## Nanostructured PEM Operates at High Temperature

*The Pitch*

Fuel cells have the potential to provide power for a wide variety of applications ranging from electronic devices to transportation vehicles. Because fuel cells operate with hydrogen and air as inputs and electric power and water as the only outputs, they produce power without degrading the environment. Polymer electrolyte membranes (PEMs), with hydrophilic proton-conducting channels embedded in a structurally sound hydrophobic matrix, play a central role in the operation of polymer-electrolyte fuel cells. However, the current state-of-the art PEMs are less than optimally efficient when operating at temperatures above 60°C and relatively low humidity (ca. 50%). To address this drawback, researchers at Lawrence Berkeley National Laboratory (LBNL) have developed nanostructured PEMs with relatively large proton conductivity at a high temperature (90°C) and low humidity (50%).

In 2005, worldwide sales of fuel cell products were about $350 million while research and development expenditures totaled about $800 million. However, given the uncertainty of the scale at which fuel cells will be employed in the future, it is difficult to predict the commercial impact of the LBNL invention.

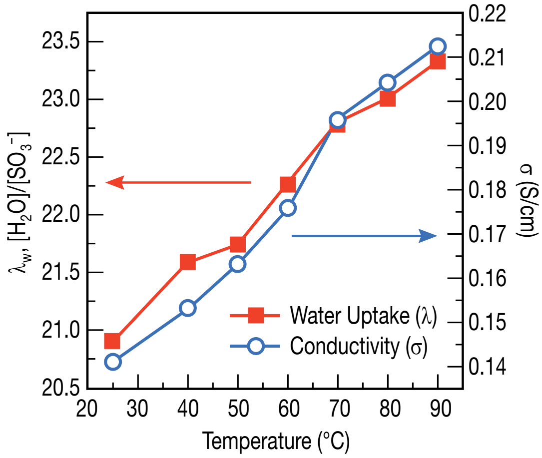


Figure 1. Water uptake and proton conductivity results for a water-retaining polymer electrolyte membrane as a function of temperature at fixed ion contents at RH = 98%. $\lambda_w$ is the number of water molecules per sulfonic acid group; % water uptake = (mass of water in membrane/mass of dry membrane) × 100.

*The Technology*

Current PEMs fall into two categories. The first is based on copolymers in which ion-containing hydrophilic groups are connected randomly to hydrophobic backbones. This category includes linear random fluorinated copolymers of poly (tetrafluoroethylene) and polysulfonyl fluoride vinyl ether, for example, perfluorosulfonic acid ionomer (commercialized under the trademark Nafion®), random linear and graft copolymers of polystyrene and polystyrene sulfonic acid, and sulfonated poly(ether ether ketone). These systems have disordered morphologies in both dry and hydrated states due to the random location of the hydrophilic and hydrophobic moieties. PEMs in the second category are made from block copolymers with hydrophilic and hydrophobic blocks. Examples include sulfonated poly(styrene-*b*-isobutylene-*b*-styrene), sulfonated poly(styrene-*b*-[ethylene-*co*-butylene]-*b*-styrene), and sulfonated poly([vinylidene difluoride-*co*-hexafluoropropylene]-*b*-styrene). In these materials, well-defined hydrophilic and hydrophobic domains are obtained in the dry state due to the balance of energetic and entropic driving forces.

The current state-of-the-art PEM, Nafion, a perfluorosulfonic acid polymer, has adequate proton conductivity (0.1 S/cm) for applications below 80°C. However, at and above 80°C, its conductivity is significantly lower due to the loss of water. While the structure of the hydrophilic channels in Nafion is still not clearly understood, it appears that they are much larger than those present in the LBNL invention.

Most moisture-laden polymer membranes become drier when heated in air at constant relative humidity. However, the polymer developed by the LBNL researchers does the opposite. It sponges up more moisture from its immediate environment as the temperature of the surrounding air rises at constant relative humidity (see Figure 1). With this property, the LBNL polymer exhibits high proton conductivity at elevated temperatures. This is important for the operation of fuel cells because they become more efficient at higher temperatures.

The unusual performance of the LBNL polymer is attributed to its nanoscale construction. It is packed with hydrophilic channels that only measure five or fewer nanometers in width. Transmission electron microscopy was used to image and measure the polymer's hydrophilic channels in the presence of water. At this scale, the channels were reluctant to give up their moisture even as the temperature was increased. For reasons not fully understood, these extremely small channels continue to draw moisture from the air at temperatures as high as 90°C, well above the point at which other polymers stop functioning.

The LBNL researchers have demonstrated that the capacity of a membrane to hold water can be affected by organizing the hydrophilic domains into extremely small channels. This is the smallest channel size known that has been made in any block copolymer system. The channels are approaching length scales in which they are still larger than a water molecule, but not that much larger, and it is believed that this may affect how the channels retain water. This work also demonstrates a new method for controlling the moisture content of nanoscale materials in general, which shows potential applications in the field of nanotechnology.

*Opportunities*

This technology (patent pending) for creating nanostructured water-retaining polymer electrolyte membranes (PEMs) for fuel cell applications is available for licensing and/or collaborative research.

*Source:* For the technology: Nitash Balsara, Materials Sciences, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA. For Licensing: Technology Transfer Dept., Lawrence Berkeley National Laboratory, MS 90-1070, Berkeley, CA 94720, USA; 510-486-6467; e-mail ttd@lbl.gov.

TECHNOLOGY ADVANCES seeks materials developments on the threshold of commercialization. Send suggestions to Renée G. Ford, Renford Communications, renford@comcast.net.





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## Diamond-Based Material Dissipates Power and Heat Problems in Electronic Devices

### *The Pitch*

The compound-semiconductor industry faces major challenges in heat management due to the impact of increasing power levels resulting from increases in device densities. This is coupled with power rf power devices and similar increases in output energy for high-luminance light-emitting diodes (LEDs) and laser diodes, which increase thermal loads on packages that do not have adequate thermal pathways for removing the heat.

For most devices in the compound semiconductor world such as rf power devices, high-brightness LEDs, and vertical-cavity surface-emitting lasers (VCSELs) and conventional laser diode arrays, heat is not generated uniformly on the chip, so some locations are considerably hotter than others. The current solution to this problem is to attach the device directly to a heat spreader so that heat is distributed across the entire area of the chip rather than being localized in specific areas. Unfortunately, this geometry still requires the heat to be extracted through the entire thickness of the chip prior to reaching either a heat spreader or a heat sink. So the potential for localized hot spots remains.

In the approach taken by *sp3* Diamond Technologies, the heat spreader is placed as close to the heat-generating areas as is physically possible. If this heat-spreader layer is constructed of a diamond layer achieved through chemical vapor deposition (CVD) and located within a micrometer or two of the active device, then the heat only has to move a few micrometers before it is spread across the entire area of the chip. The net result is to reduce both the local junction temperature as well as the overall chip temperature since the heat flow path is now the full area of the chip itself. For GaN devices, this is accomplished by growing a GaN device layer on top of a silicon-on-diamond (SOD) substrate where the silicon layer is thin and the diamond layer acts as a heat spreader that is within a few micrometers of the heat-producing area on the device, as shown in Figure 1.

### *The Technology*

A structure of this type can be achieved by fabricating the compound semiconductor device layers such as GaN on SOD wafers so that the diamond heat-spreading layer is only micrometers from the heat-producing areas. The SOD substrate is fabricated using standard CVD diamond growth coupled with wafer bonding and polishing—technology common in the silicon semiconductor world. The resulting substrate is a layered structure consisting of a thin layer of single-crystal silicon on top of a heat-spreading diamond layer with a silicon handle wafer supporting this structure. Once the SOD substrate is fabricated, the GaN device layers can be grown on the silicon layer using standard processes such as molecular beam epitaxy or metal–organic chemical vapor deposition (MOCVD). SOD substrates can be fabricated in sizes as large as 300 mm in diameter and GaN MOCVD systems can be scaled to at least 200 mm diameters. So the resulting structure not only provides optimum thermal properties but also allows process scaling to reduce volume manufacturing costs. Figure 1 shows a comparison of standard GaN and GaN on SOD technology for rf power devices.

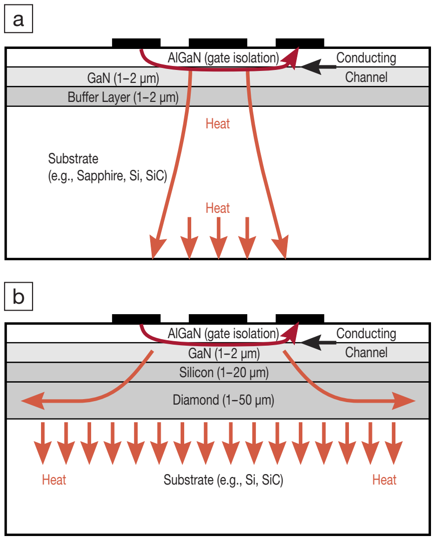


Figure 1. (a) Standard GaN-on-silicon substrate, and (b) GaN-on-silicon-on-diamond (SOD) substrate.

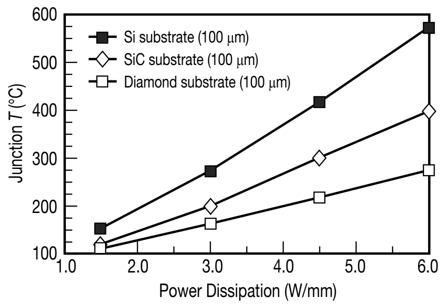


Figure 2. Silicon on diamond (SOD) performance on various substrates. *T* is temperature. *(Courtesy of Triquint Corp.)*

SOD wafers, as diagrammed in Figure 1, are equivalent to silicon-on-insulator wafers commonly used in the silicon semiconductor industry, but the insulator in an SOD wafer is diamond rather than silicon dioxide. The top layer of silicon is a micrometer or two thick, and the diamond layer is several micrometers to tens of micrometers thick, depending on the specific application. The underlying substrate is a full-thickness silicon wafer that serves as a handle for processing and can be either thinned or completely removed prior to packaging. Diamond at this thickness has a thermal conductivity that is 2–3 times greater than copper and 10 times greater than silicon. This high-thermal conductivity means that several micrometers of diamond can effectively equalize temperatures across an entire chip at the device junction level.

The limit of this technology is determined by the ability of the solders, thermal interface material layers, package materials, and heat sinks to remove heat from the diamond layer. Under actual measured conditions, power densities as high as 1000 $W/cm^2$ with junction temperatures below 120°C have been shown to be feasible on silicon devices on SOD substrates. This compares to 200 $W/cm^2$ for equivalent thicknesses of silicon substrates.

Comparable results can also be obtained with GaN devices. The high-frequency rf power device market is beginning to use GaN high-electron-mobility transistors where the GaN device layer is grown on either SiC or silicon substrates. Both of these can be replaced with SOD substrates with substantial improvements in device performance and/or reduced junction temperatures. Modeling work (shown in Figure 2) demonstrates that for a constant junction temperature and three different diamond configurations, the power level can be increased by more than 50% compared to GaN on SiC and more than 100% for GaN on silicon.

GaN-on-SOD substrates provide a path for increasing both power dissipation and reliability on a variety of compound semiconductor devices including power rf, power switching, high-luminance LEDs, and VCSEL laser diodes.

### *Opportunities*

*sp3* Diamond Technologies is seeking investment and development partners for its silicon-on-diamond product.

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## Applications of Shape- and Position-Sensing Optical Fibers

### *The Pitch*

A shape and position monitoring device using optical fiber that can measure, in three dimensions and in real-time, the shape of a length of fiber has been developed by Luna Innovations Inc. This technology is being integrated in medical instruments used for minimally invasive surgery, is assisting the navy to detect underwater threats when embedded in acoustic arrays, and could aid in search and rescue missions when attached to remotely operated vehicles crawling through debris. Unlike other position detection technologies, Luna's fiber requires only a single-ended connection to a readout system and no external sensing array, electromagnetic, or rf field is required. Figure 1 illustrates the basic idea of Luna's fiber optic shape-sensing technology. It is minimally intrusive, virtually weightless, and provides real-time feedback of its own dynamic shape and position along its entire length.

Luna's shape-sensing technology is being applied in the medical field for minimally invasive surgery and minimally invasive diagnostics to monitor the position and location of medical instruments (e.g., catheter, scopes) inside the body. Surgical tools that enable these procedures are increasingly becoming smaller and more flexible. One of the growing challenges when surgeons or physicians use these devices is knowing where the tool is inside the body. Whether it is a manually or robotically driven medical instrument, knowing the precise location of the instrument tip, or even the shape and position of the entire instrument, is critical to the success of the medical procedure.

The global market for minimally invasive surgery devices and instruments is expected to reach $18.5 billion by 2011, with an average annual growth rate of 7.5% between 2006 and 2011. Incorporating location and position information into the next-generation of devices will enhance the applications of surgical instruments and improve patient care.

Another area where shape-sensing technology can be integrated is to find the real-time location, shape, or position of undersea assets. This technology is currently being applied to tracking the shape and the position of sensor surveillance arrays used by the military for threat detection. The navy's distributed autonomous deployable system (DADS) is a distributed surveillance system composed of independent nodes spread on the ocean floor. Each node uses multiple sensors connected together on a serial string for sensing and localization of targets. Knowing the location of each sensor in the array by monitoring its shape as it lies on the bottom of the ocean is critical in surveillance operations. Luna's shape-sensing fiber will be embedded into the array cable which will enhance the ability to detect and assess threats with greater accuracy. Additionally, it could substantially reduce the weight and the cost as compared to the current system.

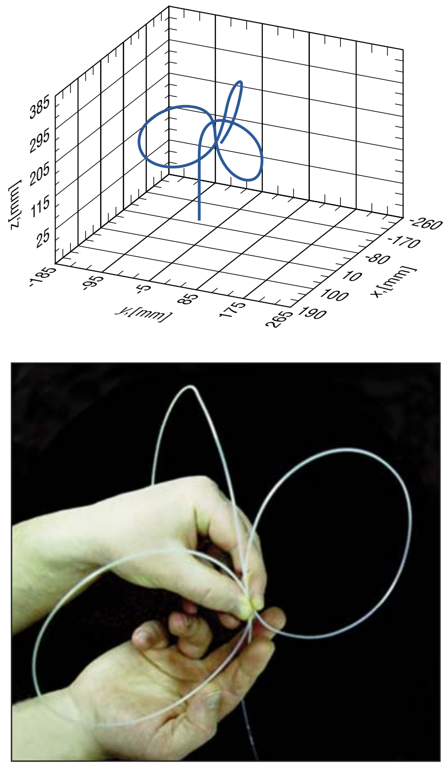


Figure 1. Illustration of a shape-sensing technology that tracks the position of a cable to a high degree of accuracy along its entire length. The shape/position measurement is direct; it does not need to be inferred from other parameters and is completely independent.

Ocean surveillance ships may also have a mission to gather underwater acoustical data—this includes submarine hunting patrols, counter drug missions, and deep-water search and rescue. Ships on hunting duty often use towed sonar arrays which consist of a string of long, flexible modules containing hydrophones that are used to locate underwater noise sources. With benefits similar to the DADS program, shape technology can enhance performance of towed sonar arrays by providing information on the disposition of the flexible cable.

In addition, embedding shape-sensing fiber in the tether of a remotely operated vehicle or unmanned undersea vehicle provides information on the exact location of the vehicles in three-dimensional space with respect to a surface ship. This can be invaluable for search and rescue missions, inspection of oil and gas platform wellheads, or locating divers as it can bring these vehicles back to the same location repeatedly and more rapidly than is currently possible.

### *The Technology*

The origins of Luna's shape-sensing optical fiber technology started in 1996 at the National Aeronautics and Space Administration (NASA) Langley Research Center. Using a technique called optical frequency-domain reflectometry (OFDR), NASA researchers were able to use tens of thousands of fiber Bragg grating (FBG) sensors on a single optical fiber, spaced 1 cm apart, to make very high spatial resolution strain measurements. The OFDR technique makes practical the collection of data from a dense array of spatially distributed sensors that is not feasible with other techniques currently available.

For shape measurements, the optical fiber consists of high-density linear arrays of FBG strain sensors in multiple fiber cores aligned in the axial dimension and packaged as a monolithic structure in a particular geometry. Advanced algorithms use the strain differential as seen by the fiber optic sensors to calculate the bends at every discrete element along the length. Because of the sensor density, each individual sensing element can be integrated to reconstruct the total shape of the fiber. When embedded or surface mounted, the sensing fiber monitors dynamic three-dimensional shapes independent of the temperature or load environment.

### *Opportunities*

Luna Innovations is currently pursuing opportunities for integration of its shape-sensing technology into medical, military, or other devices.

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