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Ceramics: Beyond the Coffee Mug

Photo courtesy of DTE Energy

These materials also carry electricity, relay phone conversations, and monitor auto exhaust fumes.

When most people think of ceramics, porcelain figurines and stoneware coffee mugs come to mind. Not many people immediately associate ceramics with watch batteries, cell phones, or chemical weapons detectors, but ceramics are necessary components of all these things. Ceramics can be insulators, electrolytes, or superconductors. You can find them in devices that mimic eyes, noses, and muscles. Ceramics carry electricity, filter out static in cell phone conversations, and warn you when the air isn't as clean as it should be. A complete rundown on all the places you find ceramics today would make this magazine as heavy as a brick (technically speaking, another type of ceramic), but here are a few of the unexpected places where ceramics are getting the job done.

From Telegraphs to Telecom

Traditional ceramics are good thermal and electrical insulators. Porcelain was used for telegraph insulators as early as the 1850s; its ability to withstand the high voltages carried by electrical power lines brought it into prominence in the 1880s. Insulators still make up a large segment of the ceramics market, but today's high-performance electrical insulators are often made from high-purity alumina, which maintains its insulating properties at temperatures and voltages that would break down porcelain. Alumina tubes are also highly impermeable to gases, a must for electrical feed-through lines in instruments, such as mass spectrometers, that require high-vacuum systems.

What is Ceramic?

Finding a good basic definition of the word “ceramic” isn´t as easy as it used to be. Go back 25 years or so, and you´re talking about “objects made from fired clay” (*2*). This definition takes in bricks, cement, terra-cotta, stoneware, porcelain, and similar materials, mostly oxides derived from mineral sources. Synthetic rocks, in other words.

A more recent definition is both more specific and more far-reaching: Ceramics are “crystalline compounds of metallic and nonmetallic elements” (*3*). This source goes on to characterize ceramics by their almost total lack of ductility; high brittleness, rigidity, and hardness; high melting points (1900–3900 °C); high strength under compression; and resistance to chemical attack. The conventional oxides still fit this definition, but so do many borides, fluorides, and nitrides.

Some definitions go still further: “In fact, a material such as silicon carbide, in which both the silicon and carbon atoms have some metallic properties, is still considered a ceramic, although here there is some overlap with the definition of a semiconductor” (*4*). The implication is that “ceramics are as ceramics do”.

Computers and other microelectronics applications place special demands on insulating materials (also called dielectrics): They must be small, durable, and inexpensive. Ceramics are losing ground to organic polymers in the on-chip insulator market, but they maintain a strong position as the microwave resonators in wireless communication devices. Large-scale dielectric ceramic resonators and filters are needed for base station applications, and smaller versions are used in handheld wireless devices such as cell phones and PDAs (*1*). Low-temperature co-fired ceramics such as lithium niobium titanates are used for telecommunications applications because they are economical to produce and can be integrated into multilayer structures and fired with the metal electrodes already in place.

The semiconductor industry’s need for ever-smaller devices is creating demand for materials with higher dielectric constants (greater insulating capabilities) than the currently used SiO_2 (*1*). New ultrathin films made from zirconia and zirconium silicate are under development for this purpose. These films can be spin-coated onto a substrate at a thickness of <5nm. Recent development has focused on optimizing crystallization behavior and homogeneity of these materials.

Superconductors Resurface Underground

For thousands of years, ceramics were insulators, and that was that. Ceramic mugs kept your coffee hot and the mug handle cool. In 1986, that idea was turned on its head with the discovery of ceramic oxide superconductors. Typically, these crystalline materials contain bismuth, alkaline earth elements, copper, and oxygen—a recipe that fits even the most rigid definition of "ceramic". Lead is often used as well, and rare earth elements are beginning to be incorporated more frequently. These compounds have all the brittleness and high compressive strength of ceramics, but put them in liquid nitrogen, and they conduct electrical current with no resistance—far better than pure copper wire. (The first known superconductors were metals and alloys, but they required much lower temperatures to become superconducting.) After the initial media splash, oxide superconductor work assumed a lower profile as research groups around the world got busy developing their materials and building prototype devices.

Winnie Wong-Ng and Larry Cook of the National Institute of Standards and Technology's (NIST) ceramic division are confident that oxide superconductors will be in the headlines again in the next four to five years, as the prototypes are scaled up for commercial production. Rows of sample bottles containing black and gray powders line one benchtop in their laboratory at NIST's facilities in Gaithersburg, MD. The formulas on the labels look like the lanthanide row of the periodic table, each composition displaying a different combination of material properties. "We don't get into the applications much. . . . Our job is to improve the material properties," says Wong-Ng, who is developing a series of phase diagrams with Cook. "The phase diagram is like a road map that shows you the best way to get from point A to point B," she continues, referring to researchers' efforts to find compositions that have high critical temperatures, are able to carry a high current density, and are practical and economical to produce commercially.

Commercial applications are already emerging. The Edison Project in Detroit, launched in October 1998, is scheduled to go live later this year (5). Facing increasing demand for electrical, telephone, television, and Internet cable conduits and the exorbitant costs of digging up urban streets, Detroit Edison Energy Distribution teamed up with the U.S. Department of Energy, American Superconductor Corp.

(Westborough, MA), Pirelli Cables and Systems North America (Columbia, SC), the Electric Power Research Institute (Palo Alto, CA), and Lotepro Corp. (a subsidiary of Linde AG) to retrofit 400 ft of the existing electrical utility grid with high-temperature superconducting (HTS) cables. Three 4-in-diam HTS cables (each 400 ft long) will carry the same amount of power as the 9 copper cables that they replaced, leaving six open ducts available for other uses (Figure 1). As of January 2002, the cables had been installed, but the project launch was delayed because the vacuum in the cooling system was insufficient to maintain the proper temperature for superconductivity. Engineers are confident that the problem will be solved with existing technology, and the cable system is set to be commissioned in the second quarter of 2002 (*6*).

Figure 1. Oxide superconductor crystallites, aligned to form microscopic "wires", are sheathed in silver ribbons. The ribbons are woven into a cable with a liquid nitrogen conduit running through the center and insulation encasing the outside.

The U.S. Navy is taking bids on superconducting motors, generators, and cables for a destroyer ship it is developing. Although the HTS components are expensive, the volume and weight are far smaller than their conventional counterparts, a must for shipboard applications, where space is at a premium. The telecommunications industry is seeing superconductors on its horizon as well, where low-resistance filters keep signals separate in busy urban areas and fill in the dead zones that annoy cell phone users. Here again, cost is a deterrent, and the razor-thin profits in today's telecommunications industry will have to fatten up before the technology can move ahead.

Working Under Pressure

Remember phonograph record players? Barium titanate was the piezoelectric (pressure-sensitive) ceramic in the needle cartridge that "read" the grooves in the vinyl disks. That same barium titanate has a new lease on life, because it's temperature-sensitive too. Its dielectric constant varies predictably with particle size and temperature, and this property can be fine-tuned by mixing in just the right amounts of alkaline earth titanates or rare earth oxides. This turns out to be important, because many electronic components, such as oscillator circuits, require a temperature-compensating device to ensure that your computer works the same way no matter how you set the room thermostat.

In ferroelectric ceramics, a special subgroup of the piezoelectrics, the electric dipoles align spontaneously when an electric field is applied. Thin ferroelectric films can be used in nonvolatile random access memory (RAM), instrument detectors that do not require cooling, and microelectromechanical systems (MEMS) (*1*, see also, "GC is in the Chips"). One system currently under investigation is lead zirconium titanate (PZT). Applying an AC electric field to PZT thin films causes the crystals in the film to change shape, producing a mechanical response that can be controlled and fine-tuned using various chemical compositions and particle structures.

This mechanical response provides the "muscles" that drive tiny robot legs. Sylvain Martel at Massachusetts Institute of Technology's Bioinstrumentation Laboratory uses piezoelectric nanoceramic legs for his 3-cm tall "nanowalker robots". These tiny tripods "walk" by extending, contracting, and bending their segmented ceramic legs in response to applied electrical voltages. Dave McIlroy of the University of Idaho's physics department (Moscow, ID) is working on another type of ceramic "muscles". His ceramic coils, each a few hundredths of a micrometer wide, could one day propel microscopic mechanisms. Although this application is far from ready for prime time, the springs could also be incorporated into composite materials to make them strong and stiff, yet capable of returning to their original shape after deformation.

Charge It, Please

So far, we have seen ceramics that conduct very little electricity or lots of electricity, or that do their work by changing properties in response to electricity. Other ceramic materials act as filters, batteries, and sensors, allowing anions or cations to diffuse through pores and defects in their crystal lattices. This "solid electrolyte" effect has a variety of uses. For example, the tiny lithium batteries in your wristwatch produce an electrical current when lithium cations migrate from one battery pole to the other through a membrane made from ceramic powder and an organic polymer. Other ceramic ion transport membranes for purifying and storing gases are under development, although the small throughput volumes and high costs limit application to the ultrapure products market (*7*).

Ceramic gas sensors operate on the same diffusion principle, but they only need to filter enough gas to register a response, and they are quite economical to produce. Ceramic oxygen sensors have been in commercial use for at least 25 years. One of their biggest applications is for continuously monitoring the air-to-fuel ratio of exhaust gases from vehicles and aircraft. A ceramic tube, typically zirconia, is placed with one surface in contact with the exhaust gas stream and the other surface in contact with the outside air. Oxygen diffuses through the ceramic, and a voltage is generated at the interface depending on the ratio of residual oxygen in the exhaust gas to oxygen in the ambient air. Platinum electrodes on the ceramic surface send a signal to the fuel injection system and the catalytic converter to maintain the most efficient air-to-fuel ratio.

Thinking Outside the Box

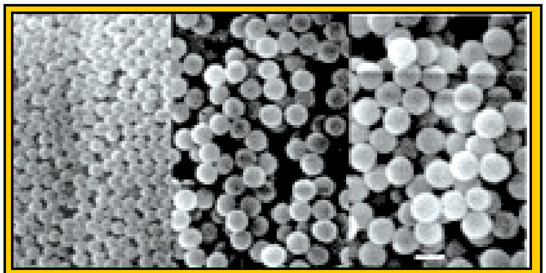

Figure 2. In the disposable "spectrophotometer on a chip", electroluminescent dyes on silica beads like the ones above indicate the presence of an analyte and pass the information to silicon detectors, which relay the information to a data processing unit.

Sometimes ceramics do their best work in a supporting role, acting as a container or scaffold for the compounds doing the work. Ed Pope, founder and owner of Matech Advanced Materials (Westlake Village, CA), is using silica microspheres to carry fluorescent dyes or other chemicals that change colors in the presence of specific chemical or biological agents (Figure 2). Pope is commercializing what he claims is the world's smallest spectrophotometer. "We're trying to eliminate the box," he said, referring to benchtop instruments and their associated computer systems. Matech's BioOptix project has as its goal a variety of postage stamp-sized chips, each containing an array of dye-treated silica microspheres in tiny wells. "It's like the tricorder on *Star Trek*," Pope says, referring to the handheld sci-fi instruments that produced an instant chemical or biological analysis with a wave of the hand. Pope foresees these tiny chips being air-dropped over battlefields or suspected bioweapons factories to scan for hazardous chemicals or biological agents. The chips could provide an instant readout, or they could be outfitted with microcomputers to transmit positive results back to a central data facility. The chips could monitor environmentally sensitive areas for pollutant leaks or inconspicuously monitor the insulin level of a diabetic patient.

Another Matech product actually filters out and destroys hazardous organics. These filter units could be as small as a microwave oven, says Pope. Ambient air or exhaust fumes are drawn through a high surface-area ceramic composite filter. Microwave radiation then heats the filter to incinerate any organic material that is present in the air. This has obvious antiterrorism applications (think nerve gas or anthrax spores), but it would also clean up volatile organic emissions from paint shops, dry cleaning businesses, or fast-food restaurants. Pope is enthusiastic about installing the units in hospitals. "You take greater care in making computer chips than in operating rooms," he says, referring to the stringent clean-room conditions required in chip-making factories. His product generates heat using microwaves, rather than burning petroleum fuels, as gas-fired thermal oxidizers do.

We haven't even touched on ceramic bone replacements, space shuttle tiles, or automobile engine parts, but your nanowalker robot butler wants to know if you want some more coffee. His ceramic photonic sensors have detected that your ceramic mug is empty, and he's making a fresh cup for you now. If his ceramic lab-on-a-chip array indicates that everything meets specifications, then it's time for your coffee break.

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