubes of different lengths and diameters through as many as 1,000 cycles that consisted of dipping them in and out of mercury and two other molten metals—gallium and Cerrolow-117, which is an alloy of Bi(44.7%), Pb(22.6%), Sn(8.3%), Cd(5.3%), and In(19.1%) with a melting point of 117°F—at a peak-to-peak amplitude of 0.1–7 μm, frequency of 0.1–10 Hz, and applied voltage of about 10–50 mV. The tubes averaged 15 nm wide and 4 μm long, but ranged 1–5 μm in length, with diameters from 1.4 nm to 50 nm. The quantum of resistance remained 12.9 kΩ.

"In classical physics, the resistance of a metal bar is proportional to its length," said Z.L. Wang, a professor in Georgia Tech's School of Materials Science and Engineering. The researchers, however, found that the electrical resistance of the MWNTs remained constant (attaining current densities $J > 10^7$ cm^{-2} amps) regardless of their length or width. This quantum conductance is not seen in larger structures. According to Walter de Heer, a professor in Georgia Tech's School of Physics, the electrons act more like waves than particles in structures whose size approaches that of the wavelength of electrons.

The researchers found that the nanotubes were not damaged at voltages as high as 6 V, which means that power dissipated is 3 mW. The researchers reported, "If we assume that this power is dissipated uniformly along the length of the nanotube and assume a bulk thermal conductivity of 10 W cm^{-1} K^{-1}, then the middle of a nanotube 1 μm long and 20 nm in diameter would attain a temperature T_{max} = 20,000 K." Because the nanotubes combustion temperature is 700°C, the researchers said that the heat dissipated elsewhere—presumably in the leads to the ballistic element and not in the element itself, indicating that the electronic transport in the nanotubes *is* ballistic. The absence of heating allows extremely large current densities to flow through the nanotubes.

Electron scattering may defeat the ballistic conductance effect at lengths of more than 5 μm, according to de Heer.

Imprinted PEG Star Polymer Gels Recognize Molecules

Kelley Keys, a chemical engineering graduate student at Purdue University, has developed star polymer gels from polyethylene glycol, or PEG, a nontoxic, noncarcinogenic substance used in many biomedical applications. A few of the up to 70-some arms on each star molecule are used to bind them together to form the gel, leaving the majority of the arms free to react. The average diameter of an individual PEG star molecule is less than 50 nm. Keys used gamma radiation to coax the star polymers into forming a gel. According to Nicholas Peppas, Keys's faculty advisor and the Showalter Distinguished Professor of Biomedical Engineering at Purdue, Keys's method gives the gels mechanical stability while maintaining a large number of active groups on the arms. According to her presentation on June 24 at the Controlled Release Society meeting in Las Vegas, some of these gels can recognize and remember specific substances through molecular imprinting, a technique developed by other researchers over the past five years.

According to Keys's report, the PEG star molecules were irradiated using a Co^{60} gamma irradiation chamber at a dose rate of 3330 rad/min for a total dose of 1–10 Mrad. She said the gels were then cut into disks and were swelled in deionized water at 37°C. She also used ultraviolet (uv) polymerization (for 20 min) to prepare PEG star polymer gels containing acrylates. These were dissolved in a solution containing poly(ethylene glycol diacrylate) (PEGDA)—an initiator—and deionized water. According to the researchers, "The equilibrium weight swelling ratio of this gel can be varied by changing the concentrations of the acrylated star PEG and PEGDA."

In her experiments, Keys imprinted a gel with the drug proxyphylline, a bronchodilator used to increase the lungs' ability to take in air. Her results showed that the gel "remembers" the proxyphylline and rebinds to the drug at a very high rate. She also passed several other similar drugs through the imprinted gel, but they did not bind to it. According to Peppas the gel can be imprinted with a variety of substances, but once imprinted, it cannot be modified to recognize a substantially different molecule. Peppas said, "The reactive ends of the star polymer's arms rearrange themselves around the molecule. When we leach out the drug or protein, the polymer remains in that configuration. Later, if we pass the same drug or protein over the gel, the polymer recognizes the molecule and binds to it."

In terms of future use, Peppas said, "One could imprint a gel so that some of the arms recognize specific cancerous cells, while other arms in the same gel carry an anticancer drug. These gels also could be used as a surface coating, such as on an artificial organ, to provide additional binding sites for cells or antibodies."

NICE^3 Provides $4 Million in Awards to Help Promote New Energy Efficient and Environmentally Friendly Technologies in Government–Industry Partnership

To help further develop and promote energy-efficient and clean processes and technologies, the U.S. Department of Energy has awarded nearly $4 million to 10 U.S. manufacturing companies. The awards are part of the National Industrial Competitiveness through Energy, Environment, and Economics (NICE^3) program, a strategic partnership among state energy, economic development, and environmental departments; industry; and the Energy Department.

The 10 NICE^3 recipients for 1998 receive about $388,000 each. Award recipients will contribute $13.8 million to project costs. Awards have been granted to the following projects.

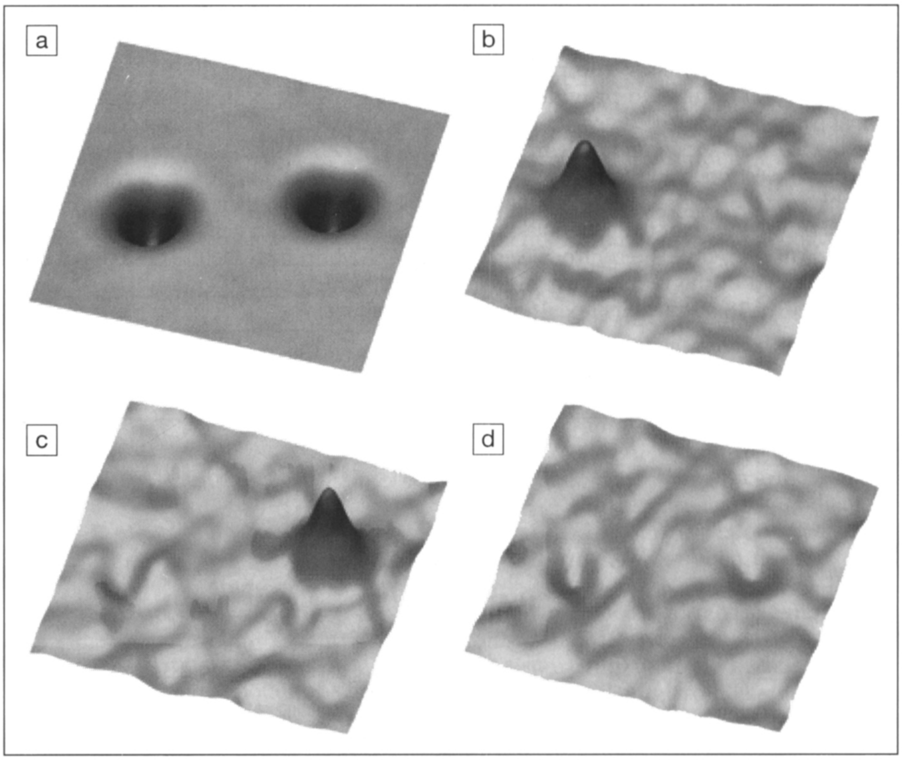
- Pollution Prevention and Energy Conservation through No-VOC (Volatile Organic Compounds—contains carbon, hydrogen, and oxygen) Coating Technologies (CA Energy Commission, AeroVironment Environmental Services Inc., $275,000). This project will demonstrate the commercial viability of the no-VOC coating technologies for metal applications.
- Recovery and Reuse of Solvent Vapors Produced as a Manufacturing Process Byproduct (CA Energy Commission, Alzeta Corp., $421,300). Currently, a specialty solvent exists that has the global warming potential that is 500 times greater than CO_2. Alzeta will demonstrate a system to recover and reuse this solvent.
- Predictive Diagnostic System for DC Motor Drives (ME Dept. of Economic and Community Development, Environmental Air Co., $425,000). The ENVAIR 1000, which is a module and computer system, will be demonstrated at a Maine paper mill to improve the operable efficiency of paper machines by implementing a predictive diagnostic system on DC motor drives and other critical system processes.
- Absorption-Augmented Engine Drive Refrigeration (MD Energy Administration, Energy Concepts Co., $425,000). The proposed system integrates a combustion engine, a compressor, and a waste heat-powered absorption system that will provide 40% more refrigeration with no additional fuel.
- Rapid Heat Treatment and Cast Aluminum Components with Automated In-Line Continuous Processing Fluidized Bed Systems (MN Office of Environmental Assistance, Technomics Inc., $414,710). This project will demonstrate a full-scale in-line heat treating and quenching system using fluidized bed technology which will greatly reduce casting time and associated energy consumption and waste generation.
- Demonstrating the Microsmooth Process on Aluminum Wheels (NY State Energy Research and Development Authority, Metal Arts Co. Inc., $400,000). An innovative nickel-plating process will be demonstrated with chrome-plated forged aluminum wheels to provide a corrosion-resistant wheel at a much lower cost than currently available while reducing energy consumption and chemical waste generation.
- A Process to Recover and Reuse Sulfur Dioxide in Metal-Casting Operations (OH Dept. of Development, Office of Energy Efficiency, Adsorption Research Inc., $239,000). A new process to recover 99.5% of the sulfur dioxide and 99.8% of the carrier gas used in metal casting operations will eliminate the need for a caustic scrubber as well as its effluent.

▪ Novel Steel Dispensing Container Uses Less Steel (PA Dept. of Environmental Protection, Dispensing Containers Corp., $425,000). A new thin-walled dispensing container using 43% less steel than conventional steel containers will be demonstrated to optimize product designs and manufacturing techniques.

▪ Energy Independent Fuel Production through Thermal Efficiency Improvements and Waste Stream Utilization (Puerto Rico Energy Affairs Administration, W2E, $425,000). Waste cooking oil will be processed to isolate the free fatty acids to be used as fuel to generate heat for the production of biodiesel and other high value byproducts.

▪ Chlorine Reduction Utilizing Stack Emissions Data During Aluminum Fluxing (VA Dept. of Environmental Quality, Reynolds Metals Co., $425,000). This project will demonstrate emission improvements and closed loop control parameters to facilitate metal quality improvement and chlorine reduction.

Proposals for NICE[3] awards for FY 1999 are due **October 20, 1998**, with awards made in February 1999. For more information, contact the Office of Industrial Technologies' NICE[3] Program Manager Lisa Barnett at 202-586-2212.



An example of vibrational microscopy with computer-generated three-dimensional images of an ordinary acetylene molecule (C_2H_2) and an acetylene molecule in which hydrogen has been replaced by deuterium (C_2D_2). (a) An ordinary scanning tunneling microscopic (STM) scan of the surface. Both molecules appear as depressions because the tip moves closer to the surface when the tip scans over them; the depressions appear circular because the molecules are rotating between two possible positions on the copper surface. (b) A scan of the surface with the STM voltage set at 358 mV, with a peak identifying the C_2H_2 molecule. (c) A scan at 266 mV, with a peak identifying the C_2D_2 molecule. (d) A scan at an intermediate voltage of 312 mV, which barely responds to either molecule.

High Precision STM Allows Identification of Single Molecules by Their Vibrational Signatures

A team of physicists at Cornell University has made a measurement of the frequency at which atoms in a bond vibrate against each other in a single molecule of acetylene. The research provides a way to identify single molecules by their vibrational signatures and to study how their bonds change during chemical processes.

As reported in the June 12 issue of *Science*, graduate students Barry Stipe and Mohammad Rezaei and professor of physics Wilson Ho used a scanning tunneling microscope (STM) cooled to 8 K to minimize molecular motion, working with acetylene (C_2H_2) molecules bonded to a copper surface. They held the STM tip at a constant height above a molecule of acetylene, and varied the voltage between 0 and 500 mV. A peak was seen at 358 mV, representing a point at which the energy of the electrons matched that of the vibration of the bond between a carbon atom and a hydrogen atom in the acetylene molecule.

According to the researchers, if a surface is scanned with the STM tip held at a constant current while the voltage is set to detect a particular molecular bond, molecules with that bond will be highlighted on the scan while other molecules will remain invisible. The researchers demonstrated this by comparing the images of an ordinary acetylene molecule with that of a molecule in which both hydrogen atoms are replaced with deuterium. At 358 mV the scan shows only the ordinary acetylene molecule, while at 266 mV it shows only the molecule of deuterated acetylene. The researchers said that by increasing the resolution, the technique they have developed can, in principle, be used to image the positions of each of the chemical bonds within a single molecule.

Previously, researchers have not been able to obtain such a clear result because the change in current at the peak was less than variations caused by unsteadiness of the STM needle, and low temperatures are needed to minimize thermal broadening of the peaks. Stipe, Rezaei, and Ho have built an STM that is capable of holding steady the height of its needle tip to better than 0.01 Å. As described in their report, "A Variable-Temperature Scanning Tunneling Microscope Capable of Single-Molecule Vibrational Spectroscopy" (submitted for publication, in *Review of Scientific Instruments*), the researchers are able to vary the temperature of the entire STM they have built, including the radiation shields. In addition, their design ensures that thermal equilibrium between the STM assembly and the radiation shields can be reached quickly. Rather than attaching a heater to the sample, the researchers have set up a transfer line that allows liquid He to flow to the cold tip, "The cold tip temperature is regulated by adjusting the cryogen flow rate with a needle valve and with the use of a heater wrapped around the cold tip. The heater is regulated with a temperature controller feedback loop.... The OFHC copper outer radiation shield surrounding the STM is cooled by the He exhaust gas from the cold tip. The [OFHC copper] inner radiation shield is equipped with a screw used to clamp the STM assembly against the back wall of the shield for rapid cool down." The researchers have suspended the STM inside the radiation shields with springs "to provide vibrational isolation from the cryostat." To isolate the STM tip socket and balls from the piezotube electrodes, the researchers used sapphire for the ring spacers and tungsten for the balls because of the materials' good thermal conductivity. The control electronics, described in the report, have signals comprised of 18 output bits and 16 input bits. The researchers report that the noise on the tunneling current was typically 25 fA $Hz^{-1/2}$ at 1 nA and 400 Hz and that the drift was 0.05 μV/s at the tip z-piezotube. To control the STM electronics, the researchers designed a software program in C under Microsoft Windows 3.1, which they describe in their report. With this software, the researchers are able to position the STM tip in real time on a specific feature, which enables them to test atomic vibrations.

MEMS Technology Combines Capillary Electrophoresis and NMR Spectroscopy

By using micro-electromechanical systems (MEMS) technology, researchers at the University of Illinois have developed a chip-based analytical system that combines capillary electrophoresis and nuclear magnetic resonance (NMR) spectroscopy.

"Capillary electrophoresis and NMR spectroscopy have competing design goals, but by integrating them with MEMS technology we can maximize the performance of both systems," said David Beebe, a professor of electrical and computer engineering and a researcher at the university's Beckman Institute for Advanced Science and Technology. "By using very small channels and samples, we can do high-performance capillary electrophoresis separations. And by performing those separations multiple times, we can collect a large enough sample to do NMR spectroscopy."

As described at the Solid-State Sensor and Actuator Workshop held in June at Hilton Head, North Carolina, Beebe and his colleagues fabricated and tested two microfluidic-NMR devices. In the first device, designed as a proof of concept, the microfluidic channels were built from layered polyimide. In the second device, the capillaries were etched into glass wafers. In both devices, the single-turn, planar NMR coils were formed from evaporated layers of chromium and copper.

Beebe said, "Although planar coils are less sensitive than solenoidal coils, they are easily integrated into batch-fabricated analytical devices. The use of MEMS fabrication techniques allows precise control over the geometric parameters and materials that are so important to the performance of NMR microcoil detection."

According to the researchers, in order to optimize the weak signal received from small sample volumes, the NMR coil must not disrupt the uniformity of the static magnetic field. By tuning the thickness of the evaporated metal layers, the coil can be made transparent to the magnetic field, preventing any perturbations in the field.

"By shrinking the sample size to the nanoliter range, the volume over which the magnetic field must be uniform is also significantly reduced," Beebe said. "This should allow either a smaller—and less expensive magnet—to be used, or multiple spectrums to be taken in parallel in a conventional magnet, thereby multiplying throughput. With the large initial expenditure for a high-field superconducting magnet and the associated cost of ownership, these benefits are significant with small samples."

Microneedle Array Provides Conduits for Transdermal Drug Delivery

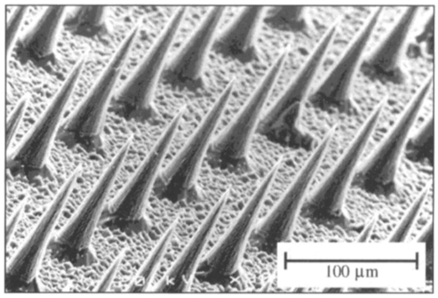
Researchers at the Georgia Institute of Technology have used a reactive ion etching microfabrication technique to create silicon microneedle arrays that pierce the skin to enhance transdermal drug delivery, including macromolecules. The 150-μm-long needles leave holes about 1 μm in diameter when removed from the skin.

The outer layer of skin, 10–15-μm thick, called the stratum corneium, contains no nerve endings. When the microneedles penetrate the outer skin, they provide a pathway for a drug to cross through to the epidermal-derman junction near where capillaries are found to take up the medication. Mark R. Prausnitz, assistant professor in Georgia Tech's School of Chemical Engineering who presented the study on June 22 at the 25th International Symposium on Controlled Release of Bioactive Materials, said, "We'd like to have needles that just penetrate that outer barrier, but not much farther, to avoid hitting nerves and causing pain."

According to the researchers' report published in the August 1998 issue of the *Journal of Pharmaceutical Sciences*, a DC-sputterer was used to deposit ~1,000 Å of chromium onto <100>-oriented, 450–550-μm thick, 10–15 Ω-cm silicon wafers. The researchers patterned the chromium layer into 20 × 20 arrays of 80-μm diameter dots. At room temperature, the researchers etched the wafers by using SF_6 and O_2 at a pressure of 150 mTorr and power of 150 W for approximately 250 min.

Calcein was used in the experiment because it is a difficult compound to deliver. With the microneedles inserted and left embedded in the skin, calcein permeability increased by more than 1,000-fold than without use of the microneedle array. However, when the array was inserted for 10 s and removed, calcein permeability increased by 10,000-fold, and when the array was removed after 1 h, skin permeability increased by 25,000-fold. Skin permeability remained up to 5 h; longer experiments were not performed. According to the researchers, when the microneedles remain embedded, "the microneedles themselves or the silicon plate supporting the array may block access to the microscopic holes created in the skin." The researchers also found that 95% of the microneedles within the array pierced across the skin, and on the very few that broke, only the top 5–10 μm was damaged.

While past research has demonstrated an increase in transdermal transport by 1 or 2 orders of magnitude, the microneedle array increases transdermal transport by more than 4 orders of magnitude.



Scanning electron micrograph of a section of 20 × 20 array of microneedles made by the reactive ion etching technique. The microneedles are uniform in size and have sharp tips.

Prausnitz said that potential problems could arise if high levels of drug under the skin cause local inflammation, or if the body reacts to the needle material itself. Whether the minute amount of silicon left behind may cause problems, or whether needle breakage could be eliminated with the use of other materials or improved needle design, must also be studied.

NPL Publishes Development of Measurement Methods for Degradation of Piezoelectric and Magnetostrictive Materials

The National Physical Laboratory (NPL) in the United Kingdom has published a technical report evaluating the degradation and fatigue properties of piezoelectric and magnetostrictive materials designed for continuous operation within demanding environments. These materials are being developed as sensors and actuators for use under conditions of high electrical and mechanical stress, and high stress rate. Research programs, supported by the UK's Department of Trade and Industry and the European Commission, are developing techniques for quantifying the degradation of these materials under typical service conditions.

A variety of techniques including acoustic, thermal, and optical imaging are being used to monitor degradation. The combination of adopting various complimentary methods allows better materials and products to be developed than are currently available.

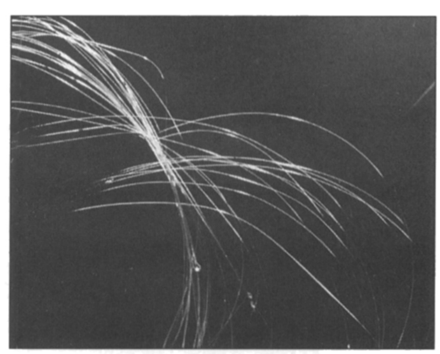
A copy of the report may be obtained from Markys Cain, National Physical Laboratory, Queens Road, Teddington TW11 0LW, United Kingdom; phone 0181-943-6599; fax 0181-943-2989; or e-mail markys.cain@npl.co.uk.

Glass Fibers Synthesized by Containerless Process

Researchers from Containerless Research, Inc. in Evanston, IL, have applied a containerless liquid-phase process to molten yttrium aluminum garnet (YAG: $Y_3Al_5O_{12}$) in order to cool the material enough to draw fibers. They have found that fiber pulling is especially successful when the melt is doped with Er_2O_3 in the presence of excess Al_2O_3. As reported in the June 25 issue of *Nature*, the samples of ~3 mm in diameter, levitated in a flow of argon gas, were heated and melted with a continuous-wave CO_2 laser heating beam. After the samples melted, Richard Weber and his colleagues stopped applying the laser beam, and cooling occurred at a rate of ~250 K s^{-1}. They used a 100-μm-diameter tungsten wire "stinger" to pull fibers from the melted sample when the melt temperature was in the range of 1600–1660 K. Fibers could not be formed at temperatures outside of that range.

According to their article, the researchers pulled glass fibers up to 0.5 m long at rates of 1–1.5 m s^{-1} before the melt crystallized. The researchers said that the "melt temperature decreased by ~75 K between fiber stinging and crystallization of the melt." They found that higher viscosities, achieved through the method of containerless undercooling, are required for fiber pulling and that they were able to pull long glass fibers from YAG compositions with an excess of 1 mol% Al_2O_3 or 1 mol Nd_2O_3 substituted for Y_2O_3.

The basic research on molten oxides was supported by NASA. Commercially oriented research to develop fiber products is being supported by the Air Force Office of Scientific Research and the National Science Foundation STTR and SBIR programs.



Photograph of glass fibers pulled from undercooled molten YAG-composition materials. The fibers were pulled from levitated drops at 1600–1660 K, ~600 K below the melting point of crystalline YAG. The fibers are ~20 μm in diameter.

Molecular Dynamics Simulations Demonstrate that Oscillating the Width of Lubricant-Filled Gap Reduces Friction Between Sliding Surfaces

Researchers at the Georgia Institute of Technology report in the June 25 *Journal of Physical Chemistry* that by rapidly oscillating the width of the lubricant-filled gap separating two sliding surfaces, they can significantly reduce friction between them. The technique keeps the lubricant in a state of dynamic disorder, preventing the formation of molecular layering that can increase friction.

Uzi Landman, director of Georgia Tech's Center for Computational Materials Science (GTCMS), said, "Through the use of small amplitude oscillations of the gap between two solid surfaces, the [molecular] ordering process of the lubricant is frustrated, which maintains the lubricant in a liquid state. This allows steady motion of the surfaces with a small coefficient of friction." Studies by Landman and colleagues Jianping Gao and W.D. Luedtke suggest that varying the gap by as little as 5% can maintain the necessary level of disorder.

The research builds on earlier studies showing that thin-film lubricant molecules confined between two solid surfaces organize themselves into well-ordered layers. In a confined film of approximately 20 Å, a lubricant such as hexadecane forms 4–5 layers in which the long-chained molecules lie parallel to the sliding plane.

The molecular organization creates what Landman calls a "semisolid." Such a structure resists the shearing forces necessary to slide the two surfaces it separates, increasing the force necessary to make them move.

In their molecular dynamics simulations, the researchers studied a classic friction problem: a block pulled across a lubricated surface by a spring. The block remains stationary until the pulling force of the spring overcomes the friction between the block and the lubricated surface. The block then slides for a while, reducing the tension in the spring. The block then slows and comes to rest until the pulling of the spring again overcomes the friction force. This phenomenon is known as "stick-slip."

As the velocity of the sliding block increases, however, the block no longer stops altogether, although its velocity varies in response to the changing relationship between the frictional and pulling forces. At very high speeds, however, the velocity of the block is sufficient to overcome all the frictional forces. This third phase is known as "superkinetic" sliding.

Using their simulations, the researchers applied small oscillations to the gap between the block and the surface. These oscillations allowed them to eliminate the stick-slip phenomena and attain superkinetic sliding at velocities much lower than would be possible otherwise.

"If we oscillate the gap distance by one Angstrom—one out of 20 is a relatively low amplitude—the sliding is free of the stick-slip phenomena," Landman said. "The friction is controlled by frustrating the lubricant's effort to organize itself, maintaining a high level of fluidity."

Certain aspects of these theoretical predictions have been confirmed in laboratory experiments conducted by Jacob Israelachvili's group at the University of California—Santa Barbara, and reported in the same issue of the *Journal of Physical Chemistry*.

According to Landman, creating small variations in the distance between the sliding surfaces upsets the ability of the lubricant molecules to fit "comfortably" between the surfaces. Decreasing the gap forces some molecules out, while increasing it allows more molecules in. This constant rearranging of molecules prevents formation of the ordered layers in the lubricant film.

Landman said that if the researchers move 1 or 2 Å away from such an ordered state, they decrease the degree of order. If they then reduce the distance again, the system returns to a state of order.

The frequency at which the gap width alterations are made is determined by the viscosity of the lubricant. Thicker liquids require more time to move from the gap when the distance is reduced, and more time to return when the gap is increased. Thus, maintaining disorder in more viscous lubricants would require less frequent oscillations than in thinner lubricants. Landman said that controlling and reducing friction by inducing small amplitude oscillations in devices such as magnetic disk drives and miniaturized machines may be feasible. □