Guest Editorial

ADVANCES IN MICROELECTROMECHANICAL SYSTEMS

Microelectromechanical systems (MEMS) are integrated microdevices or systems combining electrical and mechanical components. The mechanical microcomponents either move in response to certain stimuli (sensors) or are initiated to perform certain tasks (actuators). The microelectronic components are used to control that motion or to obtain information from that motion. These systems can sense, control, actuate, and function individually or in arrays to generate effects on the microscale. These are fabricated using integrated circuit (IC) batch processing techniques making it possible to realise the complete system on a chip. The miniaturisation of mechanical components brings the same benefit to mechanical systems that microfabrication brings to electronics. In a broader sense, technologies associated with MEMS include smart materials (e.g. shape memory alloys, ferroelectrics) and processes required to make MEMS components, integration of components to make MEMS devices (sensors, actuators, etc.) and applications that use MEMS devices. The MEMS are considered as building blocks for complex microrobots performing a variety of tasks and are used to make systems which function very close to biological systems existing in nature. Primary drivers behind this revolutionary technology are:

(a) Need to miniaturise existing devices, thereby, reducing cost by decreasing material consumption and allowing batch fabrication. In addition, allowing placing these devices in places where a traditional system won't fit.
(b) Development of new devices based on principles that do not work at larger scale.
(c) Development of new tools to interact with the microworld. An example is development of new class of microscopes. With the help of scanning near-field optical microscope one can see micromachined sharp tips with radii below 50 nm. Another example is scanning tunneling microscope with which one can see a single atom on a surface, leading to research on nanoscale components and devices.
(d) Development of techniques to bring about system integration leading to high performance closed-loop controlled MEMS. Instead of having a series of external components connected by wires or soldered on a printed circuit board, the MEMS on silicon can be integrated directly with the electronics, resulting in increased reliability and decreased assembly cost.

Fabrication of MEMS involves development of smart sensors, which communicate via feedback in closed-loop systems. A smart sensor senses a change in the environment and responds by changing one or more of its property coefficients. It tunes its response function in time and space to optimise behaviour. This requires merging computation with sensing and actuation into integrated micro-level systems that interact with the physical world. Most MEMS processes can be broken down into a repeating series of steps for metal deposition, patterning, realisation of released structures, dicing, packaging, testing that require the most advance manufacturing line. Materials for MEMS include traditional microelectronic materials (e.g., silicon, silicon dioxide, silicon nitride, polyamide, phosphorus and aluminium) as well as non-traditional ones (e.g., ferroelectric ceramics, shape memory alloys, and chemical-sensing materials). The superior piezoelectric and pyroelectric properties of ferroelectric ceramics make these ideal materials for microactuators and microsensors.

Microsystems are designed and fabricated by integrating different microcomponents into one functional unit comprising sensors, actuators, ICs for data processing, etc. In this development a variety of micromachining technologies, ranging from the conventional silicon bulk and surface micromachining to LIGA and laser techniques are employed, each one having specific advantage or merit for a specific product. Another process useful for MEMS application is substrate bonding. Silicon, glass, metal, and polymeric substrate can be bonded together through several processes, i.e., fusion bonding, anodic bonding, eutectic bonding, and adhesive bonding. Substrate bonding helps in achieving a structure that is difficult to form otherwise, e.g., hermetically-sealed large cavities, a complex system of enclosed channels or simply to add mechanical support and protection.

One of the key challenges in micromachining process is combining the electronic devices with the mechanical, optical or chemical function of the MEMS device. Earlier, a hybrid approach was used in which the MEMS device was fabricated independent of the interface electronics, however, presently there are several examples of integrated sensors and other devices being fabricated. Silicon has emerged as the major material used for micromachining and microengineering because of its excellent mechanical properties in addition to well-known electronic properties. Its tensile strength and Young's modulus is comparable to steel, density is less than that of aluminium, and it has low value of thermal coefficient of expansion. The recent rapid rise of silicon-MEMS was due to major advances in silicon microfabrication technology, especially surface micromachining, deep reactive ion etching, and CMOS integrated MEMS.

Past decades have seen enormous research on different aspects of smart materials, structures, and systems. These include-development of new actuator and sensor materials, material processing, device design, fabrication, electronics, packaging, smart structural design for optimum power and performance, development of control algorithms, and finally, applications. The evolution and maturity of these technologies are clearly seen over the years. Recently, microstereolithography has rapidly revolutionised the MEMS industry. Using this technique it is possible to fabricate three-dimensional intricate microstructures and devices from computer-aided design without the need of conventional lithographic process. This involves use of polymeric materials

A wide variety of MEMS devices are now being produced for aerospace and defence applications, e.g., accelerometers, pressure sensors, RF devices, actuators, and microbatteries. Smart actuators based on smart materials, like piezoceramics, shape memory alloys, acive fluids, and magnetostrictive materials are used in the aerospace industry. Vibration control, actuators for deployment of small control surfaces, and permanent couplings are well known applications. Smart sensors are also used in the structural and functional health monitoring of launch vehicles and spacecrafts. These are being developed in realising smart structures where measurement and control of environment over large surface area is required. Real-time flight data on structural loads and environmental data like temperature, vibration, etc cannot only make flight course management safer and more efficient, but also make future designs better.

The MEMS devices also have many under-water applications where acoustic sensors, and conductivity temperature depth (CTD) sensors are required. The MEMS-based products created a US $ 8 billion market in 2005, which is forecasted to grow over US $ 40 billion in 2015 and over US $ 200 billion in 2025. These devices are increasingly being used in a number of fields like automobile, civil and military aviation, biomedical, robotics, and manufacturing control. Accelerometers for automobile industry are being mass-produced for use in air bags during a crash and for active suspension control.

Another important use is in vibration monitoring of rotating machinery. Microscopic pressure sensors embedded in automobile tyres have led to huge savings in oil. Tiny blood pressure sensors are popularly used in many medical applications. Piezoelectric acoustic sensors are designed for both audible and high-frequency sensing and have use in hearing aids. An infrared focal plane array (FPA) of a microbolometer with read-out electronics on monolithic silicon chip is an important application in night-vision devices.

The MEMS technology is able to provide probe tips close to atomic dimensions integrated with sense and drive electronics for the probe of an atomic force microscope. The miniaturisation of a complete microsystem represents one of the greatest challenges to the field of MEMS. One well-known example of a chip-scale microsystem is the ADXL 50 accelerometer manufactured by Analog Devices Inc. This is a closed-loop microsystem where capacitive displacement detection is used to measure the motion of the proof mass, integrated circuit, to determine the voltage necessary to balance initial motion, and electrostatic actuators to control the position of the proof mass. Microfluidic systems constitute the majority of present microsystem efforts due to their broad applicability, particularly as bio-chemical analysis systems. Future defence applications include MEMS-based guidance systems built into projectiles and air-dropped weapons. Smart sensors and MEMS are also expected to play a significant role in space missions in the near future. Increasing demand for miniaturisation to get the system with more functionality, more efficiency/sensitivity, and reduced cost is pushing the present microsystems to nano level.

Nurturing such an innovative technology has unlimited benefits and has to be tapped by initiating adequate measures and providing a big push which is bound to result in advancement of the technology resulting in quality products for various applications. Several organisations in the country including DRDO laboratories are actively pursuing research in this area. Over the last decade, the Institute of Smart Materials and Structures has been the prime promoter of highly application-oriented technology of MEMS and microsystems in the country. Launching of a multi-departmental National Programme on Smart Materials (NPSM) has given a great thrust to the establishment of this technology in India. The achievements in this area are giving momentum to design concepts of practical systems in aerospace, automation control, medicine, defence, and other fields.

In consonance with its focus on publishing, original research papers having direct bearing on defence, it was decided to bring out a special issue of DSJ on ‘Advances in MEMS Technology’. Prospective researchers were invited to submit review articles, research papers, and short communications covering the following broad areas:

- Microelectromechanical systems (MEMS)–State-of-the-art.
- Design, fabrication, packaging, and applications with special reference to defence and aerospace for microsensors (inertial, physical, optical, chemical), microactuators, microfluidics, BioMEMS, RFMEMS, and microelectromechanical system integration.

The MEMS technology is an interdisciplinary field with developments occurring along different directions, therefore, it is not possible to cover every aspect of this amazing field in one volume. In this special issue, 13 papers have been selected that cover various devices being developed using this technology and important issues like design, fabrication aspects, characterisation and integration of mechanical structures with electronics, are discussed. First paper gives a review of the CMOS-MEMS integrated systems including mechanical, chemical, and biochemical sensors fabricated and marketed by different organisations. Papers on important devices used in aerospace and defence, e.g., RF MEMS for communication and radar applications, microbolometers for IR imaging, deformable mirrors for wavefront corrections in adaptive optics, are included. A review of dielectrophoresis devices, which provides an effective way to manipulate and separate micro- or nano-particles, has been included. These devices have applications in the development of lab-on-a chip for use in biological and medical fields. A review paper on novel experimental techniques on measurement of mechanical properties of materials used in MEMS focuses on design as well as reliability of MEMS structures. A brief description of facilities established at DMRL, Hydrabad, is given for the benefit of readers. Another paper describes the novel techniques of microstereolithography and facilities established at NPOL, Cochin, for fabrication of 3-D MEMS structures.

There are four research papers describing work on design aspects of following MEMS devices:

- Circular micromachined ultrasonic transducer widely used in medical imaging,
- Analysis of RF MEMS shunt switch,
- Design and simulation of different geometries of the microcantilever beams with wide ranging applications in sensing of chemical and biological species, and
- Simulation studies of a MEMS-based microballon actuator for aerodynamic control of flight vehicles.

The twelfth paper deals with error modelling and error analysis of MEMS inertial measurement unit for a low-cost strap-down inertial navigation system. A paper on next generation observation system called global environmental MEMS sensors (GEMS) describes the use of this revolutionary technology for understanding and predicting vital environmental phenomena for civil and military communication and measurement.

I am very grateful to all the authors who have contributed papers covering various facets of this upcoming technology. I am indebted to all the reviewers for offering valuable suggestions. Finally, I would like to thank Director, DESIDOC and his team for their untiring efforts in bringing out this special issue.

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