Boston MicroSystems Extends MEMS Sensor Materials Fabrication Technology

MEMS (microelectromechanical systems) devices are manufactured using micromachining techniques and integrated circuit fabrication processes and materials. MEMS devices, which represent the marriage of microelectronics and micromechanics, are typically fabricated onto a substrate (chip) that can also contain the electronics required to interact with the MEMS device. At present, MEMS devices that are quite widely used in the marketplace include ink jet print heads, read/write disk drive heads, pressure sensors, and accelerometers. Emerging applications for MEMS devices with keen growth potential going forward include RF MEMS; electronic noses; medical diagnosis and assays; drug delivery systems; micro displays; detection of explosives, toxic chemicals, and biological agents; environmental emissions monitoring; process control; as well as optical MEMS components.

Micromachining involves the fabrication of miniature three-dimensional structures, including those with dimensions as small as one hundredth the diameter of a human hair. Instead of using mechanical means for machining (e.g. drills and milling machines), the tiny features are selectively etched into materials by using chemicals or reactive gases. The minute features can be etched into a crystalline wafer via bulk micromachining, or created via surface micromachining (which involves selectively removing parts of layers deposited onto the crystalline wafer). The physical properties of bulk micromachined structures tend to be more reproducible and robust, while surface micromachined structures are typically less costly to produce.

Historically, micromachining technology has been limited in its ability to efficiently create structures from materials that are capable of withstanding harsh environments. Highly robust materials are resistant to being etched by conventional means. Standard micromachining methods also have exhibited limitations in achieving high dimensional control (which can require exceptionally selective etch stops that may not be attainable using standard bulk micromachining methods).

Boston MicroSystems (Woburn, MA, 781-933-5100) (www.bostonmicrosystems.com) is using their patented fabrication techniques and advanced sensor and actuator materials to develop highly sensitive microsensors that integrate III-V nitrides (e.g., single-crystal piezoelectric films) onto a silicon carbide MEMS structure. Such capabilities extend MEMS technology beyond the realm of silicon to include wide band gap and refractory compounds.

Boston MicroSystems, moreover, has been developing patent-pending microhotplate sensing technology that uses silicon carbide and semiconducting oxide films and purportedly offers a novel, efficient transduction mechanism designed to provide long-term stability by addressing the problem of thermal stress. Conventional gas sensors that use conductometric semiconducting metal oxide films are subject to long-term stability problems arising from thermal stresses due to heating and cooling, noted Dr. Richard Mlcak, co-founder and president of Boston MicroSystems.

Boston MicroSystems' sensing devices are being developed for monitoring toxic as well as industrial chemicals, biological agents, explosives, and fluid properties. Their microresonator sensing technology that integrates piezoelectric film and silicon carbide is purportedly smaller, consumes less power, and more sensitive, compared to the typical SAW (surface acoustic wave)-based sensor. Target applications for Boston MicroSystems' microsensor devices (which lend themselves to use in portable detectors) include national security, personnel safety, environmental emissions monitoring, and industrial process control.

During 2002, Boston MicroSystems garnered various SBIR (Small Business Innovation Research) Phase I grants, as well as Naval Research Laboratory contracts (pertaining to silicon carbide AlN microresonators for trace chemical detection). The SBIR grants awarded to Boston MicroSystems last year include those for developing: a silicon carbide microhotplate

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conductometric sensor array for NOx, CO, and hydrocarbons for monitoring hot engine emissions; a rapid reagentless multi-channel biological agent detector; robust MEMS viscosity meters for condition-based maintenance of HVAC refrigeration systems; a fast-response conductometric oxygen sensor for combustion and fire environments; and robust micromechanical silicon carbide environmental sensors based on silicon carbide microhotplate arrays.

Boston MicroSystems uses several approaches for detecting various gases, chemicals and biological species. The role of the sensor film is to selectively adsorb or bind to the species of interest, thereby affecting the electrical and/or micromechanical properties of the sensor for detecting the species' presence. To detect gases, Boston MicroSystems employs a suite of semiconducting metal oxides whose electrical properties are highly sensitive to the gaseous environment. For detecting explosives and toxic chemicals, they utilize chemically selective polymer films designed to adsorb the species of interest. To detect biological species, antibodies that selectively bind to the pathogen's antigens are immobilized on the sensor surface. Boston Microsystems collaborates with university, government and commercial laboratories in the selection and development of highly selective sensor films.

Mlcak explained that Boston MicroSystems' patented photoelectrochemical (PEC) micromachining technologies allow precise and reproducible micromechanical structures to be fabricated in semiconductor materials, such as silicon and single crystal silicon carbide (a hard diamond-like material that is highly resistant to chemical attack and is capable of operating in very high temperature environments). Single crystal silicon carbide (SiC) micromechanical structures are very stable and are not susceptible to chemical attack, and cannot be fabricated using traditional micromachining techniques.

The PEC micromachining process is highly versatile, since there are a variety of ways in which anodic current can be spatially controlled within the semiconductor, using applied biases, electron-hole photo-generation, electron-hole recombination, and p-n junctions. By exploiting the inherent differences in p- and n-semiconductors, in combination with the electrical characteristics of p-n junctions within semiconductor substrates, Boston MicroSystems has developed a number of novel, patented p-n junction etch stops, allowing selective etching of n-type regions or p-type regions with etch stop selectivity as high as 10 million. This etch stop selectivity is purportedly around 10,000 times better than the etch stop selectivity achieved in conventional bulk micromachining. Their patented p-n junction etch stops provide superior dimensional control and enhanced reproducibility in silicon, silicon carbide and other elemental and compound semiconductors. PEC micromachining allows highly sensitive and stable sensors to be fabricated for challenging environments.

Silicon carbide (SiC), a hard diamond-like material, is highly resistant to chemical attack and capable of operating in temperatures exceeding 1000 C. It is a wide band gap semiconductor and, therefore, a key candidate for high power/high temperature electronics. Like diamond, SiC exhibits extremely high thermal conductivity leading to very high thermal uniformity even at elevated temperatures. Boston MicroSystems notes that the unique combination of electronic, mechanical, thermal and chemical properties of silicon carbide render it an ideal MEMS material. The company's proprietary micromachining processes allow fabrication of SiC-based MEMS devices that are capable of operating in harsh environments exceeding the capabilities of silicon-based MEMS devices.

Boston MicroSystems is developing electrical contacts for SiC that are based on the refractory Ti3SiC2 compound. The patent pending electrode, which is in thermodynamic equilibrium with SiC, is suitable for use in high temperature and corrosive environments. Boston MicroSystems expects to have developed such electrical contacts within 12-18 months. The SiC contacts are being developed for harsh environment applications, primarily to extend the capabilities of their microhotplate gas sensor platform for use in hot,

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corrosive environments (e.g., engine emissions, smoke stacks).

Mlcak noted that Boston MicroSystems has developed new MEMS microfabrication technologies for non-traditional materials. For example, they discovered that silicon carbide and the III-V Nitrides (e.g., InN, GaN, and AlN) are very compatible MEMS materials, with nearly identical lattice constants and thermal expansion coefficients. The III-V Nitrides are direct band gap semiconductors, with band gap energy ranging from 1.9 eV to 6.2 eV, spanning the visible and ultraviolet portions of the electromagnetic spectrum. Owing to their wide bandgap and refractory properties, they find applications in varied devices, including emitters, detectors, high power and high frequency devices. Moreover, III-V Nitrides (especially AlN) have excellent piezoelectric properties, rendering them ideal for the fabrication of electromechanical devices.

Boston MicroSystems uses MBE and HVPE processes, in collaboration with professor Theodore Moustakas at Boston University, to grow single crystal III-V nitrides, such as piezoelectric AlN, onto their SiC devices. Mlcak noted that such processes produce single-crystal III-V nitride films with superior and more reproducible electrical, mechanical, and optical properties, compared to, for example, polycrystalline films formed via sputtering or sol-gel techniques. He added that AlN is preferable for piezoelectric device applications; whereas there are advantages to using GaN for optoelectronic devices, or as part of AlGaN quantum well devices (such as those used in Boston MicroSystems' patented giant piezoresistive (GPR) traces, which have greater piezoresistive coefficients than silicon and, as wide bandgap stable materials, can operate in environments requiring capabilities exceeding those of silicon).

Boston MicroSystems is integrating III-V nitrides with SiC MEMS technology to manufacture sensors for such applications as explosives detection, chemical and biological agent detection, fluid systems/process control, and RF (radio frequency) microelectronics.

In the national security arena, opportunities for Boston MicroSystems' microresonator sensors are being driven by intensified concern for the threat of terrorist activities. The events of September 11 have fueled a need for widely distributed, rapid and affordable sensors to detect explosives, toxic chemicals and biological agents. Portal explosives scanners, now being installed in airports, tend to be very expensive, large and slow. They tend to be inadequate in areas where the terrorist threat is diffuse, such as in airport lobbies, government buildings, train or bus terminals or other areas of mass convergence. Moreover, such systems do not protect against toxic chemicals or biological threats. In addition, local and state water resource authorities and the military are becoming increasingly aware of a need for chemical and biological agent detectors to safeguard drinking and source water supplies.

Boston MicroSystems is focusing on developing MEMS-based sensor platforms that "will drive next-generation detection systems," Mlcak stated. The platforms can be targeted to different applications by selecting the appropriate chemically or biologically sensitive film. Their microprocessor-based trace chemical sensor platform is being targeted at homeland security to provide low-cost, convenient, and/or autonomous networked detection systems that can be widely dispersed to protect the population from hazardous agents, such as explosives, chemical warfare agents, and toxic industrial chemicals.

Explaining the microresonator's transduction principle, Mlcak noted that the micro/nano-balance device is essentially a piezoelectrically driven bimorph operating at its resonant frequency. A change in mass, resulting from adsorption of vapors onto chemically-sensitive films on the resonator, or the binding of pathogens to antibodies immobilized on the resonator's surface, shifts the resonant frequency. The magnitude of the mass change can be correlated to the concentration of vapors or biological agents in the sample.

Boston MicroSystems is collaborating with the Naval Research Laboratory to apply the microresonator sensors to specific applications

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related to national security. Prototype SiC-AlN microresonator sensors using NRL-applied explosive-sensitive films have demonstrated their ability to exhibit a reproducible response to explosives of vital concern. In accord with a contract from NRL, Boston MicroSystems is packaging the SiC- AlN microresonator arrays to allow for more extreme testing of these devices.

In the area of biosensors/ biological agent detection, Boston MicroSystems notes there is a key need for portable, low cost, easy to use devices that can rapidly detect and identify pathogenic organisms threatening national security and public health. Applications where such sensing devices can be beneficial include defense against biological weapons of mass destruction, diagnosis of infectious diseases in healthcare and agribusiness, ensuring the safety of food and drinking water supplies, and detection naturally occurring pathogens in the environment. Such rapid, portable devices can potentially reduce the time and cost of analysis, lead to increased monitoring, provide early warnings to minimize the number of exposed personnel, and provide timely information for effective treatment of those infected.

Boston MicroSystems notes that, presently, there are no widely commercially available handheld, rapid biological agent detectors, primarily because most detection systems depend on time-consuming amplification, which adds appreciably to the cost, complexity, power requirements and size of the detection equipment. Therefore, pathogen detection in healthcare, agribusiness, and food and water safety still primarily relies on shipping samples for laboratory analysis, incurring delays before test results are known. Moreover, separate time consuming assays typically need to be performed to identify different types of pathogens in a sample.

The challenge, therefore, exists to develop a rapid, portable, low cost and convenient biological agent detection system, capable of simultaneously detecting and identifying multiple pathogens of interest, which can be broadly deployed to protect public health. To address this need, Boston MicroSystems is developing a rapid reagentless multi-channel biological agent detector based on their proprietary MEMS microresonator sensor platform. The biosensor will be designed to allow commercialization of low cost, portable (handheld) instruments for rapid and simultaneous detection of multiple biological agents, such as anthrax, salmonella, E. coli, cryptosporidium, and rickettsia.

The microresonator used in the biological agent detector and that used for national security applications are essentially the same type of devices, except that the microresonator for biological agent detection is coated with antibodies corresponding to the antigens on the pathogens of interest, while the microresonator for national security is coated with vapor-absorbent films.

The resonators for biological species/agents allow for detection of whole, live pathogens without the need for reagents, lysing, or amplification. When fabricated in arrays with different antibodies immobilized on different resonators in the array, they allow for simultaneous detection of multiple biological agents. Virtually any type of recognition molecule that is capable of binding to pathogens of interest and of being immobilized onto the resonator' surface (e.g., polyclonal antibodies, monoclonal antibodies, recombinant antibodies, DNA aptamers, peptide aptamers) can be used in Boston MicroSystems' microresonators for detecting biological species. Currently, Boston MicroSystems is using polyclonal antibodies for bacillus globigii, a simulant for anthrax spores.

In the area of environmental monitoring, Boston MicroSystems notes that increasingly sophisticated sensing devices are required for monitoring and control of emissions from automobiles and power and chemical plants into the atmosphere and drinking water. Sensors are vital for limiting hydrocarbon, carbon monoxide (CO), and NOx (oxides of nitrogen) emissions from auto exhaust and other combustion systems. However, conventional sensors can be slow in reaching operating status and can have limitations with respect to direct monitoring of CO or NOx emissions. Other limitations exhibited by various types of gas sensors include susceptibility to

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fouling (in, for example, smoke stack environments), large size, high power requirements, and deficiencies in sensitivity and selectivity.

Miniature sensor arrays, fabricated from harsh environment-compatible materials, can provide key benefits in environmental monitoring, such as protection from degradation and fouling, reduced start-up time, and improved sensitivity, selectivity, and stability. Boston MicroSystems' microhotplate-based sensor technology includes pinpoint-sized heaters that can be heated to hundreds of degrees centigrade in thousandths of a second. Each microhotplate is coated with a semiconducting oxide film optimized to detect specific gases. Low-power requirements facilitate portable operation. Boston MicroSystems' gas sensor development benefits from the support of professor Harry L. Tuller of MIT, a Boston MicroSystems co-founder and expert on functional electroceramic films.

By fabricating microhotplates from silicon carbide, Boston MicroSystems is able to produce a simplified tethered structure in which the tethers can provide multiple functions, i.e., mechanical support, ohmic heating, and electrical contact to the conductometric semiconducting metal oxide films. The microhotplate sensors are compatible with semiconducting metal oxides typically used in bulk devices (e.g., tin oxide, tungsten oxide, etc.). Key target applications for the microhotplate sensors include air quality monitoring, auto emissions monitoring, and engine controls.

Boston MicroSystems' flexural plate wave fluid sensors, fabricated from SiC-AlN materials, allow long-term exposure to corrosive, high-temperature, and abrasive fluids. Such miniature fluid sensors can be used to monitor viscosity, density, electrical conductivity, scaling (mineral deposits), and bio-film growth in fluid systems. Suitable applications for such sensors include process control in chemical reactors, condition-based maintenance of vehicles and industrial equipment, quality control, and oil well logging.

Boston MicroSystems' essential business strategy is to forge strategic partnerships with market leaders in their respective fields that can generate market pull for and accelerate the entry of high value-added detection systems based on Boston MicroSystems' sensors. In return for an exclusive license to Boston MicroSystems' devices in their fields of use, the strategic partner provides development funds, performance/packaging specifications, and testing/validation for the sensors developed for their applications. Boston MicroSystems serves as the OEM source for the sensors and/or detection systems, and their strategic partners (typically end-users of their devices) provide enhanced capabilities and greater value to their customers. Boston MicroSystems then identifies derivative products that can be developed for other customers, markets, and applications.

SBD pegs the overall market for pressure, temperature, and chemical/gas sensors used in harsh environments (excluding fuel cells) at over $1.6 billion in 2001 and envisions opportunities for the harsh environment market (excluding fuel cells) for such sensors to reach about $5.3 billion over a ten-year period.

The global market for established and emerging MST (microsystem technology) products totaled about $30.6 billion in 2000 and is projected to rise about 20% annually to reach about $67.3 billion in 2005, according to the NEXUS (Grenoble, France, ++33-438-78-43-47) task force's Market Analysis for Microsystems, 2000-2005 report.

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