Lewis Acid Stabilizes Surface of Light-Emitting Porous Silicon

Jillian Buriak, assistant professor in chemistry at Purdue University, has developed a way to stabilize the surface of porous silicon, a light-emitting material. According to an article published in the February 17 issue of the *Journal of the American Chemical Society*, Buriak coats the porous surface of the silicon with a Lewis acid, a solution that brings about a reaction that produces a hydrophilic coating that protects the surface while allowing the porous silicon to maintain its photoluminescent properties.

To test how well the treatment stands up to environmental stresses, Buriak boiled samples of treated and untreated porous silicon in a highly basic solution of potassium hydroxide for an hour.

"Silicon and silica compounds generally dissolve in a solution with a pH greater than 7," she said. "By boiling it, we are accelerating the aging process to test how well this stabilizing method will stand up to rigorous conditions over a period of time."

The treated surfaces showed no oxidation and only minor changes in photoluminescent properties, while the surfaces of the untreated samples dissolved.

"This indicates that, once it is treated, the surface will remain stable for long periods of time," she said.

The new treatment will also allow scientists to add other compounds to the surface, so that the light-emitting properties of porous silicon can be manipulated to respond to certain chemicals or conditions.

Buriak said, "When uv light strikes the surface of porous silicon, it reradiates back in the red wavelength, producing a bright orange color. But if we add, for example, a chemical that binds to sodium ions, when sodium is present it will cause the reradiated wavelength to shift, producing a different color such as yellow or red. So you could look at the color difference and see whether sodium is present, and at what concentration it's present."

Ultrathin Film Si-Based Circuits Fabricated on Polyimide Substrate

A process demonstrated by researchers from Iowa State University's Microelectronics Research Center and Mankato State University in which crystalline and noncrystalline thin-film silicon-based circuits are deposited on polyimide has created working integrated circuits less than 5-μm thick. Currently, devices of similar dimension (lengths of 2–6 μm) are on substrates 400 μm in depth.

According to a paper published in *Electrochemical Society Proceedings Volume 94-35*, the research team began the process by using a spin-on technique to coat a rigid 100-mm oxidized *n*-type <100> silicon wafer with 6-μm-thick polyimide. The film is then cured in several stages at temperatures up to 350°C. This approach produces the surface needed for photolithography while easing the removal of the film and circuit.

After application of polyimide to the wafer, the surface of the polyimide is treated to promote adhesion of the electronics. A thin oxide layer is then deposited onto the treated polyimide. This layer acts to electrically isolate the electronics from the polyimide.

The electronics are deposited in a 7-step (mask) process. Deposition and etching of subsequent dielectric, metal, and silicon films are completed at low temperature and power settings to minimize damage to the still exposed polyimide. Multiple layer circuits can be created as successive layers of polyimide with devices added, making complex two- and three-dimensional integrated circuits possible. Interconnection can be made through vias.

Magnetically Actuated Microrelay on Circuit Board Offers Low Actuation Voltages, Large Current Switching

Magnetically actuated microrelays, developed by researchers at the Georgia Institute of Technology, can be integrated onto circuit boards because their fabrication techniques are compatible with standard microelectronic processing. The design allows similar configurations to be used for both normally on and normally off relays as well as for multipole relays.

William P. Taylor, who developed the devices at Georgia Tech's School of Electrical and Computer Engineering, said, "The significant issue in using a magnetically actuated relay is that you can achieve larger forces and a greater air gap between contacts when compared to electrostatic relays. The larger gap holds off a higher voltage, which allows you to switch higher voltage signals than would be permitted with other types of microrelays."

Fabrication begins with a silicon wafer that has been oxidized. The researchers then deposit a seed layer and electroplate a lower magnetic core, adding an insulating polymer mold above that. Then a coil is electrodeposited and coated with an insulator. The remainder of the fabrication is completed by alternating steps of polymer mold deposition and electroplating.

"By doing it in this way, many devices can be built on the same wafer at the same time, so there is no need for hybrid assembly," Taylor said.

The microrelay fabrication is based on standard polyimide mold electroplating techniques and consists of an integrated planar meander coil and one or more pairs of relay contacts positioned above the coil. A movable magnetic plate, made of a magnetic nickel-iron material, is surface micromachined above the contacts. When current is applied to the coil, the magnetic flux generated pulls the nickel-iron plate down until it touches the contacts, closing the circuit.

The relay designed to operate in a normally closed position works in the opposite way, using a permanent magnet to hold the actuating plate down and the contacts closed. When current is sent through the relay's coil, the plate moves up off of the contacts, opening the circuit.

The permanent magnet for this type of relay is not currently made through micromachining techniques and therefore must be added during the fabrication process.

The magnetically actuated microrelays operate at five volts, which would allow them to be driven by digital logic circuits and used as part of equipment for which higher voltages could be undesirable. They have a contact resistance of less than 100 mΩ and the ability to switch currents of up to 1.2 A. The microrelays range in size from 3 mm × 4 mm up to 7 mm × 8 mm, and are less than 200 μm in height.

Gibala Awarded First Frances H. Van Vlack Chair of MSE at Michigan

Ronald Gibala of the University of Michigan and vice-president of the Materials Research Society has been awarded the first Frances H. Van Vlack chair of Materials Science and Engineering at the university. Focusing his research on internal friction and the mechanical behavior of alloys and other materials, Gibala joined the faculty in 1984 and has received numerous awards for his research and innovative teaching methods. As chair of the MSE department from 1984 to 1994, Gibala also led a series of curriculum revisions and faculty additions that broadened its scope to include not only metallurgical engineering but a balance of all materials areas.

MSE department chair Albert Yee said, "Ron Gibala has been a pioneer in materials science and engineering education. He is a leader in MSE in improving the quality and content of the undergraduate educational experience."

He received his BS degree in metallurgical engineering from Carnegie Mellon University in 1960, and his MS (1962) and PhD (1964) degrees from the University of Illinois.

The new endowed chair is named for Frances Van Vlack, the deceased wife of emeritus professor Lawrence Van Vlack who published the textbook, *Elements of Materials Science and Engineering*.

Nanocrystalline Copper Softened at Small Grain Sizes

Researchers from the Technical University of Denmark have determined that the large fraction of atoms (30–50%) in grain boundaries soften copper. J. Schiotz, F.D. Di Tolla, and K.W. Jacobsen of the Center for Atomic-Scale Materials Physics and the Department of Physics use the computer to simulate the behavior of nanocrystalline copper based on structures that have been observed experimentally. According to their report in the February 5 issue of *Nature*, "Each sample contains 8–64 grains in a 10.6-nm cube of material, resulting in grain sizes from 3.3 to 6.6 nm."

"Deformation" of the sample is accomplished by expanding the simulation cell in one direction and relaxing the size in the two perpendicular directions. During deformation, the researchers calculated stress. While increasing yield stress and hardness typically accompany a decrease in grain size of most materials, known as the Hall-Petch effect, nanocrystalline metals soften with smaller grain sizes, which the researchers recognize as a reverse Hall-Petch effect. The researchers observed that only a few atoms moved with respect to one another causing small sliding events of atomic planes at the grain boundaries during deformation. According to the researchers, "As the grain size is reduced a larger fraction of the atoms belongs to the grain boundaries, and grain-boundary sliding becomes easier. This leads to a softening of the material as the grain size is reduced."

Past explanations of the reverse Hall-Petch effect include increased porosity at small grain sizes, suppression of dislocation pile-ups, dislocation motion through multiple grains, enhanced diffusional creep in the grain boundaries, and sliding in the grain boundaries. The present study shows that the reverse Hall-Petch effect occurs in the absence of porosity and of thermally activated processes. The researchers derived similar results with palladium.

Hydrogen Kinetics on Silicon Surfaces Observed Directly Through STM

Using a scanning tunneling microscope, chemists at the University of North Carolina at Chapel Hill have observed directly how hydrogen atoms unpair, hop back and forth on the surface of silicon, and sometimes exchange partners at high temperatures. As described in the January 23 issue of *Science*, the research involved bombarding tiny samples of silicon with deuterium in a vacuum chamber so that hydrogen atoms covered the silicon surface and filled in almost all

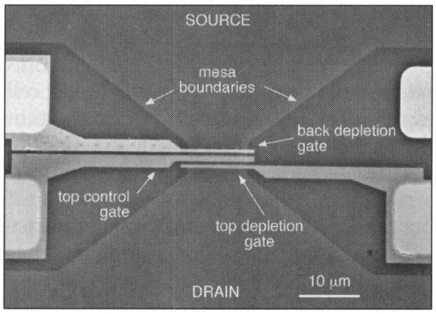
https://doi.org/10.1557/S0883769400030141 Published online by Cambridge University Press

dangling bonds. Chemists then imaged the silicon surface—10 nm × 10 nm or 350 dimers— every 15 s after they heated it to about 613 K. Depending on the temperature, the remaining dangling bonds on the surface, which were initially paired, unpaired and efficiently re-paired multiple times.

In a 10-min series of STM images at 620 K, a dangling bond (DB) diffusion site transformed into a fluxional site that then dissociated into two smaller fluxional sites that moved along the dimer row, later recombining to form a large fluxional feature that then converted back to a paired DB site at a new dimer location. Researchers M. McEllistrem, M. Allgeier, and J.J. Boland determined that "the small, mobile fluxional features are Si dimers that contain a single D atom and an unpaired DB. The large composite fluxional sites then are single D atoms on each of two adjacent dimers." They said that the "fluxional character results from D-atom hopping between sites on the same dimer." Below the temperature of 565 ± 20 K, interdimer hopping was suppressed, and under 500 K, intradimer hopping was also suppressed. Thus at low temperatures, DB movements are limited to the nearest neighbor sites, but become more frequent at higher temperatures.

Planar Quantum Tunneling Device Shows Promise of Ease of Integration and Multifunctionality for High-Speed Integrated Circuits

Researchers at Sandia National Laboratories have developed a novel quantum tunneling transistor based on resonant tunneling with an entirely planar structure. The quantum device, the double electron layer tunneling transistor (DELTT), is based on the gate control of 2D-2D resonant tunneling between the two electron layers in a double quantum well (QW) heterostructure. Quantum devices based on resonant tunneling have long been of great interest because they are the fastest devices known, due to the short characteristic time of the coherent tunneling process. For example, the double-barrier-resonant tunneling diode (DBRTD) has been demonstrated to operate at frequencies up to 712 GHz. In addition to high speed applications, various novel digital circuit applications have been demonstrated which rely on the negative differential resistance characteristics inherent in resonant tunneling. However, all previous such circuits have been constructed using either two-terminal RTD devices, or hybrids formed by combining RTD structures with conven-



Photograph of the DELTT transistor, seen from above. The semiconductor epitaxial layers, which contain the two layers of electrons, are sufficiently thin (0.25 µm) that light can penetrate them, rendering gates on both sides of the device visible. The top and back depletion gates allow independent contact to the two electron layers, while the top control gate turns the transistor on and off. (Source and drain contacts are outside the photo margins.)

tional transistors. This approach suffers from either the lack of isolation between input and output terminals, an increase in circuit complexity, or a reduction in speed from the presence of conventional devices. While the addition of a third gate-controlled terminal to an RTD would be ideal, such geometries have typically required lateral depletion and/or lateral quantum confinement. The resulting stringent lithographic tolerance requirements render these devices extremely difficult to fabricate in the large numbers necessary for real-world applications, a difficulty that is shared by single electron transistors. According to Jerry A. Simmons of Sandia, "The big advance of this device is that it is entirely planar, so that its electrical characteristics do not sensitively depend on its lateral dimensions. This means that large numbers of them can be easily joined together to form integrated circuits. We expect that this will allow us to reap the tremendous benefits of quantum tunneling—extremely high speed, and a great reduction in the number of transistors needed for a given circuit due to the DELTT's multifunctionality."

As reported in the *Technical Digest* of the 1997 IEEE International Electron Devices Meeting, Washington DC, devices were processed from a molecular-beam-epitaxial-grown heterostructure with two modulation-doped 12 nm GaAs QWs separated by a 12.5 nm $Al_{0.3}Ga_{0.7}As$ barrier. The top and bottom QWs had electron densities of 8.0 and 2.0×10^{11} cm^{-2}, respectively. The source (top QW) and drain (bottom QW) contacts are formed by diffusing Au/Ge/ Ni to both QWs, and then using Ti/Au gates to deplete whichever QW one does not wish to contact. Vertically aligned 200×500 μm^2 front and back gates act as the third and fourth terminals, modulating the density of the top and bottom QWs respectively. An innovative flip-chip epoxy-bond-and-stop-etch (EBASE) processing technique developed by the authors allows placement of the backgates less than 2 µm from the bottom QW. According to Simmons, the researchers have recently extended the EBASE technique to make it compatible with electron-beam lithography, and have fabricated working DELTT devices with submicron gate lengths.

The team at Sandia has demonstrated the performance of several digital logic devices based upon DELTT technology. Bistable static memories using a single DELLT and a load resistor have been demonstrated at both 1.5 K and 77 K. Memories composed of two DELTTs in series behave like CMOS, exhibiting complementary performance in a unipolar configuration.

Ink-Jet Printing Directly Deposits Patterned Luminescent-Doped Polymers

While organic polymers are preferred materials for application of light-emitting diodes (LEDs) for color flat-panel displays, the conventional photoresist and wet processing techniques required are somewhat impractical because of the material's solubility in and sensitivity to aqueous solutions. Researchers at Princeton University have developed a way to directly deposit patterned luminescent doped polymers by ink-jet printing.

As reported in the February 2 issue of *Applied Physics Letters*, doped polymer blends were used in which organic LEDs with over 1% external quantum efficiency and brightness of 4,000 cd/m^2 were produced. The researchers dissolved hole-transport polymer polyvinylcarbazol and light-emtting dyes coumarin 6 (C6), coumarin 47 (C47), and nile red into a chloroform solution. The chloroform solution was stirred and passed through 0.45 µm filters, then the ink-jet printed thin films onto a 175-µm-thick flexible polyester coated with indium tin oxide (ITO). This film served as the anode needed to release energy as light.

To create the cathode, the researchers loaded the sample, after ink-jet printing, into a vacuum chamber with a base pressure of $<10^{-7}$ Torr for the metal evaporation step. According to the researchers, "Top metal cathodes were deposited through a shadow mask to form an array of 250-µm-diameter devices on the polymer film. Metal alloys such as Mg:Ag (10:1) were deposited by co-evaporation from two separate sources, followed by the deposition of Ag as a protective layer."

While the researchers have successfully fabricated organic LEDs from ink-jet deposited doped polymers, more work is needed to improve the device efficiency by adding an electronic transport material to the organic material. The researchers concluded that, currently, "efficiency of the ink-jet printed device is about a factor of 2 less efficient than the spin-coated device."

Weaver Named Scientist of the Year by *R&D Magazine*

John H. Weaver, professor of materials science at the University of Minnesota, has been named 1997 Scientist of the Year by *R&D Magazine*. According to the article in the November 1997 issue of the magazine, Weaver's career "exemplifies basic research at its best." His work in materials research has focused on surfaces, interfaces, and thin films, with interests in materials that have ranged from cuprates to fullerenes to semiconductor interfaces and overlayers.

The advent of cuprate superconductor thin films in 1987 led Weaver to recognize "the importance of thin films as contacts and passivating layers." Four years later, in a completely different area, his co-authored article on fullerenes, "Electronic Structure of Solid C_{60}: Experiment and Theory," published in the April 1 issue of *Physical Review Letters*, became one of the most cited papers in science.

Weaver is currently investigating clusters and structures grown by cluster assembly. According to Weaver, his research group developed the "buffer-layer-assisted" growth process some years ago, as described in the March 22, 1991 issue of *Science*, "Cluster Assembly of Interfaces: Nanoscale Engineering." To eliminate direct atom substrate interactions, Weaver created large atom clusters "so that their deposition onto the surface would resemble the contacting of two solids," thus establishing solid-solid rather than atom-solid interactions. Weaver's current papers visualize the growth processes of nanostructures and their interaction with the surfaces to which they are delivered. Weaver said, "The key point is that 'configurations' or hybrid structures can be prepared that cannot be produced any other way. That's important in materials science as we try to make things that Nature 'doesn't like.'"

In yet another area of materials research, Weaver is looking at how halogens remove material from Si(100) or GaAs(110) via etching. He is most interested in how the surface morphology changes at the atomic level, and he uses scanning tunneling microscopy to visualize these changes during surface processing.

Weaver received his PhD degree in solid-state physics from Iowa State University in 1972. He is a Fellow of the American Physical Society, has served on the Board of Directors and the presidency of the American Vacuum Society, and as principal editor of the *Journal of Materials Research* published by the Materials Research Society.

For details, see <www.cems.umn. edu/~weaver/jhw/jhw.html> □

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https://doi.org/10.1557/S0883769400030141 Published online by Cambridge University Press