DEPARTMENT OF DEFENCE
DEFENCE SCIENCE & TECHNOLOGY ORGANISATION
DSTO

Feb 2002

A Review of Some Current Research in Microelectromechanical Systems (MEMS) with Defence Applications

A. White

DSTO-GD-0316

A Review of Some Current Research in Microelectromechanical Systems (MEMS) with Defence Applications

A. White

Weapons Systems Division
Aeronautical and Maritime Research Laboratory

DSTO-GD-0316

ABSTRACT

This report reviews some research in microelectromechanical systems (MEMS) published during the period 1999 - 2000. Research in defence applications of MEMS or MEMS research with potential applications for the Australian Defence Organisation are also discussed.

RELEASE LIMITATION

Approved for public release

DEPARTMENT OF DEFENCE
DEFENCE SCIENCE & TECHNOLOGY ORGANISATION
DSTO

Published by

DSTO Aeronautical and Maritime Research Laboratory
506 Lorimer St
Fishermans Bend Vic 3207 Australia

Telephone: (03) 9626 7000
Fax: (03) 9626 7999

AR-012-138
February 2002

APPROVED FOR PUBLIC RELEASE

A Review of Some Current Research in Microelectromechanical Systems (MEMS) with Defence Applications

Executive Summary

A microelectromechanical system (MEMS) is one that is small (micro-scale) and is a system composed of both micromechanical components (such as microgears, microlevers, etc), which move to perform certain tasks, and microelectronic components to control that motion or to obtain information from that motion. However, MEMS technology is generally used in a broader sense, including the technologies of materials and processes required to make MEMS components, integration of components to make MEMS devices (sensors, actuators, etc) and applications that use MEMS devices. In addition, other microsystems such as microchemical reactors, microthermal systems and "smart materials" are also usually included by virtue of their utility as sensors, power sources, heat sinks, etc for MEMS.

In the civilian and commercial arenas, MEMS devices offer many advantages in applications such as automotive control and safety systems, communication, satellite control, medical devices and health monitoring. In 1997, there were some 80 US companies in the MEMS field with a world market for MEMS of US$2 billion, forecast to rise to over US$8 billion by 2003.

For defence, MEMS technology promises to deliver major advances in many diverse areas such as munition guidance, information gathering and soldier survivability. Most civilian or commercial applications will also find applicability in defence, either directly or through procurement of Commercial-Off-The-Shelf (COTS) equipment. In the United States of America, the Defense Advanced Research Projects Agency (DARPA) funds a large amount of research with possible applications to defence. DARPA funding for MEMS and integrated microsystems technology is currently around US$75M/yr, although this is expected to decrease dramatically to around US$37M/yr for the US financial years 2001 and 2002, and to around US$24M/yr for FY2003 and FY2004.

MEMS devices, such as accelerometers, are now available and are becoming more prevalent everyday. Consequently, it is necessary for DSTO to be aware of the state of the art and to be ready to take full advantage of their capabilities for the Australian Defence Organisation. This document aims to indicate the present state of MEMS technology by briefly discussing some of the publicly available current research. Emphasis is given to those aspects of MEMS technology directed towards potential defence applications. This survey was undertaken as a prelude to a more focussed study addressing applications of MEMS in rocket propulsion systems, which will be discussed in a subsequent publication.

Contents

1. Introduction

A microelectromechanical system (MEMS) is one that is small (micro-scale) and is composed of:

- micromechanical components (such as microgears, microlevers, etc), which either move in response to certain stimuli (sensors) or are initiated to perform certain tasks (actuators); and
- microelectronic components to obtain information from, or control, that motion.

In a broader sense, technologies associated with MEMS include materials and processes required to make MEMS components, integration of components to make MEMS devices (sensors, actuators, etc) and applications that use MEMS devices. In addition, other microsystems such as microchemical reactors, microthermal systems and smart materials (such as shape memory alloys) are also sometimes included in "MEMS technology" by virtue of their utility in sensors or actuators or as power sources, heat sinks, etc. for MEMS.

In civilian and commercial applications, MEMS offers advantages in many diverse areas such as automotive control and safety systems, communication, satellite control, medical devices and health monitoring; however, non-MEMS devices often already exist for these applications. If the development of a MEMS alternative is to be worthwhile, the MEMS device must either fill a capability gap, i.e., it must either perform a new function, perform the function better than can currently be performed or be cheaper, lighter or smaller than currently available devices. For commercial applications, it must also be economically viable, i.e., there must be sufficient demand for the new device to be profitable.

For defence, MEMS technology promises to deliver major advances in areas such as munition guidance, information gathering and soldier survivability. Many devices developed for civilian or commercial applications will also find applicability in defence, either directly or through procurement of Commercial-Off-The-Shelf (COTS) equipment.

The pace of change in MEMS technology is so rapid that the Internet and conference papers are indispensable tools in attempting to keep abreast of current research directions and advances. The Institute of Electrical and Electronics Engineers (IEEE) holds a major international MEMS conference each year and the International Society for Optical Engineering (SPIE) holds several conferences each year, covering specific areas of MEMS technology and applications. In addition, there are several journals published regularly, including the Journal of Microelectromechanical Systems (jointly published by the IEEE and the American Society of Mechanical Engineers, ASME) and the Journal of Micromechanics and Microengineering (published by the Institute of Physics). As an indication of the range of MEMS research currently being pursued, a general bibliography of recent publications is given at the end of this report.

This document aims to indicate the present state of MEMS technology with possible defence applications by briefly discussing some of the publicly available current research; emphasis is given to those aspects of MEMS technology directed towards potential defence applications. The quantity of work being conducted and published is so large that the scope of this report is limited to information available to the author as at December 2000 and generally not published before 1999 (apart from some introductory works). This survey was undertaken as a prelude to a more focussed study addressing applications of MEMS in rocket propulsion systems.

2. Classification of MEMS Technology Research

Current activities in MEMS research can be broadly described as falling into one of four general technology areas: fabrication, structures, devices and applications (Figure 1).

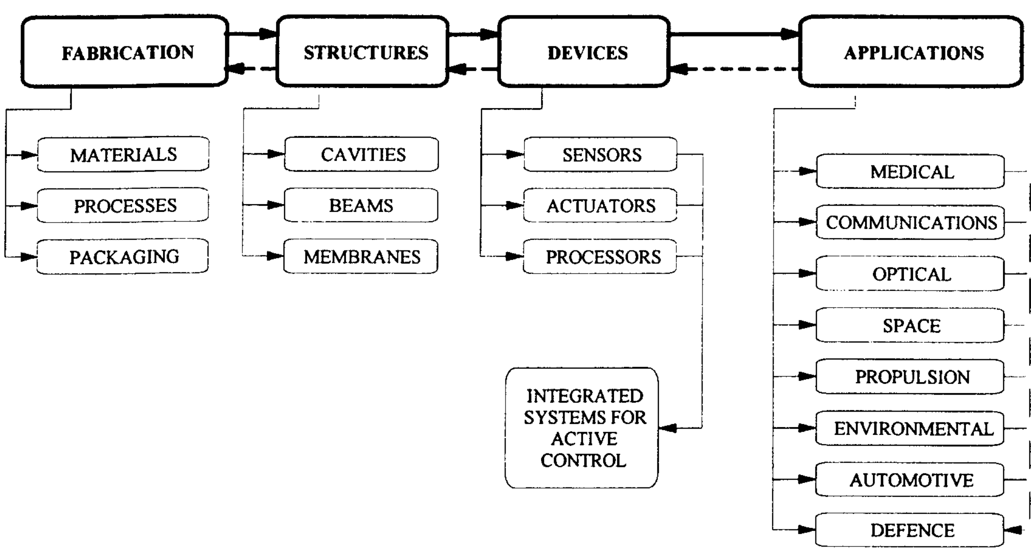

Figure 1: Classification of MEMS Technology

Fabrication is the practice of taking materials and processing them to form elemental structures[1]. Structures such as cavities, beams and membranes may be combined into devices: sensors to detect certain properties (such as pressure) and actuators to perform certain tasks (such as moving a mirror). The devices may have many civilian applications in many different fields, such as medicine, communications and optics;

[1] Packaging of MEMS devices is also generally included in the science of fabrication as it is very important for forming robust devices from the very small and fragile components involved.

however advances in these areas are also likely to have implications for defence. Fabrication of materials into structures and devices leads ultimately to applications. Alternatively, a specific application may require the development of a new device, requiring in turn some novel manufacturing aspects.

Linking together sensors and actuators with the appropriate processing electronics can produce integrated systems for active control. For example, sensors that detect certain conditions (such as temperature) in a system may be linked to actuators (such as fans) that are activated as required by the electronics to maintain the system in the required state. In this way, due to the small size of the MEMS devices, very accurate localised control may be achieved with very fast response times.

3. Some Organisations Conducting MEMS Research

The Rand Corporation published a report on military applications of MEMS in 1993 [1]. At the time, little research had been conducted on military systems applications of MEMS with the total research expenditure on MEMS in the US estimated to be around US$15 - 20m/yr, behind that of Japan (US$150 - 200m/yr), The Netherlands (US$100m/yr) and Germany (US$70 - 100m/yr).

US expenditure on MEMS research in general, and defence applications in particular, has increased significantly since the Rand report. In 1997, there were some 80 US companies active in the MEMS field with a world market for MEMS of US$2 billion, forecast to rise to over US$8 billion by 2003 [2]; however, the net worth of MEMS in the commercial world is limited by the small number of "niche" applications and the relatively small cost-per-unit of MEMS [3]. Even the worldwide market for airbag crash sensors, considered to be one of the major applications for MEMS, is only estimated at US$150m/yr, based on US$3 per unit over the fifty million vehicles manufactured each year [3]. The other major commercial application is inkjet printer heads [3, 4]. The military and aerospace market represents only about 6% of the total market (projected from pre-1997 data) [3].

In the US, a large amount of research with possible applications to defence is funded by the Defense Advanced Research Projects Agency (DARPA) [5]. DARPA funding for MEMS and integrated microsystems technology is currently around US$75m/yr, although this is expected to decrease dramatically to around US$37m/yr for the US financial years 2001 and 2002, and to around US$24m/yr for FY2003 and FY2004 [6].

The US$74.7m for FY2000 is allocated as follows [6]:
- US$20.5m for MEMS devices and processes;
- US$16.2m for MEMS system design and development (Phase II);
- US$25.0m for MEMS micropower generation;
- US$9.0m for bio-fluidic chips (BioFlips); and
- US$4.0m for microdevice manufacture at the Center for Advanced Microstructures and Devices (CAMD).

For FY2001, the US$37.7m planned expenditure on MEMS is split between US$19.8m for MEMS micropower generation and US$17.9m for BioFlips, indicating that DARPA funding for MEMS devices, processes, system design and development is being withdrawn, presumable with these technologies reaching a stage of maturity where they are commercially viable. Selected MEMS projects funded by DARPA as at February 2000 [7] are discussed below, along with other projects investigating MEMS with possible defence applications.

Some non-government companies or laboratories involved in MEMS research are given in Table 1. As indicated above, these are just a sample of the many companies with an interest in MEMS. Some US Government research laboratories are listed in Table 2, and some academic research laboratories investigating MEMS and associated technologies are shown in Table 3. The large number of academic institutions investigating MEMS attests to the novelty of the technology; however, the lines between academic, government and commercial institutions are increasingly becoming blurred. In particular, US Department of Energy laboratories are often operated externally: Battelle operates Pacific Northwest National Laboratory, Oak Ridge National Laboratory (with the University of Tennessee) and Brookhaven National Laboratory (with the State University of New York); Los Alamos National Laboratory is operated by the University of California; and Sandia National Laboratory is operated by the Sandia Corporation, a Lockheed Martin Company.

Table 1: Some MEMS Companies or Non-Government Research Laboratories (all US).

Organisation	Website
Analog Devices iMEMS	http://www.analog.com/iMEMS/
Cronos Integrated Microsystems	http://www.memsrus.com/
MEMS Optical LLC	http://www.memsoptical.com/
Microsensors Inc.	http://www.microsensors.com/
Standard MEMS Inc.	http://www.stdmems.com/
Tanner Research	http://www.tanner.com/
Xerox Palo Alto Research Center	http://www.parc.xerox.com/

Table 2: Some Government Non-Academic MEMS Research Laboratories (all US).

Organisation	**Laboratory / website**
Pacific Northwest National Laboratory	Micro Chemical and Thermal Systems (MicroCats) http://www.pnl.gov/microcats/
Sandia National Laboratory	Microsystems Science, Technology and Components http://www.mdl.sandia.gov/

Table 3: Some Academic MEMS Research Laboratories.

Organisation	**Laboratory / website**
Dalhousie University, Canada	MEMS Laboratory at DalTech http://micron.me.dal.ca/
Technical University of Denmark, Denmark	Mikroelektron Centret http://www.mic.dtu.dk/
Berlin Technical University, Germany	Microsensor and Actuator Technology (MAT) http://www-mat.ee.tu-berlin.de/
Uppsala University, Sweden	Microstructure technology http://www.mst.material.uu.se/
University of Neuchâtel, Switzerland	Sensors, Actuators and Microsystem Lab. (SAMLab) http://www-samlab.unine.ch/
Delft University of Technology, The Netherlands	Delft Institute of Microelectronics and Submicron Technology (DIMES) http://www.dimes.tudelft.nl/
University of Southampton, UK	Microelectronics Centre, MEMS Group http://www.mems.ecs.soton.ac.uk/
California Institute of Technology, USA	Caltech Micromachining Lab http://touch.caltech.edu/
University of California, Berkeley, USA	Berkeley Sensor and Actuator Center (BSAC) http://bsac.eecs.berkeley.edu/
University of California, Los Angeles, USA	UCLA MEMS http://www.ee.ucla.edu/research/judylab/

4. Manufacturing Technology

4.1 Materials

Silicon is the most widely used material for manufacturing MEMS because, due to the integrated circuit industry, it is readily and economically available in crystalline wafers with excellent and well-defined mechanical and electrical properties [3]. Polycrystalline silicon ("polysilicon") is also useful as a structural material in the surface micromachining process [3, 8, 9]. A new method of crystallizing polysilicon, metalinduced lateral crystallization (MILC) is claimed to give a material with greatly improved performance [10].

Silicon oxide can be used as the sacrificial layer material in the surface micromachining process because it is susceptible to etching with hydrogen fluoride whereas silicon is resistant to etching [3]. Similarly, silicon nitride is a useful masking material for alkaline etch solutions and also as an insulating thin film [3]. Silicon nitride can also be used to make MEMS membranes [11], plates and cantilevers, however, thin resonating structures operating in air may show an unstable resonance frequency due to surface oxidation [12]. Silicon carbide offers advantages in hardness and resistance to harsh environments and high temperatures [13, 14, 15, 16, 17]. Polymers are useful in sensing of chemical gases because of their absorption and adsorption properties [18] and polymethylmethacrylate (PMMA) is a useful polymer in the LIGA process (see below) for forming high aspect ratio structures.

Plastic microdevices are useful for microfluidic applications for biosensors and biological assays and, as no batch processes techniques are established for plastics, the University of Michigan is investigating surface and bulk micromachining of plastics and the embedding of silicon devices into cast plastic substrates [19]. Harvard University is also exploring new organic polymers and processes such as micromoulding and microprinting to produce structures from them [20].

Research in new materials for MEMS is also active. For example:

- amorphous alloys show promise as future materials for MEMS, being able to be extruded and forged using micro-dies [21];
- polycaprolactone is a biodegradable polymer, which makes it advantageous for implantable biomedical microdevices [22];
- tantalum oxide can act as a protective coating for sensors [23, 24]; and
- polycrystalline silicon-germanium can be deposited and annealed to activate dopants (impurities added to affect the semiconductor properties of the silicon) at much lower temperatures than polysilicon and hence is a good candidate structural material [25, 26, 27].

Two microdevices, a microgripper and a probe for atomic force microscopy (AFM), have been fabricated from diamond using chemical vapour deposition [28].

4.2 Processes

Conventionally, the two main classes of micromachining were bulk micromachining and surface micromachining. Bulk micromachining involved masking to protect areas of the substrate (bulk silicon) followed by wet etching to remove material from the substrate to leave structures. Surface micromachining involved removal of a sacrificial thin film from a surface using lithography. However, other techniques are now available for etching (such as reactive ion etching), lithography (such as LIGA, which allows the production of high aspect ratio structures from a high-energy lithographic process) and deposition of material onto the substrate.

Common etching processes include:

- **Isotropic Wet Etching**. A strong acid such as a mixture of hydrofluoric, nitric and acetic acids (known as "HNA" or "poly-etch") will dissolve silicon uniformly [3, 8], allowing the imposition of texture on a silicon surface.
- **Anisotropic Wet Etching**. Certain wet enchants such as potassium hydroxide (KOH) dissolves different crystallographic planes in silicon at different rates [29], the ratio of rates of etching for the {100}, {110} and {111} planes being typically 400 : 200 : 1 [30]. Thus V-shaped grooves and trenches can be produced, delineated by {111} planes [3], allowing the manufacture of structures such as diaphragms and beams. Silicon nitride [8] or thin metal films [31] can be used as a mask to protect surfaces from etching. However, KOH is not "cleanroom compatible" [32] and tetramethyl ammonium hydroxide (TMAH), which has different etching properties [33, 34, 35], may be more suitable, depending on the application.
- **Plasma-phase (Dry) Etching**[2]. Plasma-phase etching involves accelerating chemically reactive species towards a substrate using an electric or magnetic field [3, 8]. Deep Reactive Ion Etching (DRIE) [36, 37, 38] allows the manufacture of high aspect ratio structures in silicon by etching very deep trenches (up to 500μm) with nearly vertical sidewalls [3]. The method involves a high-density (inductively coupled) plasma source and an alternating process of etching and protective polymer deposition [8].

Conventional lithography involves the application of a photosensitive emulsion layer (the "resist") to the substrate, optically exposing it and immersing the whole in a developer [3, 39]. The exposed resist is dissolved, leaving the features of the unexposed resist protruding above the surface of the substrate. Aspect ratios of up to about 3:1 are achievable. In polysilicon surface micromachining [9], a stack of alternating thin layers of polysilicon and silicon oxide is built. Each layer is lithographically etched before the next layer is deposited. Finally the silicon oxide is dissolved out to leave polysilicon structures. In this way, gears, micromotors and hinged plates can be created and devices such as accelerometers and yaw-rate sensors have been produced.

LIGA (Lithographie galvanoformung abformung - German acronym for lithography, electroplating and moulding) is a process for producing high aspect ratio microstructures (HARMs) [3, 39]. Unlike conventional optical lithography, X-rays are used to produce the mould made from a polymer resist (eg, polymethylmethacrylate (PMMA) [40]) and a thin metal base. Electroplating is used to fill the mould with a metal and the remainder of the resist is removed, leaving HARMs. X-ray lithography allows the production of HARMs with aspect ratios of more than 100, however, the use of collimated X-rays from synchrotrons makes this process expensive [3] (synchrotron

[2] Dry vapour-phase etching is also possible however it is not as common as plasma-phase etching [0].

radiation sources and applications are reviewed in [41]). LIGA type processes have been used to produce HARM structures in Ni-Co [42] and PZT (lead zirconate titanate) [43]. The LIGA process is also being investigated at Sandia National Laboratories [44]. Nanometre-scale X-ray lithography is reviewed in [45].

SCREAM (Single Crystal Reactive Etching and Metallization) [46] is a combined lithographic / etching process. Standard lithography is used to produce trenches in single-crystal silicon (SCS), which are then protected with a coating of silicon dioxide deposited by plasma enhanced chemical vapour deposition (PECVD). An anisotropic etch removes the coating only at the bottom of the trench, subsequently allowing a plasma silicon etch to extend the depth of the trench and a dry isotopic etch with sulphur hexafluoride is used to laterally etch the exposed sidewalls, undercutting adjacent structures and allowing the manufacture of suspended structures. Some applications for which this technology has been used are high-density memory [47], an x-y micropositioning stage [48], a low-g microaccelerometer [49] and a micromirror array [50].

Some deposition processes include [3]:

- **Epitaxy.** Epitaxy is used to deposit a silicon layer on an existing silicon substrate by vapour-phase chemical deposition. This allows layers with differing types and amounts of dopant.
- **Sputter deposition.** An object made from the material to be deposited is bombarded with inert ions (eg, Ar, He) in a vacuum, causing material to be ejected from the object. This ejected material is deposited onto the substrate.
- **Evaporation.** The material to be deposited is heated to a vapour, which then condenses on the substrate.
- **Chemical Vapour Deposition (CVD).** A reaction is initiated in a chamber over a heated substrate, causing the deposition of a reaction product. Depending on the pressure and the nature of the species present, types of CVD include atmospheric pressure (CVD), low pressure (LPCVD) and plasma enhanced (PECVD). Polysilicon, silicon dioxide and silicon nitrides can be deposited via this method.

A novel method of producing MEMS structures is Inkjet Fabrication, being investigated by the Massachusetts Institute of Technology (MIT) [51]. In this method, a sacrificial layer of PMMA is laid on a substrate, an inkjet printer head is used to deposit nanoparticles of silver onto the PMMA and then the PMMA is dissolved by sonication in acetone. Alternatives to PMMA are photoresist and polyimide, which can also be deposited using inkjet deposition. A similar method is being investigated at Uppsala University to build microstructures from PZT [52].

Another method of producing MEMS structures is high-resolution powder blasting or Abrasive Jet Machining [53, 54]. It can be used to make coarse features for MEMS (< 50 μm minimum feature size, compared with sub-micron size for RIE etching) [53].

Katoh et al. [55], describe a method for three-dimensional microfabrication of PTFE by direct writing with a TIEGA process (Teflon Included Etching and GAlvanicforming), a LIGA-like process which replaces hard x-ray lithography with synchrotron radiation (SR) direct photo-etching.

Mitsubishi Electric Corporation in conjunction with Delft University of Technology DIMES have developed a new wet etching technique, termed Single-step Electrochemical Etching for Micro Structures (SEEMS) [56]. It is a hydrofluoric acid etch process using one mask to fabricate freestanding structures made of single crystal silicon. An accelerometer structure has been made using the process.

Manufacturing technologies being investigated under several DARPA-funded projects including the LIGA process mentioned above [57, 58, 59], the dissolved wafer process [60] and microcasting for high temperature MEMS [61, 62].

4.3 Elemental structures

Some examples of structures that can be produced using the above processes include:
- **cavities (pits, trenches, grooves, etc).** Etched depressions of various geometries, which may have straight or sloping sides, may be flat-bottomed or V-shaped depending on the etch method;
- **cantilever beams.** Linear structures supported at one end;
- **doubly supported beams.** Linear structures supported at both ends;
- **diaphragms.** Thin flexible planar structures surrounded by a thicker substrate [63];
- **capillaries.** Thin tubes, pipettes [64, 65, 66];
- **springs.** Elastic structures (usually thin beams) which can reversibly flex with a defined amount of resistance [67]; and
- **hinges.** Two flat surfaces joined together at an axis about which one or both surface can rotate [68]. Thus this is one method of producing HARMs using planar silicon wafer technology. For example, the University of Colorado's self-assembly method [69] or the University of California, Berkeley's "pop-up" method [68] can be used to produce corner cube reflectors (CCRs) for optical communication or for Identification Friend or Foe [1] applications.

These elemental structures can be combined to from more complex ones, which can then be integrated and packaged to produce MEMS devices.

4.4 Packaging

Packaging is an important part of manufacturing robust MEMS devices, due to their inherent fragility. In conventional integrated circuits, up to 95% of the manufacturing cost is attributable to the packaging process and may run higher for MEMS [70].

MEMS packaging technologies are being investigated by Raytheon [71], Bell Laboratories [72], Lawrence Livermore National Laboratories [73], the University of California at Berkeley [74, 75] and the University of Tokyo [76]. The Raytheon devices are being demonstrated in Autonomous Networked Tactical Sentries (ANTS), wireless communication and torpedo fuzing and safety and arming systems.

Vacuum encapsulation is required in many MEMS devices to prevent problems due to temperature-induced gas expansion, squeeze film damping [77] and stiction [78]. Friction is also important in micro-scale objects composed of silicon [79] and long term stability and service life of MEMS remain important issues [80, 81].

4.5 Modelling and simulation

Modelling and simulation studies of MEMS manufacturing issues include:

- 3D simulation of natural frequency shift due to external forces [82];
- optimal synthesis of microaccelerometers [83];
- simulation of anisotropic wet-chemical etching [84];
- modelling and simulation of the squeeze film effect [85]; and
- modelling effects of surface tension on surface topology in spin coating [86].

5. Devices

The processing methods described in Section 4.2, and the structures so formed (described in Section 4.3) can be used to manufacture MEMS devices, which are generally classified as either sensors or actuators. Sensors detect something or measure some property while actuators perform some action. In effect, they are both transducers, converting one form of energy into another. Sensors generally convert some other form of energy into electricity, so that a measurement may be recorded, transmitted, etc. Actuators may convert electrical energy into movement however, there are other methods of actuation such as thermal, impact, piezoelectric and shape memory alloy [3, B1[3]]. As described in Section 2 above, the small size of MEMS devices also leads to the possibility of "active control", where deviations from a standard condition are sensed by MEMS sensors and are corrected at the same point by MEMS actuators, without recourse to a central processor.

[3] "B1" refers to item 1 in the Bibliography.

5.1 Sensors

Macroscopic sensors such as gyroscopes have been in use for a long time [B39 - B46]. Sensors may be classified by the type of property that they measure as indicated in Figure 2[4]. The mechanical nature of MEMS means that they are particularly suited to the measurement of mechanical properties, however, as indicated below, they can also be used for measuring other properties.

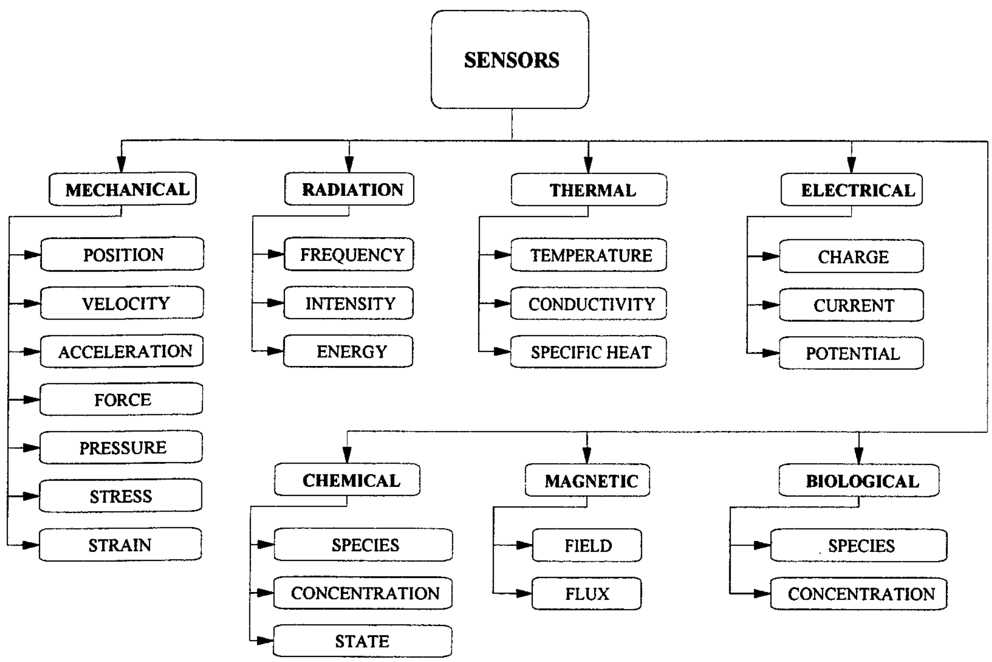

Figure 2: Some possible sensor types and measurands

5.1.1 Pressure

Some of the earliest MEMS devices constructed were piezoresistive pressure sensors [88, 89]. These can be made using a silicon diaphragm containing four thin-film resistors near the edges in a Wheatstone bridge configuration. One side of the diaphragm is in a sealed cavity at a reference pressure. Changes in pressure on the other side of the diaphragm cause it to flex, which increases the resistance in two of the resistors and decreases it in the other two. By previously calibrating the device, changes in resistance can be converted to pressure measurements. In measuring

[4] Although not pursued further here, sensors could also be classified by other criteria, for example, by their specifications (sensitivity, resolution, etc), materials or fields of application [0].

differential pressure, two such devices in tandem can be used to offset errors due to changes in static pressure and ambient temperature [90].

Various other pressure sensors being investigated include:
- a differential pressure sensor with a sealed gap to prevent contamination [91];
- a low cost batch-sealed capacitive pressure sensor [92];
- a low-voltage force-balanced pressure sensor [93];
- wireless ceramic pressure sensors for high-temperature applications [94];
- capacitive microphones for applications such as hearing aids [95, 96];
- sensors integrated into car tyres to read and transmit inflation pressure [97];
- an integrated 3D tactile sensor for space robotic applications [98];
- a multi-function integrated film (MIF) tactile sensor [99];
- a hybrid silicon-fibre optic pressure sensor array for tactile sensing [100]; and
- a piezoelectric tactile sensor for an endoscopic grasper [101].

5.1.2 Mass / load

A silicon load cell has been developed with a surface area of 1 cm^2 and which can measure loads up to 1000 kg [102]. An array of sensing elements is used to make the load cell less sensitive to non-homogeneous load distributions. The design has two bonded silicon wafers, the bottom layer containing an electrode pattern forming an array of capacitors with the top wafer as a common electrode. A load placed on the top wafer compresses the cell, increasing the capacitance. An accuracy of 0.2% of full scale was demonstrated in the prototype and an accuracy of 0.03% is planned with future improvements such as optimisation of the measurement set-up and an increased number of capacitors.

A micromachined capacitive silicon scale has been designed and fabricated by VTT in Finland [103]. It can weigh masses of around 1 g with a resolution of 1 ppm. The device measures the capacitance between a flexible electrode and a rigid electrode. The rigid electrode is divided into three sections to detect differences in capacitance caused by tilting of the flexible electrode due to an off-centre load. Electrostatic force feedback is used to keep the top electrode horizontal to correct for this. The resolution can be improved down to 0.01 ppm, but this kind of device can only be used in very stable environments.

5.1.3 Acceleration, velocity, position, orientation and IMUs

MEMS accelerometers generally consist of a proof-mass suspended by a "spring", which in MEMS is usually a cantilever or beam [3]. When the device is subjected to acceleration, the inertia of the mass causes changes in the gap between it and the bulk of the device. Vibration sensors can operate using the same principle [104]. The mass may move out of the plane of the silicon wafer or in the plane (as is common in surface micromachined devices). The displacement of the mass may be measured using many different methods, for example:

- capacitively - by measuring the change in the gap between the mass and the bulk of the device or between combs fitted to the mass and the bulk device [105]. For space-based inertial systems, capacitive force balanced accelerometers appear to be most attractive [106];
- piezoresistively - by measuring the flexing of the spring, in a similar manner to the pressure transducers described above [105, 107];
- thermally - the temperature flux from a heater to a heat-sink is inversely proportional to their separation (temperature measured using thermopiles) [105];
- using quantum tunnelling - changes in a tunnelling current flowing between one tunnelling tip and its counter electrode is used to sense displacement [105];
- using resonance - the proof-mass inertial force is transferred to axial force on resonant beams, thus changing their frequency [105];
- using changes in Surface Acoustic Waves (SAWs) [108, B36] - surface acoustic waves travel on silicon or a piezoelectric substrate between a pair of Inter-Digital Transducers (IDTs, metal fingers). The time of travel depends on the physical variables [109] and hence changes in the phase of the wave can be used to measure acceleration;
- optically - the displacement of the mass is measured by changes in intensity of light, either through displacement of a waveguide or displacement of a micromachine such as a mirror reflecting light back into the optical fibre [110]; and
- using Modulated Integrative Differential Optical Sensing (MIDOS) - an optical method that measures the change in illumination of photodiodes obscured by the proof-mass [111].

An early version of a capacitive accelerometer is described in [89]. It is manufactured by forming a cantilever beam with a gold weight on the end over a flat-bottomed cavity. A metal layer is deposited over the top of the cantilever forming a capacitor between itself and the silicon on the bottom of the well. If the device is moved suddenly, the inertia of the gold weight causes the beam to flex, changing the air gap between the beam and the silicon and changing the capacitance. Capacitive pressure sensors operate on a similar principle, using a diaphragm made of polysilicon as the top electrode and an electrode on the bottom of the cavity below [112].

The Toyohashi University of Technology is investigating fabrication of a three-axis accelerometer [113]. The accelerometer is integrated with commercial CMOS circuits to reduce the total cost of the device.

Rotation sensors are useful for tachometers and for measurement and control of objects such as gears or shafts. A non-contact high-speed MEMS rotation sensor has been developed [114]. It is produced by surface-micromachining using the MCNC (now Cronos) Multi-User MEMS Processes (MUMPs) facility. It has polysilicon cantilever beams supporting a multi-layered mass platform. On rotation, the mass is pushed outwards and the deflection of the beams causes a change in resistance in the polysilicon that can be converted into a measurable change of voltage by connecting the sensors in a Wheatstone-bridge configuration. The device can measure rotation speeds of 100 - 6000 rpm. It is planned that it will be linked to a wireless transmission chip for communication.

Micro-gyroscopes are being developed in the US [115], Germany [116], Japan [117, 118], Korea [119, 120, 121] and Singapore [122]. Applications include automotive, camcorders and virtual reality head mounted displays (HMD) [119]. Gyroscopes can also be made from SAW devices [108].

A surface micromachined sensor, which measures magnetic fields using the Lorentz force, has been developed by the Robert Bosch GmbH Automotive Equipment Division [123]. A defined current through a conducting beam interacting with an external magnetic field causes lateral displacement of the beam, which is converted into a capacitance change by comb-electrodes forming a differential capacitor. An alternative magnetic field sensor design is being developed at the University of Montpellier in France [124]. The sensing principle is based on the deformation of a ferromagnetic mechanical structure due to magnetic forces.

Many MEMS projects sponsored by DARPA involve development of sensors for measurement of acceleration, velocity and orientation (via magnetometry), with obvious applicability to missile and projectile guidance. DARPA-funded MEMS accelerometer research is being conducted by Integrated Micro Instruments [125], the University of Michigan [126, 105, 127] and the University of California, Los Angeles (UCLA) [128].

DARPA-funded MEMS inertial measurement units (IMUs) are being developed by Carnegie Mellon University [129, 130, 131, 132] and Draper Laboratory [133, 134]. IMUs have three accelerometer sensors, providing all the information on acceleration needed to determine actual position for inertial navigation [135]. Depending on the accuracy of the IMU, Global Positioning System (GPS) guidance may be required to correct errors in the inertial navigation [135]. Candidate systems for the Draper MEMS IMUs are the US Navy's 5" Extended Range Guided Munition (ERGM) Ex-171 projectile and the US Army's XM-982 155 mm guided projectile [133]. Draper has also been chosen to design, fabricate and test the gyro package for the US Army's Precision Guided Mortar Munition (PGMM) program. The US Air Force is evaluating Draper's gyros for MEMS insertion into its Wind Corrected Munitions Dispenser (WCMD) [133].

5.1.4 Flow

The California Institute of Technology is developing MEMS flow sensors for nano-fluidic applications [136]. The sensors use a boron-doped polysilicon thin-film heater that is embedded in the silicon nitride wall of a microchannel. The sensors have a flow rate resolution of less than 10 nL/min. Applications include microchromatography, biochemical detection and mass spectrometry.

Another flow sensor is based on a common piezoresistive pressure sensor with an orifice in the sensor diaphragm that forms a flow restriction [137]. The measurement range of the sensor is between about 2 - 32 mL/min with orifice diameters of 100 - 400 μm.

Particle image velocimetry (PIV) can be used to measure high-speed particle flow velocities in microchannels such as micronozzles for thrusters for small-scale aircraft and spacecraft [138].

A micromachined Coulter counter has been designed at the University of Southampton [139]. A Coulter counter measures the number and size of particles in an electrically conducting fluid by the change in electrical resistance between two electrodes as particles pass between them. One particular application is the counting of red blood cells in blood.

A combination blood pressure/flow/oxygen sensor chip has been developed at the Delft University of Technology that can be fitted to a catheter [140, 141]. It contains an absolute pressure sensor to measure blood pressure, a thermal flow sensor to measure blood flow velocity and a colour sensor to measure blood oxygen saturation [140]. The pressure sensor operates via a Wheatstone bridge of polysilicon piezoresistors that measure the deflection of a polysilicon membrane with pressure. The flow velocity is measured using the principle of thermal transfer. The blood is locally heated to 2°C above ambient with a polysilicon resistor, and the temperature rise is measured upstream and downstream of the heater using polysilicon - aluminium thermopiles. The colour sensor consists of two vertically stacked photodiodes, the top diode giving a signal from both IR and visible red light, while the deeper diode only gives a signal from the IR light, due to the greater penetration of the IR photons. Together, absorption in both wavelengths can be determined and the oxygen saturation calculated. The light required is applied via a separate optical fibre in the catheter. The chip containing the three sensors is 1 mm wide and 7 mm long.

5.1.5 Shear stress and strain

MEMS sensors have great potential for measurement of aerodynamic information on the surface of aerial vehicles, however attaching sensors is difficult because the surfaces of aerial vehicles are not flat. One method is to install arrays of MEMS sensors in a flexible skin so that the can be applied to a surface "like a Scotch tape" [142]. This new skin technology uses DRIE to improve yield and allows the skins to be array bonded to flexible Kapton PCBs, completely avoiding bonding wires [142]. The shear stress sensors themselves are vacuum-insulated diaphragm-type thermal sensors capable of measuring the wall shear stress exerted by viscous flow [143]. The new sensor system has been successfully tested in wind tunnel and UAV trials. The system will eventually be used for the real-time manoeuvring control of the UAV.

Two air flow sensors modelled on wind receptor hairs of insects has been fabricated at the University of Tokyo [144]. Both sensors have cantilevers ("hairs"), which have strain gauges at the bottom to detect deflection of the cantilever. The output voltage was found to be proportional to the velocity of air flow, in good agreement with theory.

A multi-sensor chip for use as a mass flowmeter has been developed at the California Institute of Technology containing a 1D array of pressure, temperature and shear stress sensors [145]. The shear stress sensor is a heated resistor sitting on a vacuum cavity. The heat loss of the resistor is a function of the velocity gradient, i.e., the wall shear stress of the ambient fluid.

MEMS low profile, low power, uni- and multi-axial strain transducers are being developed by Sarcos Research Corporation under a DARPA-funded project for the measurement of strain for structural health monitoring of aircraft [146, 147].

A laterally deflecting device that can be used to electronically monitor residual strain via differential capacitance change is being developed at the University of Wisconsin [148]. The device can also supply Young's modulus of microstructural materials by plotting capacitance against voltage.

Wireless embedded MEMS strain sensors have been used to measure in-plane strains in laminate fibre-reinforced polymer composites [149]. Three different piezoresistive strain sensor designs were fabricated on silicon wafers: a monofilament, a cantilever beam and a curved (hoop) cantilever beam. The sensors were evaluated for sensitivity, repeatability and reliability under cyclic loading. The monofilament sensors were the most sensitive, but also showed the greatest variability. Only the curved-beam off-surface sensors responded consistently to loads (whether applied under uniaxial or bending conditions) and were insensitive to the laminate thickness of the composite. The cantilever beam sensors showed similarly responses to the curved beam sensors, but their response to compression loads indicated a greater tendency for buckling.

5.1.6 Radiation and microscopy

There are two types of infrared (IR) detectors [150]:

- photon detectors in which the absorbed photons directly produce free electrons and holes. Sensors with very high detectivity can be manufactured using this method, but are very expensive and require cryogenic cooling; and
- thermal detectors in which the absorbed photons produce a temperature change which is then indirectly measured using a temperature dependent property of the detector material. A bolometer is one type of thermal IR detector. The design approach and technology of the development of IR-sensing microbolometers for uncooled thermal IR arrays are discussed in [150]. Another approach uses the absorbed radiation to produce a temperature difference in two materials [151].

Conductors connecting the two materials produce a voltage difference proportional to the temperature difference.

The Korea Advanced Institute of Science and Technology (KAIST) is investigating a Micromachined Isolated Silicon Diode for IR detection (MISIR) [152]. The device can be operated at room temperature without cryogenic cooling. It shows a very high detectivity of 1.2×10^{10} cm.Hz^{½}/W. A MISIR imaging system is under development.

In a DARPA-funded project, the University of California, Berkeley with Raytheon are investigating a direct-view uncooled micro-optomechanical IR camera [153] based on thermomechanical sensing, with a focal plane array consisting of bimaterial cantilever beams in each pixel. Absorption of incident IR radiation by a particular cantilever raises its temperature, resulting in deflection (bending) due to differences in thermal expansion coefficients of the two materials. A visible optical system simultaneously measures the deflections of all the cantilevers using either diffraction or interferometry and projects a visible image of the IR radiation onto the human eye.

The Sarnoff Corporation is investigating a MEMS direct-view IR vision system under another DARPA-funded project [154]. The objective is to demonstrate that arrays of IR detectors can be built and have the required performance to act as imaging IR pixels for night vision. The approach uses bi-material detectors and field emitters to provide a direct conversion of IR photons to a visible display without the intervening electronics.

Various visible sensors are also being developed including a visual sensor based on a fly's compound eye to aid in real-time sensory-guided flight [155, 156] and an optical scanner with dimensions 2.0 x 4.0 x 2.8 mm [157]. MEMS technology is also being applied to the manufacture of probes for scanning near-field optical microscopy (SNOM) [158, 159] and atomic force microscopy (AFM) [160, 161,162].

5.1.7 Chemical

Many gas sensors operate by adsorption of gas molecules onto the surface of a metal-oxide element, reducing the surface conductivity [3, 163]. Different metal oxides are selective for different gases.

A "polychromator" is being developed by Honeywell under a DARPA contract [164]. It is a MEMS-based optical correlation spectrometer and has applications in remote detection and analysis of chemical species such as chemical weapons detection, combustion exhaust plumes and environmental compliance monitoring.

The Federal Institute of Technology, Zurich, Switzerland (ETH) is investigating calorimetric chemical sensors [165, 166, 167]. The sensors measure enthalpy changes that occur when an analyte is absorbed into, or desorbed from, a chemically sensitive layer (eg, a polymer as mentioned in section 4.1). The enthalpy changes cause a temperature change, which is measured by a temperature sensor. The chemical sensors have been used to measure toluene and ethanol vapour concentration. ETH is also investigating capacitive chemical microsensors for discriminating organic vapours by using thick chemically sensitive polymer layers in CMOS capacitors [168]. For thin polymer layers, the capacitance increases for all analytes, whereas for thick polymers, the direction of the capacitance change depends on the dielectric constant of the analyte. Thus, for example, the sensor can be made to be sensitive to ethanol, while insensitive to octane.

A micro gas sensor based on both mass and conductivity measurement developed by the Peking University offers an improvement in the selectivity of gas-sensitive films to the detected gas [169]. The principle of operation is that the charge-mass ratio of the detected gas is obtained, thus identifying the gas molecule. The charge is obtained by measuring the conductivity change of a gas-sensitive film on adsorption. The gas-sensitive film sits on a resonator, and the mass of the molecule is obtained by measuring the shift in resonator frequency on adsorption.

A novel MOSFET gas sensor has been designed, fabricated and characterised [170]. The device consists of a heating resistor, a diode used as a temperature sensor and an array of four MOSFETs, operating at a temperature of 170°C. Three of the MOSFET gates are covered with thin layers of catalytic materials so that they can act as gas sensors. The fourth is covered with the standard nitride coating, which could act as a reference. The device shows good sensitivity to hydrogen and ammonia.

A humidity sensor is being developed by the University of Michigan [171]. The sensor is 1 mm^2 and designed to fit into a hermetic micropackage, such as an implantable microstimulator. The sensor consists of a thin layer of polyimide, which can absorb moisture, sandwiched between two conductive electrodes to form a moisture sensitive capacitor. The sensitivity is 0.86 pF/ %RH.

Other MEMS applications for chemical sensors being developed include:

- laser-induced fluorescence for analysis of aromatic compounds in water [172];
- a waveguide immunofluorescence sensor for water pollution analysis [173];
- ion selective sensors for groundwater monitoring [174];
- polymer-coated quartz crystal resonators for organic chemical detection [175, 176];
- acoustic plate mode sensors for metal ion solutions analysis [177];
- a chemically selective coated quartz microbalance array for detection of volatile organic compounds [178];
- work function sensors (measuring changes in surface potential on adsorption) for gas detection at room temperatures [179];
- surface acoustic wave sensors for the detection of volatile organics [180, 181, 182];
- detection of hydrocarbon vapours by ATR-leaky mode spectroscopy [183];
- voltametric sensors for trace metals analysis [184];
- stripping electrochemistry / piezoelectric sensors for heavy metal detection [185];
- a lead sulphide detector for near infrared spectroscopy [186];
- a colorimetric spectrometer for NH_3 determination in a flow injection cell [187];
- a near infrared microspectrometer based on LIGA technology [188];

- a micro-sensor for NMR spectroscopy of nanolitre sample volumes [189]; and
- a mass imaging spectrometer on a chip (MISOC) [190].

5.1.8 Smart tongues and noses

Smart tongues "taste" a solution, while smart noses "smell" vapours. Both involve the identification and quantification of complex mixtures using multiple microsensors. These technologies are reviewed in [191, 192].

Three different types of polymer-coated CMOS-based chemical microsensors suitable for use in micronoses were studied at ETH Zurich in Switzerland [193]. The first sensor is a microcapacitor sensitive to changes in dielectric properties of the polymer caused by analyte absorption. The second sensor is a resonant cantilever sensitive to mass changes. The third sensor is a microcalorimeter that measures the absorption or desorption heat of organic volatiles in the polymer layer.

A nanomechanical "nose" is being developed in Switzerland by the IBM Research Division Zurich Research Laboratory, in conjunction with the University of Basel [194]. It is based on a microfabricated array of silicon cantilevers, each of which is sensitised with a metal coating for the detection of various analytes (eg, ethene or water). Analytes absorbing on the coating produce a change in surface stress, resulting in bending of the cantilever. The bending is measured using a time-multiplexed optical beam-deflection technique, giving quantitative information on analyte species and concentration. The advantage of this sensor is that it can use reference sensors to subtract the background for differential measurements.

An electronic "tongue", i.e. a micromachined sensor array for the rapid characterisation of multi-component mixtures in aqueous media, is being developed at the University of Texas [195]. The sensor uses an array of individually immobilised polystyrene-polyethylene glycol composite microspheres. Sensing occurs via colorimetric or fluorometric changes to indicator molecules that are covalently bound to amine termination sites on the polymeric microspheres.

5.2 Actuators

By definition, MEMS actuators perform some action. Solid objects can be moved in a number of ways such as translation (eg, pistons, comb drive, barrier insertion for optical switches), rotation (eg, cogs, gears, micromotors) and tilting (eg, mirrors).

Actuators may also be classified by their method of actuation [3, B1]:

- **Electrostatic:** creating opposite electric charges on two objects will cause an attractive force between them.
- **Magnetic:** electrical current through a conductive element in a permanent magnetic field gives rise to an electromagnetic force (the Lorentz force) [196].

- **Piezoelectric:** applying a potential to a piezoelectric material causes it to change size, exerting force [197].
- **Thermal:** changes in temperature cause materials to expand or contract, exerting force (eg, electrothermal [198] or bent-beam actuators [199, 200]). Careful design can make the degree of actuation dependent on absolute temperature or on a difference in temperature.
- **Shape-memory alloys:** Some materials can be deformed but, after heating above a critical temperature, will return to their original shape [201, 202]. This form of actuation offers the greatest energy density. For example, this technology has been used to make active catheters, which can be controllably steered in blood vessels [203, 204, 205, 206, 99] and for microelectrodes that can grip nerves for insect neural recording [207, 208].
- **Polyimide joint technology:** An alternative to shape memory alloys is based on the thermal expansion properties of polyimide [209]. By inserting polyimide into a number of V-grooves in joints and varying the cure temperature allows for out-of-plane bending to construct 3D devices. In addition, the relatively large thermal expansion of polyimide allows it to be used in dynamic applications for actuators. Examples of applications using this technology include a 3D hot-wire flow sensor [209] and a microconveyor based on arrays of movable silicon legs [210].

5.2.1 Micromirrors

There is much ongoing research in micromirrors, especially with application as components of deformable mirrors for adaptive optics [211]. In a DARPA-funded project, Boston University is investigating silicon based deformable mirrors [212]. The mirrors are composed of a massively parallel system of electrostatically controlled, interconnected, surface normal microactuators. Above the actuator array is a continuous or segmented mirror membrane. Applications include astronomy, medical imaging and optical correlation. In another DARPA contract, UCLA is investigating aerogel MEMS fast steering mirrors for inter-satellite communications and other satellite applications [213].

Single laser beam mirror devices require large deflection angles and reflective areas, such as that designed to make up the deflection part of the telemetric system of a 3D-laser camera for robotic applications [214]. Research aimed towards improving optical properties of micromirrors is also topical [215]. MEMS lenses can also be fabricated [216, 217] and also curved antennas that can change their reflector shape through the use of piezoelectric actuators [218].

Other applications for micromirrors include data storage [219, 220], microscanners [221], bar code readers [222, 223], head mounted displays [224, 225], satellite signal focussing [226], accelerometers [227], optical data interconnect [228], real-time image recognition [228], optical interferometry [228], spectroscopy [228], aberration correction [228], optical switches [229, 230] and astrophysics [231].

5.2.2 Microfluidic devices

Actuators for fluids include microvalves, micropumps and mixers.

Microvalves may be actuated using many different methods, including piezoelectric [232, 233], electrostatic [232, 233], thermal expansion [232], bimetallic [233], pneumatic [234], electromagnetic [235], thermopneumatic [236, 237], capillarity [238] and shape memory alloys [239]. For example, a thermopneumatic microvalve can be made by inserting a resistive heater into an enclosed cavity behind a diaphragm. Applying a current to the heater causes it to deliver heat to the fluid in the cavity, which then expands, pushing the diaphragm out. The extended diaphragm can be used to block a channel, acting as a valve [236, 237].

A micropump can be made in a similar manner, with the extending diaphragm compressing a chamber of the fluid to be pumped. The chamber has check-valves at the inlet and outlet, controlling the direction of flow [3]. Other pump designs include diffuser pumps [240, 241], rotary pumps [242] and gear pumps [243, 244]. A valve-less pump has also been designed based on the dependence of liquid viscosity on temperature [245]. One of the main commercial applications of micro-pumps is drug delivery [246, 247], although microfluidic devices are also required for miniature chemical analysis systems [248].

The Institute of Physical and Chemical Research (RIKEN) in Japan has developed a device for mixing liquid droplets with picolitre or nanolitre volumes [249]. Two droplets with volumes of 5 nL were pneumatically manipulated and joined in a microchannel. The air between the droplets is drawn off using a hydrophobic microcapillary vent (HMCV) and the droplets mix by diffusion. The mixer may be used as a component of integrated multi-step Micro Total Analysis Systems (μTAS, "lab on a chip").

An integrated liquid mixer/valve has been developed at the Massachusetts Institute of Technology [250]. A reagent is injected via a flapper valve into a stream of sample flowing through a channel. Mixing then occurs diffusively and the mixture flows out of the device.

Nagoya University is developing biochemical microdevices containing multiple microfluidic devices such as pumps, reactors, concentrators and valves [239, 251, 252]. A shape memory alloy (SMA) micro actuator is used to drive the pump, the pumping rate being of the order of 10 μL/min. The volume of the microreactor is 3 μL.

5.2.3 Other actuator devices

The University of Michigan is investigating, in a DARPA-funded project, electrokinetic fluid microactuators for boundary layer drag reduction and on-demand leading edge vortex generation for control of aircraft [253]. Stanford University is also investigating MEMS-based transducers for active boundary layer control to reduce drag in turbulent flows [254]. The Arizona State University has a DARPA-funded project [255] for similar applications, however using distributed arrays of micropistons to vary the roughness (from 4 to 20 microns) on the leading edge of swept wings to control transition to turbulence.

An electrostatically actuated MEMS power switch has been developed at MIT [256]. The application is to replace automotive relays, with a projected market of 225 million per year in the US alone. The intention is to embed MEMS switches at the point of use, rather than running wires to a central relay block.

A microelectromechanical pressure switch has been designed by Honeywell [257]. It uses electronic switching using a moving gate field effect transistor (MOGFET) that eliminates direct contact switches. It is expected that the switches will be applied to accelerometer applications.

Micromechanical relays (MMRs) are also being pursued in several other organisations [258, 259]. One of the main applications of interest for MMRs is in automatic test equipment where large arrays of relays are used [258]. MMRs have several advantages over conventional electromechanical relays (EMR), such as small size and integratability, or solid-state relays (SSR), such as better high frequency characteristics and low contact resistance [259].

Other actuator devices being developed include:

- a long range translation actuator, designed to operate as the moving mirror in a miniature Michelson Fourier transform spectrometer [260];
- a polymer-based MEMS microactuator with macroscopic action [261];
- a soft micromanipulation device for soft dextrous motion in 3 and 6-DOF [262];
- switches for logic elements in circuits [263];
- a two-dimensional microconveyor using electrostatic actuators [264];
- an electrostatic actuator with extended range of travel [265];
- actuators for read/write heads of hard disk drives [266, 267, 268];
- integrated force array (IFA) and spiral wound transducer (SWT) actuators which deform metallised plastic membranes by applying a voltage [269]; and
- smart materials for aerospace structures such as missile control surfaces [270].

5.3 Integrated Systems and Active Control

In a DARPA-funded project, the Georgia Institute of Technology is aiming to demonstrate new MEMS and materials for MEMS for applications in Unmanned Aerial Vehicles (UAVs) [271]. In particular, they have fabricated an array of MEMS pressure sensors and an array of MEMS modulators using stainless steel as a substrate for orifice-based control of microjets. It is planned that Boeing/Saint Louis will test the sensors and actuators on UAV-class vehicles at the end of the program.

UCLA has two projects funded by DARPA to investigate integrated sensor-processor-actuator systems, which UCLA call M3 (microsensor-microelectronics-microactuator) systems. The first project is to develop an aircraft for low altitude surveillance [272]. A new aircraft without a tail will be designed to demonstrate the concept of achieving aerodynamic manoeuvring through a micromachine-based deformable smart surface. The second project is to investigate M3 systems for controlling near-wall structures in the turbulent boundary layer to reduce drag due to surface shear stress [273]. Thermal shear stress sensor arrays are linked to electromagnetic actuators with driving circuitry using neural network logic for the control system to apply the sensing-decision-actuation task in real-time.

In a similar DARPA project, the University of Florida is investigating MEMS for controlling flows around Micro Air Vehicles (MAVs) with the goal of providing improved aerodynamic performance and mechanisms for flight control [274]. Again, a MEMS shear sensor array is used and neural networks are being investigated for control algorithms. Particle image velocimetry (PIV) is used to conduct flow field measurements.

The purpose of a DARPA project being conducted by Sarcos [275] is to demonstrate active control of the buckling instability in a solid beam instrumented with MEMS uni-axial strain transducers (UASTs). The UASTs are currently being evaluated for use in helicopters (with Boeing and Sikorsky), submarines (with NAVSEA and Newport News Shipbuilding) and aircraft (with Boeing).

As part of the University of Michigan DARPA project investigating electrokinetic fluid microactuators (see Section 5.2), an integrated electrokinetic-based MEMS sensor-processor-actuator array suitable for elementary vehicle control will be produced and tested in a wind tunnel [253]. The Xerox Palo Alto Research Center is also conducting system-level research to develop and demonstrate MEMS-based sensor-processor-actuator arrays [276]. The Center is also investigating the development of software and architectures for coordinating the actions of large numbers of distributed devices.

The DARPA-funded "Smart Dust" project being conducted at the University of California, Berkeley, is concerned with creating massively distributed sensor networks consisting of many autonomous sensor nodes [277]. Each sensor node ("mote") contains a sensor, electronics, power supply and communications hardware, all in a cubic millimetre volume [277]. The motes will be delivered from Micro Air Vehicles (MAVs). The current goals of the project are to explore the fundamental size limits of autonomous sensor platforms and new applications that become possible with sub-cubic millimetre-sized platforms. The project previously demonstrated laser communication from a 1 cubic inch (approx. 16 cm^3) weather station at a distance of 21 km, sensor network communication and flights of 24-inch (61 cm) MAVs.

In a similar vein, the low power wireless integrated microsensor (LWIM) program at UCLA is aimed at developing a revolutionary battlespace information system enabled by a distributed MEMS network [278, 279]. Sensors include microseismometers, magnetometers, microaccelerometers and infrared motion detectors.

An axisymmetric jet nozzle equipped with a row of eighteen miniature electromagnetic flap actuators on its lip for active flow control has been developed at the University of Tokyo [280]. The actuators can control coherent vortical structures and gives a large range of control over the jet velocity (~45% of the natural jet velocity) with only a small amount of control energy required.

A new concept for a pressure control unit for gases has been developed at the University of Stuttgart [281]. It consists of a microprocessor for digital control, electrostatically actuated microvalves and a pressure sensor. The system minimises dead volume, gives a fast response time and low power consumption. Such systems can be used in pneumatics, gas analysis and medical engineering.

5.4 Modelling and simulation

Some modelling and simulation studies of MEMS devices include:

- modelling of:
  - an electrostatic membrane actuator for micropumps [282];
  - micropumps using unimorph piezoelectric actuator and ball valves [283];
  - quadrature error of a microgyroscope [284];
  - an optical torsion micromirror [285]; and
  - flexural plate wave devices [286].
- simulation of:
  - gas and odour sensors [287];
  - gas flow in micro devices using Navier-Stokes simulations [288];
  - sensitivity and linearity of piezoresistive pressure sensors [289]; and
  - low-velocity microflows in MEMS devices using a modified direct simulation Monte Carlo (DSMC) method [290].
- optimisation of:
  - sample injection components in microfluidic systems [291]; and
  - thin film gas sensors for environmental monitoring [292].
- theoretical studies of:
  - comparison of noise in three types of pressure sensors [293]; and
  - effects of geometrical dimensions on the viscosity of fluids flowing in micro-systems [294].

6. Applications with Possible Defence Relevance

In 1995, the US Department of Defense conducted an industrial assessment of MEMS [295] in which it was said that "MEMS will create new military capabilities, make high-end functionality affordable to low-end military systems, and extend the operational performance and lifetimes of existing weapons platforms". Twelve defence applications were identified, grouped under three major areas [295]:

- **Inertial measurement applications :**
  1. Weapons safing, arming and fuzing (improve operation, safety and reliability of warheads and bomblets, reducing unexploded ordnance);
  2. Competent munitions (integrate MEMS IMUs into conventional munitions to reduce the dispersion of projectiles on point targets);
  3. Platform stabilisation (replace conventional accelerometers and gyroscopes with MEMS devices, reducing cost and power requirements);
  4. Personal/vehicle navigation (use MEMS INUs to augment personnel and vehicle GPS);
- **Distributed sensing and control applications:**
  5. Condition-based maintenance (eg, using embedded sensors and actuators in components of materiel to monitor and report on their condition in real time);
  6. Situational awareness (eg, distributed unattended sensors for perimeter security, area surveillance, shipboard automation, etc);
  7. Miniature analytical instruments (eg, for detection of fuels, explosives, drugs or NBC operations);
  8. Identify-friend-or-foe (eg, using modulation of deformable and active surfaces with a smart reflector and secure communications);
  9. Biomedical devices (for monitoring vital signs of combatants and delivering trauma care);
  10. Active structures (eg, active conformal surfaces for distributed aerodynamic control of aircraft);
- **Information technology applications:**
  11. Mass data storage (eg, for digital maps, manuals for a highly mobile force);
  12. Displays (eg, for display of maps, etc);

The weakest areas in terms of technical maturity were identified as [295]:

- personal/vehicle navigation;
- miniature analytical instruments;
- identify-friend-or-foe;
- active structures; and
- mass data storage;

Perhaps not surprisingly, as will be seen below, these areas are receiving a great deal of research attention. In addition, several technology areas are also emerging which, although not specific to defence, will have implications for defence in areas such as communications, mobility and propulsion.

6.1 Microrobots, flight and Micro Aerial Vehicles (MAVs)

Microrobots may find use as vehicles for micro-surveillance, chemical analysis or weapons systems. A piezoelectric microactuator array, which will be the key component of a remotely controlled, wireless, solar-powered microsystem that should be capable of locomotion is described in [296]. A few hundred "walking cells" are arranged in a hexagonal array, each cell having a "leg" 300 μm high. The legs are actuated using three piezoelectric biomorph beams that allow the leg to reach any position within an ellipsoid. Another method of mobility mimics the way that six-legged insects walk [297].

Three-dimensional burrs have been developed using the LIGA process [298]. The burrs are designed to be used on a device that can attach itself to human hosts who "could be enemy troops or persons who have entered a restricted area". The device could carry sensors for tracking or information gathering.

The University of Tokyo is investigating flight using a vehicle with 2 mm long rotational wings [299, 300]. The wings are made of cobalt-nickel alloy and rotate in an alternating magnetic field. They succeeded in lifting a silicon body weighing 1.6 mg.

A battery-powered ornithopter (flapping-wing) MAV is being developed with MEMS wings [301]. The 7 cm long wings have a titanium-alloy frame, a Parylene C membrane and are manufactured using MEMS photolithography technology. The mass of the MAV is 7 - 10 g and flight durations of 5 - 18 seconds have been achieved.

6.2 Space

There is a DARPA-funded project addressing space applications of MEMS and microtechnology being conducted by Aerospace Corporation [302]. The purpose is to exploit and develop MEMS and microsystems for mass producible miniature spacecraft DARPA envisions individual nanosatellites that can also operate in "cooperative constellations, clusters and on-demand swarms". The applications are communications and remote sensing and action. At the time of the report, Aerospace Corporation were preparing flight assemblies for very small satellites (approx. 2.5 × 7.5 × 10 cm, weighing 275 g each) for launch into space for risk reduction testing in mid-2000.

6.3 Communications

RF signal switching arrays and tracking filters based on MEMS switches and MEMS tunable capacitors offer performance enhancements for military secure communications systems [303]. Potential applications include the AIU (antenna interface unit) tracking filter for the F-22 Air Superiority Fighter, the AIU tracking filter for the RAH-66 Comanche helicopter and the preselector for the Joint Service ARC-210(V) military radio receiver.

The University of California, Berkeley is investigating MEMS microrelays for batch transfer integration in RF systems [304]. The LG Corporate Institute of Technology in Seoul, Korea is also investigating MEMS RF switches with very small actuation voltages [305].

The University of Michigan has a DARPA-funded project entitled "MEMS for wireless communications" [306]. The aims are to identify the performance limits for micro-mechanical resonators when extended into VHF, UHF and S-band ranges, implement high-Q micromechanical filters and oscillators in these ranges and incorporate these components into compact, inexpensive wireless transceivers. Development of high-Q resonators is discussed in [307] and [308] and micromechanical bandpass filters are discussed in [309].

California Institute of Technology is investigating submicron scale electromechanical systems (nanometre-scale electromechanical systems or NEMS) [310]. One of the main aims is the evaluation of the potential of NEMS for ultralow power, high frequency electroacoustic signal processing components. Future research is aimed at testing the limits to the applicability of NEMS, developing prototype NEMS components and expanding the technology base for producing and coupling NEMS.

6.4 Data storage

DARPA sponsors several projects to investigate communications and data storage applications of MEMS. This is an important area if MEMS are to be used as remote sensors or if communication between MEMS devices is required for coordinated action.

The goal of one DARPA-funded project being conducted by Carnegie Mellon University is to develop an ultra-high-density, miniature, rewritable cache for low-power communication of bursts of information from sensor arrays [311]. An example is for communication between systems used in situational awareness such as distributed millibots, nanosatellites or micro-air vehicles. The target specifications for the cache are 7 Gb capacity on an 8 x 8 mm magnetic media (10 Gb/cm^2) with a system footprint of 20 x 20 mm and a total system volume, including packaging of 2500 mm^3. Active power should be under 1 W and standby power under 10 mW. The data transfer rate should be over 17 Mb/s with access time under 10 ms.

The goals of a Cornell University project funded by DARPA [47] are to develop (using the "SCREAM" process described in Section 4.2) massively parallel scanned-probed arrays for high-density memory storage and high aspect ratio, single crystal silicon processes, devices and systems for communications and robotic applications.

Another DARPA-funded project investigating MEMS-based data storage is being conducted at the Hewlett Packard Laboratory [312]. The project appears to be concentrating on etching technology for producing high aspect ratio structures for components which will assist in the realisation of small, light, low power, rugged storage devices.

IBM is investigating high-density storage using MEMS [268]. A micro-actuator can improve the capacity and performance of current hard disk drives by moving the magnetic head with very high speed and accuracy.

Kionix are developing a ROM data storage card fabricated entirely from silicon MEMS [313]. The device is anticipated to have two chips, one containing a large element array of torsional z-actuators while the other is wafer-bonded directly below containing an x-y scanning stage. The data storage element is being evaluated for use in satellite applications, with environmental survivability during launch being one of the key facets.

The Corporate Institute of Technology in Seoul, Korea is investigating an actuated micromirror for nano-tracking of a laser beam for high-density optical storage [219]. The integrated micromirror is translated along the out-of-plane vertical direction (up to several micrometers) by metal/PZT/metal thin film actuators.

The IBM Research Division, Zurich Research Laboratory is investigating NEMS for high-density data storage [314]. The device has an array of 32 x 32 (1024) 2D cantilevers in a chip measuring 3 mm x 3 mm. It uses thermomechanical writing to locally soften a thin polymer film with a heated tip, simultaneously applying light pressure to put nanometre scale indentations representing the bits of information. On reading, the depth of indentation is measured using the heater platform in a low-power mode as a thermal sensor, measuring the rate of heat loss to the storage medium, which increases when the probe is in an indentation due to the greater contact area.

6.5 Reaction / combustion / power generation

Palladium-based micromembranes that can control hydrogen flux have been fabricated at MIT funded by the DARPA MicroFlumes program [63]. The membranes can be used for hydrogen purification or hydrogenation/dehydrogenation reactions.

A microscale combustor/evaporator is being developed by Pacific Northwest National Laboratory (operated by Battelle) under a DARPA contract [315]. Progress on aspects of this work has also been reported in several other publications [316, 317, 318]. The device uses microscale flow channels that increase the available surface area for heat transfer and reduce the fluid boundary layer, giving heat fluxes in excess of 25 W/cm^2 and thermal efficiencies of 80 - 90%. There are several possible defence applications in the area of man-portable power, heating and cooling.

The aim of a project being performed by Battelle and Case Western Reserve University for DARPA is to demonstrate an integrated liquid fuel cell/fuel processor for microscale power generation [319, 320]. Wireless MEMS require electrical power for operation and communication and current technology cannot produce batteries with the energy and power densities required and which are of a size comparable to the MEMS device. Consequently, alternatives to batteries are being investigated. The device that is the object of the current study uses a liquid fuel, a fuel processor that produces hydrogen from the liquid fuel and a fuel cell that produces electric power from the hydrogen. The initial demonstration involves a device that will produce 10 mWe (milliWatts electric) from a clean liquid fuel such as methanol or butane followed by a device that will produce 50 mWe from a logistics fuel such as JP-8.

Another project investigating a fuel processor is being conducted at MIT [321]. The microprocessor is designed to convert a chemical fuel into a form usable for electric power generation. Technologies to be investigated include hydrogen generation by ammonia and propane cracking, hydrogen purification using inorganic membranes and thermoelectric and thermophotovoltaic power generation. The microsystem will consist of integrated catalytic microreactors [322, 323], flow sensors, heaters, temperature sensors, microvalves, micropumps and controllers.

Georgia Institute of Technology [324] and Honeywell [325] are working on microscale combustion engines for electrical power generation. The University of California, Berkeley is looking at a MEMS rotary internal combustion engine [326].

The goal of a project being conducted by the University of Southern California is to fabricate miniature power generators with no moving parts that are capable of powering MEMS devices [327]. If sufficient power can be generated, the project will investigate the replacement of batteries in large man-portable systems such as weapons, computers, radios and GPS receivers. The microgenerator will be designed to burn readily available fuels such as butane.

Silicon atomisers developed by BF Goodrich are being tested by NAWC - China Lake as part of a liquid-fuelled active combustion control system for model ramjet dump combustors [328].

Workers at the Fraunhofer-Institut für Chemische Technologie ICT, at its annual meeting in 2000, reported on the potential of microreactors for the synthesis of energetic materials [329] and the monitoring of nitration reactions in microreactors using Fourier transform infrared microscopy [330].

6.6 Rotors, turbines and motors

The University of Wisconsin is investigating a rotor manufactured by surface micromachining that is driven using a piezoelectric plate mounted at the back of the silicon dye, thus eliminating the need for electrical interconnects [331]. The University of Neuchâtel is also investigating piezoelectric motors, although using the elastic force motor (EFM) concept [332]. The EFM principle involves generating an oscillating vertical motion in a stator by a piezoelectric layer operating at the resonance frequency of the stator. This vertical motion is then converted to rotation by elastic beams on a rotor. The initial impetus for the EFM work was the development of a motor for wristwatch applications, which require motors with small dimensions, high torque (1 μNm) and low power consumption (10 μW).

MIT have fabricated a micro turbine/bearing rig using a 5-level wafer-bonded micromachining [333]. The fabrication process can be used to build devices with complicated microfluidic connections with applications in micro-valves, pumps, coolers and propulsion devices.

6.7 Propulsion Systems

A DARPA-funded project at MIT is examining MEMS-based control for air breathing propulsion [334]. The aim is to develop flow control suitable for gas turbine engines, in particular control of tip leakage flows and control of engine noise from hot jet exhausts, using MEMS shear and temperature sensors and micro glow discharge actuators.

The University of Michigan is investigating micromachined acoustic ejectors that are based on the principle of Helmholtz resonators, in which entrapped air resonates at a characteristic frequency. [335, 336]. They will have a thrust-to-weight ratio of greater than 10, no rotating or sliding parts, low power operation and negligible thermal signature. The ejectors will be integrated into large arrays which can be used as the primary propulsion fro Micro Airborne Robotics Platforms and Constellations.

The use of MEMS actuators to reduce high cycle fatigue in turbine engines is being explored at the Virginia Polytechnical and State University using Surface Acoustic Wave (SAW) microsensors (see discussion of SAWs in Section 5.1.3) [337]. The microsensors will be used for flow measurements and MEMS-based microvalves will be used for active flow control.

6.8 Digital Micropropulsion

There is a large DARPA-sponsored project (US$3.5m [338]) to investigate digital micropropulsion [339, 340]. The work is being jointly conducted by TRW, the Aerospace Corporation and the California Institute of Technology. Reports of this work have appeared in the popular science literature, including Technology Review [341], Scientific American [342] and New Scientist [343]. In addition, a paper was presented at an IEEE meeting [344] and an article was published in Sensors and Actuators [345].

The aim of the digital micropropulsion project is to develop micro-rocket engines for control of micro-satellites, nano-satellites ("nanosats" [346]) and spacecraft [340]. Each engine is a chamber filled with a gaseous, liquid or solid propellant with a heater at one end and a burst disk at the other [339]. The heater either ignites the propellant or heats the gas in the chamber, the disk bursts under the pressure and the escaping gas delivers an impulse force to the satellite or spacecraft. Each engine is smaller than the head of a pin and will be fabricated in arrays of up to 10^4 - 10^6 engines.

Some of the advantages of digital micropropulsion over conventional rocket propulsion technology include [339, 340]:

- propulsion systems of the same order of size as the other components of the vehicle;
- vastly reduced number of parts;
- no moving parts;
- no tanks, lines or valves; and
- the ability to deliver thrust in very precise and predetermined amounts.

The first microthrusters in the program were fired in vacuum in September (1998). Microthrusters were first launched into space in July 1999 aboard the Space Shuttle Columbia, but were not fired; however, further launches are planned.

6.9 Weapons systems fuzing / safety and arming

The US Army Armament Research Development and Engineering Center (ARDEC) is developing a MEMS-based safety and arming (S&A) device for 20 mm projectiles for the Objective Individual Combat Weapon (OICW) [347]. The goal is to demonstrate a functional MEMS S&A device. The approach is to conceive and develop MEMS component elements such as zigzag (inertial delay) sliders, arming sliders, biasing springs, sequential actuating interlocks, inertial actuators and a "micro-energetic initiator" (MEI). These will then be developed, fabricated, optimised and combined to give an architecture that will accomplish the S&A function.

Another project to investigate MEMS fuzing and S&A devices is being conducted at the US Naval Surface Warfare Center [348]. The main focus here is for torpedoes, where a wide spectrum of MEMS sensors (accelerometers, IMUs, and magnetic, acoustic, pressure and flow sensors) can be utilised. Also being developed is a generic miniaturized explosive train and fireset that will be compatible with a MEMS fuze and S&A device and a macro-sized warhead. The design uses a low-cost ceramic detonator chip fabricated by Cronos/MCNC.

Integrated Sensing Systems is collaborating with NWSC to incorporate its CAPS devices into fuzing and safety and arming applications [60].

6.10 Materiel health monitoring and condition-based maintenance

The George Washington University Institute for MEMS and VLSI is investigating military applications of MEMS [349]. In particular, they are reviewing defence prospects for the use of radio frequency (RF) MEMS, developing concepts for Application Specific Integrated Microsystems (ASIMs) and promoting the insertion of MEMS into major military acquisition programs to reduce life-cycle costs. The main target is new classes of US Navy ships where the fitting of over 100 000 microsensors per ship will enable such advances as condition-based maintenance, reducing required staffing levels and consequential costs.

The US Office of Naval Research is funding a team of universities and companies to continue research into Remotely-Queried Embedded Microsensors (RQEM), sensors such as strain gauges to be embedded in composite structures for the lifetime of the structure and which can be queried using methods that do not require hard connections [350]. An integrated embeddable sensor package has been developed which can measure three components of strain and temperature within a graphite-epoxy or other aerospace composite [350, 351]. To test their robustness, RQEM devices have been deployed on the USS Radford and on a Boeing AV-8B Harrier T1 aircraft [352]. Both devices survived the electromagnetic, vibration, temperature and acoustic environments of the platforms and remain installed for future analysis.

Pennsylvania State University are applying MEMS to structural health monitoring of critical aircraft components [353]. Various sensors (acoustic, strain, acceleration an vibration) are integrated with signal processing electronics to provide real-time indicators of incipient failure of aircraft components.

Health monitoring and condition-based maintenance of weapon propulsion systems will be discussed in detail in a future publication [354].

7. Conclusions

One method of classifying MEMS technology research is into four general areas: fabrication, structures, devices and applications. Materials may be fabricated into structures, which in turn can be combined into devices for particular applications. Sensor and actuator devices can also be linked together with appropriate feedback electronics to form active control units, giving accurate local control with very fast response times.

Materials for MEMS are primarily based around silicon, because it is readily and economically available from the integrated circuit industry. Silicon oxide is useful as a sacrificial layer for etching, silicon nitride for MEMS structures and silicon carbide for resistance to harsh environments. Polymers and plastics are also useful for certain applications, such as gas sensing, but are more difficult to micromachine. New materials under investigation for manufacturing MEMS include amorphous alloys, polycaprolactone, tantalum oxide and diamond.

New methods of deep etching and lithography are now available which produce high aspect ratio microstructures (HARMs). For example, the LIGA process uses X-rays to produce a high aspect ratio mould from which to fabricate HARMs. However, the process is expensive and inconvenient due to the requirement for collimated X-rays from a synchrotron.

Many MEMS sensors have been produced, or are being developed, for measuring pressure, load, vibration, acceleration, rotation, magnetic fields, air flow, liquid flow, shear stress, strain, infrared detection, infrared and visible imaging, and chemical detection and analysis. MEMS actuators have been developed using various methods of activation, including magnetic, piezoelectric and thermal. Applications include mirrors, valves, pumps, mixers, power switches, pressure switches, relays and aerial vehicle control surfaces. MEMS sensors and actuators may be combined to form integrated systems for active control. Applications include orifice-based control of microjets, aerodynamic control of an UAV without a tail for low altitude surveillance, drag reduction on control surfaces and a gas pressure control unit.

Modelling and simulation is also a very active area of MEMS research. Studies include modelling of effects such as surface tension on manufacturing, sensor sensitivity, gas flow and fluid viscosity in micro devices, noise, and optimisation of manufacturing, components and devices.

This document has attempted to present a "snapshot" of current research in MEMS technology with potential applications to defence, based on material available to the author at the end of the year 2000. This survey was undertaken as a prelude to a more focussed study addressing applications of MEMS in rocket propulsion systems for control and health monitoring.

It can be seen from the discussion above that there is an enormous amount of research currently being conducted into MEMS technology. A large amount of research is directed at defence applications, much of which is sponsored in the US by the Defense Advanced Research Projects Agency (DARPA). Defence applications for MEMS devices include weapons safety, arming and fuzing, personal / vehicle navigation, condition-based maintenance, situational awareness, identify-friend-or-foe, miniature analytical instruments, power generation, propulsion, biomedical devices, mass data storage and displays. Many of these applications are not unique to defence, and devices developed for defence will, no doubt, find service in the civilian and commercial fields, and vice versa.

8. References

1. Brendley, K.W. and Steeb, R., Military applications of microelectromechanical systems, MR-175-OSD/AF/A, Rand, Santa Monica (1993).

2. Pisano, A.P. in Maluf, N., An introduction to Microelectromechanical Systems Engineering, Artech House, Boston (2000).

3. Maluf, N., An introduction to Microelectromechanical Systems Engineering, Artech House, Boston (2000).

4. Kamisuki, S., Fujii, M., Takekoshi, T., Tezuka, C. and Atobe, M., A high resolution, electrostatically-driven commercial inkjet head, in B2 [5], pp. 793 – 798.

5. DARPA Microsystems Technology Office Core Technology Areas (26/09/2000): http://www.darpa.mil/MTO/RADPrograms.html

6. US Department of Defense FY2001 budget estimates – research, development, test and evaluation, defense wide: Volume 1 – Defense Advanced Research Projects Agency (26/09/2000): http://www.dtic.mil/comptroller/fy2001budget/budget_justification/pdfs/rdtande/fy01pb_darpa.pdf

7. DARPA MEMS project summaries (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/index.html

8. Kovacs, G.T.A., Maluf, N.I. and Petersen, K.E., Bulk micromachining of silicon, Proc. IEEE, **86(8)**, pp. 1536 – 1551 (1998).

9. Bustillo, J.M., Howe, R.T. and Muller, R.S. Surface micromachining for microelectromechanical systems, Proc. IEEE, **86(8)**, pp. 1552 – 1574 (1998).

10. Wang, M., Meng, Z., Zohar, Y. and Wong, M., A new polycrystalline silicon technology for integrated sensor applications, in B2, pp. 114 – 119.

11. Winchester, K., Spaargaren, S.M.R. and Dell, J.M., Transferable silicon nitride cavities, in B14, pp. 142 – 151.

12. Kazinczi, R., Mollinger, J.R. and Bossche, A., New failure mechanism in silicon nitride resonators, in B2, pp. 229 – 234.

13. Mehregany, M., Zorman, C.A., Rajan, N. and Wu, C.H., Silicon carbide MEMS for harsh environments, Proc. IEEE, **86(8)**, pp. 1594 – 1610 (1998).

---

[5] refers to item 2 in the Bibliography below.

14. Materials and processes for SiC MEMS, Case Western Reserve University, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_17.html

15. Yasseen, A.A., Wu, C.-H., Zorman, C.A. and Mehregany, M., Fabrication and testing of surface micromachined silicon carbide micromotors, in B3, pp. 644 - 649.

16. Burla, R.K., Roy, S., Haria, V.M., Zorman, C.A. and Mehregany, M., High temperature testing of nickel wire bonds for SiC devices, in B9, pp. 324 – 333.

17. Rajan, N., Mehregany, M., Zorman, C.A., Stefanescu, S. and Kicher, T.P., Fabrication and testing of micromachined silicon carbide and nickel fuel atomizers for gas turbine engines, JMEMS, **8(3)**, pp. 251 – 257 (1999).

18. Gutierrez Monreal, J. and Mari, C.M., The use of polymer materials as sensitive elements in physical and chemical sensors, Sensors and Actuators, **12**, pp. 129 - 144 (1987).

19. Microfabrication techniques for plastic MEMS, University of Michigan, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_69.html

20. New organic materials and processes for MEMS, Harvard University, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_28.html

21. Saotome, Y. and Inoue, A., New amorphous alloys as micromaterials and the processing technologies, in B2, pp. 288 – 293.

22. Armani, D.K. and Liu, C., Microfabrication technology for polycaprolactone, a biodegradable polymer, in B2, pp. 294 – 299.

23. Christensen, C., de Reus, R. and Bouwstra, S., Tantalum oxide thin films as protective coatings for sensors, J. Micromech. Microeng., **9(2)**, pp. 113 – 118 (1999).

24. Christensen, C., de Reus, R. and Bouwstra, S., Tantalum oxide thin films as protective coatings for sensors, in B3, pp. 267 – 272.

25. Franke, A.E., Bilic, D., Chang, D.T., Jones, P.T., King, T.-J., Howe, R.T. and Johnson, G.C., Post-COMS integration of germanium microstructures, in B3, pp. 630 – 637.

26. Li, B., Xiong, B., Jiang, L., Zohar, Y. and Wong, M., Applications of germanium to low temperature micro-machining, in B3, pp. 638 – 643.

27. Li, B., Xiong, B., Jiang, L., Zohar, Y. and Wong, M., Germanium as a versatile material for low-temperature micromachining, JMEMS, **8(4)**, pp. 366 – 372 (1999).

28. Shibata, T., Kitamoto, Y., Unno, K. and Makino, E., Micromachining of diamond film for MEMS applications, JMEMS, **9(1)**, pp. 47 – 51 (2000).

29. Bean, K.E., Anisotropic etching of silicon, IEEE Transactions on Electron Devices, ED-25 (10), pp. 1185 – 1193 (1978). Reproduced in B1, pp. 50 – 57.

30. Sturland, I.M., Design, fabrication and mechanical issues relating to the use of micro-engineered devices in future guided weapons, in B52, pp 3.1 – 3.8.

31. Munch, U., Brand, O., Paul, O., Baltes, H. and Bossel, M., Metal film protection of CMOS wafers against KOH, in B2, pp. 608 – 613.

32. French, P.J., Integration of MEMS devices, in B14, pp. 55 – 64.

33. Yan, G.-z., Chan, P.C.H., Hsing, I.-M., Sharma, R.K. and Sin, J.K.O., An improved TMAH Si-etching solution without attacking exposed aluminum, in B2, pp. 562 - 567.

34. Shikida, M., Sato, K., Tokoro, K. and Uchikawa, D., Comparison of anisotropic etching properties between KOH and TMAH solutions, in B3, pp. 315 – 320.

35. Sekimura, M., Anisotropic etching of surfactant-added TMAH solution, in B3, pp. 650 – 655.

36. Li, X., Abe, T. and Esashi, M., Deep reactive ion etching of Pyrex glass, in B2, pp. 271 – 276.

37. Ohara, J., Kano, K., Takeuchi, Y., Ohya, N., Otsuka, Y. and Akita, S., A new deep reactive ion etching process by dual sidewall protection layer, in B2, pp. 277 - 282.

38. Chabloz, M., Jiao, J., Yoshida, Y., Matsuura, T. and Tsutsumi, K., A method to evade microloading effect in deep reactive ion etching for anodically bonded glass-silicon structures, in B0, pp. 277 – 282.

39. De Los Santos, H.J., Introduction to Microelectromechanical (MEM) Microwave Systems, Artech House, Boston (1999).

40. Ueno, H., Nishi, N. and Sugiyama, S., Fabrication of sub-micron structures with high aspect ratio for MEMS using deep X-ray lithography, in B2, pp. 596 – 601.

41. Khan Malek, C. and Siale, V., Application domains for synchrotron radiation sources of various energies, in B14, pp. 60 – 68.

42. Khan Malek, C. and Thomas, L., High-aspect-ratio electroformed Ni-Co microstructures with improved mold adhesion using a LIGA-like process and a Novolak sublayer, in B10, pp. 484 – 491.

43. Egashira, M., Shinya, N. and Saito, H., Development of focused micro-sized particle beam technology and its application to micro-fabrication, in B26, pp. 141 - 147.

44. Christenson, T.R. and Schmale, D.T., A batch wafer scale LIGA assembly and packaging technique via diffusion bonding, in B3, pp. 476 – 481.

45. Hartley, F.T. and Khan Malek, C., Nanometer X-ray lithography, in B14, pp. 69 - 79.

46. Shaw, K.A., Zhang, Z.L. and MacDonald, N.C., SCREAM I: A single mask, single-crystal silicon, reactive ion etching process for microelectromechanical structures, Sensors and Actuators, **A40**, pp. 63 – 70 (1994).

47. SCREAM MEMS for communications and atomic manipulation, Cornell University, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_18.html

48. Lee, C.S.B., Han, S. and MacDonald, N.C., Single crystal silicon (SCS) x-y-stage fabricated by DRIE and IR alignment, in B2, pp. 28 – 33.

49. Tay, F.E.H., Logeeswaran, V.J. and Liang, Y.C., A SCREAM micromachined high aspect ratio low-g microaccelerometer, in B10, pp. 344 – 353.

50. Lee, C.S.B., Webb, R.Y., Chong, J.M. and MacDonald, N.C., Single crystal silicon (SCS) micromirror arrays using deep silicon etching and IR alignment, in B2, pp. 441 - 448.

51. Fuller, S. and Jacobson, J., Ink jet fabricated nanoparticle MEMS, in B2, pp. 138 - 141.

52. Klintberg, L., Thornell, G. and Johansson, S., Drop-by-drop deposition of ceramic slurry for fabrication of PZT microstructures, in B14, pp. 158 – 165.

53. Wensink, H., Berenschot, J.W., Jansen, H.V. and Elwenspoek, M.C., High resolution powder blast micromachining, in B2, pp. 769 – 774.

54. Lee, G.S., Jin, Y.Y., Park, S.J., Ajmera, P.K., Khan Malek, C., Wang, J.T. and Tang, F., A LIGA-like process for high-aspect ratio PZT microstructures, in B26, pp. 127 - 132.

55. Direct writing for three-dimensional microfabrication using synchrotron radiation etching, in B2, pp. 556 – 561.

56. Ohji, H., Gennissen, P.T.J., French, P.J. and Tsutsumi, K., Fabrication of accelerometer using single-step electrochemical etching for micro structures (SEEMS), in B3, pp. 61 – 65.

57. Mechanical properties of MEMS materials, Johns Hopkins University, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_35.html

58. MEMS heat exchangers for harsh environments, Louisiana State University, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_38.html

59. Applications and mass production of high aspect ratio microstructures, Louisiana State University, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_39.html

60. Flexible manufacturing of dissolved-wafer silicon capacitive sensors (CAPS), Integrated Sensing Systems, Inc., DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_34.html

61. Injectable ceramic microcast SiCN MEMS for extreme temperature environments, University of Colorado, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_64.html

62. An, L., Zhang, W., Bright, V.M., Dunn, M.L. and Raj, R., Development of injectable polymer-derived ceramics for high temperature MEMS, in B2, pp. 619 - 623.

63. Franz, A.J., Jensen, K.F. and Schmidt, M.A., Palladium based micromembranes for hydrogen separation and hydrogenation/dehydrogenation reactions, in B3, pp. 382 – 387.

64. Chun, K., Hashiguchi, G., Toshiyoshi, H., Fujita, H., Kikuchi, Y., Ishikawa, J., Murakami, Y. and Tamiya, E., An array of hollow microcapillaries for the controlled injection of genetic materials into animal/plant cells, in B3, pp. 406 - 411.

65. Wang, X.-Q., Desai, A., Tai, Y.-C., Licklider, L. and Lee, T.D., Polymer-based electrospray chips for mass spectrometry, in B3, pp. 523 – 528.

66. Rusu, C., van't Oever, R., de Boer, M., Jansen, H., Berenschot, E., Elwenspoek, M., Bennink, M.L., Kanger, J.S., de Grooth, B.G., Greve, J., Brugger, J. and van den

Berg, A., Micromachined pipettes integrated into a flow channel for single DNA molecule study by optical trapping, in B49, pp. 41 – 49.

67. Brenner, W., Haddad, Gh., Rennhofer, H., Rennhofer, M., Vujanic, A. and Popovic, G., New types of silicon torsion microspring and their characterisation, in B10, pp. 462 – 470.

68. Hui, E.E., Howe, R.T. and Rodgers, M.S., Single-step assembly of complex 3-D microstructures, in B2, pp. 602 – 607.

69. MEMS and solder self-assembly for 3-D MEMS and MEMS arrays, University of Colorado, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_65.html

70. Massively parallel post-packaging for MEMS, University of Michigan, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_71.html

71. Vacuum Packaging for MEMS, Raytheon Systems Corporation, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_46.html

72. Kim, J., Bolle, C.A., Boie, R.A., Gates, J.V., Ramirez, A.G., Jin, S. and Bishop, D.J., Integration and packaging of MEMS relays, in B10, pp. 333 – 341.

73. Pocha, M.D., Garrett, H.E., Patel, R.R., Jones II, L.M., Larson, M.C., Emanuel, M.A., Bond, S.W., Deri, R.J., Drayton, R.F., Petersen, H.E. and Lowry, M.E., Glass, plastic and semiconductors: packaging techniques for miniature optoelectronic components, in B49, pp. 130 – 140.

74. Lebouitz, K.S., Mazaheri, A., Howe, R.T. and Pisano, A.P., Vacuum encapsulation of resonant devices using permeable polysilicon, in B3, pp. 470 – 475.

75. Maharbiz, M.M., Cohn, M.B., Howe, R.T., Horowitz, R. and Pisano, A.P., Batch micropackaging by compression-bonded wafer-wafer transfer, in B3, pp. 482 - 489.

76. Tixier, A., Mita, Y., Oshima, S., Gouy, J.-P. and Fujita, H., 3-D microsystem packaging for interconnecting electrical, optical and mechanical microdevices to the external world, in B2, pp. 698 – 703.

77. Kim, E.-S., Cho, Y.-H. and Kim, M.-U., Effect of holes and edges on the squeeze film damping of perforated micromechanical structures, in B3, pp. 296 – 301.

78. Chavan, A.V. and Wise, K.D., A monolithic fully-integrated vacuum-sealed CMOS pressure sensor, in B2, pp. 341 – 346.

79. Chen, Q. and Carman, G.P., Microscale tribology (friction) measurement and influence of crystal orientation and fabrication process, in B2, pp. 657 – 661.

80. Long term stability of MEMS arrays, Exponent Failure Analysis Associates Inc., DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_24.html

81. Fatigue of polysilicon MEMS devices, University of California, Berkeley, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_55.html

82. He, Y., Marchetti, J., Gallegos, C. and Maseeh, F., Accurate fully-coupled natural frequency shift of MEMS actuators due to voltage bias and other external forces, in B3, pp. 321 – 325.

83. Mukherjee, T., Zhou, Y. and Fedder, G.K., Automated optimal synthesis of microaccelerometers, in B3, pp. 326 – 331.

84. van Suchtelen, J., Sato, K., van Veenendaal, E., Nijdam, A.J., Gardeniers, J.G.E., van Enckevort, W.J.P. and Elwenspoek, M., Simulation of anisotropic wet-chemical etching using a physical model, in B3, pp. 332 – 337.

85. Minami, K., Matsunaga, T. and Esashi, M., Simple modeling and simulation of the squeeze film effect and transient response of the MEMS device, in B3, pp. 338 - 343.

86. Kucherenko, S.S. and Leaver, K.D., Modelling effects of surface tension on surface topology in spin coatings for integrated optics and micromechanics, J. Micromech. Microeng., **10(3)**, pp. 299 – 308 (2000).

87. White, R.M., A sensor classification scheme, IEEE Trans. Ultrason. Ferroelec. Freq. Contr., UFFC-34 (2), pp. 124 – 126 (1987). Reproduced in B38, pp 3 – 5.

88. Petersen, K.E., Silicon as a mechanical material, Proc. IEEE, **70(5)**, pp. 420 –457 (1982). Reprinted in B1, pp. 58 – 95 and B38, pp 39 – 76.

89. Angell, J.B., Terry, S.C. and Barth, P.W., Silicon micromechanical devices, Scientific American, 248, pp 44 – 55 (1983). Reprinted in B1, pp. 38 – 49.

90. Kato, S., Watanabe, T., Kato, C., Suzuki, Y., Kamimura, K., Suzuki, H., Suzuki, K., Hamanaka, H. and Ikeda, K., High-precision silicon differential pressure sensor

monolithically integrated with twin diaphragms and micro over-range protection structures, in B2, pp. 347 – 351.

91. Wang, C.C., Gogoi, B.P., Monk, D.J. and Mastrangelo, C.H., Contamination insensitive differential capacitive pressure sensors, in B2, pp. 551 – 555.

92. Park, J.-S. and Gianchandani, Y.B., A low cost batch-sealed capacitive pressure sensor, in B3, pp. 82 – 87.

93. Gogoi, B.P. and Mastrangelo, C.H., A low-voltage force-balanced pressure sensor with hermitically sealed servomechanism, in B3, pp. 493 – 498.

94. English, J.M. and Allen, M.G., Wireless micromachined ceramic pressure sensors, in B3, pp. 511 – 516.

95. Chowdhury, S., Jullien, G.A., Ahmadi, M.A., Miller, W.C., Keating, D. and Finch, N., Acoustic and magnetic MEMS components for a hearing aid instrument, in B10, pp. 122 – 133.

96. Bay, J., Hansen, O. and Bouwstra, S., Micromachined double backplate differential capacitive microphone, J. Micromech. Microeng., **9(1)**, pp. 30 – 33 (1999).

97. Dunn, W.F., Integrated MEMS based IQ intelligent tire applications, in B26, pp. 77 - 83.

98. Mei, T., Ge, Y., Chen, Y., Ni, L., Liao, W.-H., Xu, Y. and Li, W.J., Design and fabrication of an integrated three-dimensional tactile sensor for space robotic applications, in B3, pp. 112 – 117.

99. Takizawa, H., Tosaka, H., Ohta, R. Kaneko, S. and Ueda, Y., Development of a microfine active bending catheter equipped with MIF tactile sensors, in B3, pp. 412 - 417.

100. Shaligram, A.D., Apte, P.R., Gharpure, D.C. and Sudha, L., Design of an hybrid silicon-fiber optic pressure sensing array for tactile sensing, in B15, pp. 216 – 222.

101. Dargahi, J., Parameswaran, M. and Payandeh, S., A micromachined piezoelectric tactile sensor for an endoscopic grasper – theory, fabrication and experiments, JMEMS, **9(3)**, pp. 329 – 335 (2000).

102. Wiegerink, R., Zwijze, R., Krijnen, G., Lammerink, T. and Elwenspoek, M., Quasi monolithic silicon load cell for loads up to 1000 kg with insensitivity to non-homogeneous load distributions, in B3, pp. 558 – 563.

103. Oja, A., Sillanpää, T., Seppä, H., Kiihamäki, J., Seppälä, P., Karttunen, J. and Riski, K., Micromechanical silicon precision scale, in B10, pp. 498 – 505.

104. Gupta, A., Singh, R., Jain, V.K. and Kumar, V., Development of micromachined vibration sensors for MEMS applications, in B15, pp. 153 – 161.

105. Yazdi, N., Ayazi, F. and Najafi, K., Micromachined inertial sensors, Proc. IEEE, **86(8)**, pp. 1640 – 1659 (1998).

106. Saha, I., Islam, R., Kanakaraju, K., Jain, Y.K. and Alex, T.K., Silicon micromachined accelerometers for space inertial systems, in B15, pp. 162 – 170.

107. Partridge, A., Reynolds, J.K., Chui, B.W., Chow, E.M., Fitzgerald, A.M., Zhang, L., Maluf, N.I. and Kenny, T.W., A high-performance planar piezoresistive accelerometer, JMEMS, **9(1)**, 58 – 66 (2000).

108. Varadan, V.K., Xavier, P., Varadan, V.V., Suh, D., Atashbar, M. and Jose, K.A., MEMS-IDT based accelerometers and gyroscopes, in B26, pp. 182 – 189.

109. Piscotty, D., Jose, K.A., Varadan, V.V. and Varadan, V.K., Design and development of 150 MHz wireless telemetry system for MEMS-IDT based sensor, in B26, pp. 165 – 172.

110. Guldimann, B., Thiébaud, P., de Rooij, N.F. and Turpin, R.A., Micromachined, fiber-optic based accelerometer with shutter modulation, in B0, pp. 710 – 714.

111. Bochobza-Degani, O., Seter, D.J., Socher, E., Kaldor, S., Scher, E. and Nemirovsky, Y., Comparative study of novel micromachined accelerometers employing MIDOS, in B3, pp. 66 – 71.

112. Trieu, H.K., Knier, M., Köster, O., Kappert, H., Schmidt, M. and Mokwa, W., Monolithic integrated surface micromachined pressure sensors with analog on-chip linearization and temperature compensation, in B2, pp. 547 – 550.

113. Takao, H., Fukumoto, H. and Ishida, M., Fabrication of a three-axis accelerometer integrated with commercial 0.8 μm-CMOS circuits, in B2, pp. 781 – 786.

114. Sun, W., Ho, W.-T., Li, W.J., Mai, J.D. and Mei, T., A foundry fabricated high-speed rotation sensor using off-chip RF wireless signal transmission, in B2, pp. 358 - 363.

115. Kubena, R.L., Vickers-Kirby, D.J., Joyce, R.J. and Stratton, F.P., A new tunneling-based sensor for inertial rotation rate measurements, JMEMS, **8(4)**, pp. 439 – 447 (1999).

116. Funk, K., Emmerich, H., Schilp, A., Offenberg, M., Neul, R. and Lärmer, F., A surface micromachined silicon gyroscope using a thick polysilicon layer, in B3, pp. 57 – 60.

117. Abe, M., Shinohara, E., Hasegawa, K., Murata, S. and Esashi, M., Trident-type tuning fork silicon gyroscope by the phase difference detection, in B2, pp. 508 - 513.

118. Mochida, Y., Tamura, M. and Ohwada, K., A micromachined vibrating rate gyroscope with independent beams for the drive and detection modes, in B3, pp. 618 - 623.

119. Song, H., Oh, Y.S., Song, I.S., Kang, S.J., Choi, S.O., Kim, H.C., Ha, B.J., Baek, S.S. and Song, C.M., Wafer level vacuum packaged de-coupled vertical gyroscope by a new fabrication process, in B2, pp. 520 – 524.

120. Baek, S.S., Oh, Y.S., Ha, B.J., An, S.D., An, B.H., Song, H. and Song, C.M., A symmetrical z-axis gyroscope with a high aspect ratio using simple and new process, in B3, pp. 612 – 617.

121. An, S., Park, K.Y., Oh, Y. and Song, C., Two-input axis angular rate sensor, in B26, pp. 219 – 229.

122. Zheng, L., Asundi, A.K., Liu, A.Q. and Chollet, F., Polysilicon surface micromachined optical rotating sensor, in B26, pp. 202 – 209.

123. Emmerich, H., Schöfthaler, M. and Knauß, U., A novel micromachined magnetic-field sensor, in B3, pp. 94 – 99.

124. Latorre, L., Beroulle, V., Bertrand, Y., Nouet, P. and Salesse, I., Micromachined CMOS magnetic field sensor with ferromagnetic actuation, in B10, pp. 398 – 405.

125. Development of high-g accelerometers integrated with support circuitry using SOI-MEMS fabrication, Integrated Micro Instruments, Inc., DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_33.html

126. Micromachined precision inertial instruments, University of Michigan, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_70.html

127. Yazdi, N., Salian, A. and Najafi, K., A high sensitivity capacitive microaccelerometer with a folded-electrode structure, in B3, pp. 600 – 605.

128. Valoff, S. and Kaiser, W.J., Presettable micromachined MEMS accelerometers, in B3, pp. 72 – 76.

129. Integrated MEMS inertial measurement unit, Carnegie Mellon University, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_15.html

130. Xie, H. and Fedder, G.K., A CMOS z-axis capacitive accelerometer with comb-finger sensing, in B2, pp. 496 – 501.

131. Luo, H., Fedder, G.K. and Carley, L.R., A 1mG lateral CMOS-MEMS accelerometer, in B2, pp. 502 – 507.

132. Zhang, G., Xie, H., de Rosset, L.E. and Fedder, G.K., A lateral capacitive CMOS accelerometer with structural curl compensation, in B3, pp. 606 – 611.

133. Manufacturing low-cost MEMS inertial sensors, Draper Laboratory, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_21.html

134. High-g IMU on a chip, Draper Laboratory, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_22.html

135. Teichmann, H., Integrated optical sensors: New developments, Chapter 7 in B46.

136. Wu, S., Lin, Q., Yuen, Y. and Tai, Y.C., MEMS flow sensors for nano-fluidic applications, in B2, pp. 745 – 750.

137. Richter, M., Wackerle, M., Woias, P. and Hillerich, B., A novel flow sensor with high time resolution based on differential pressure principle, in B3, pp. 118 – 123.

138. Development of micro-resolution PIV and analysis of microthrusters for small scale aircraft and spacecraft, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_63.html

139. Koch, M., Evans, A.G.R. and Brunnschweiler, A., Design and fabrication of a micromachined Coulter counter, J. Micromech. Microeng., **9(2)**, pp. 159 – 161 (1999).

140. Goosen, J.F.L., French, P.J. and Sarro, P.M., Pressure, flow and oxygen saturation sensors on one chip for use in catheters, in B2, pp. 537 – 540.

141. Goosen, J.F.L., French, P.J. and Sarro, P.M., Pressure and flow sensor for use in catheters, in B16, pp. 38 – 45.

142. Jiang, F., Xu, Y., Weng, T., Han, Z. and Tai, Y.-C., Flexible shear stress sensor skin for aerodynamic applications, in B2, pp. 364 – 369.

143. Jiang, F., Tai, Y.-C., Walsh, K., Tsao, T., Lee, G.-B. and Ho, C.-H., A flexible MEMS technology and its first application to shear stress sensor skins, in B5, pp. 465 - 470.

144. Ozaki, Y., Ohyama, T., Yasuda, T. and Shimoyama, I., An air flow sensor modeled on wind receptor hairs of insects, in B2, pp. 531 – 536.

145. Xu, Y., Chiu, C.-W., Jiang, F., Lin, Q. and Tai, Y.-C., Mass flowmeter using a multi-sensor chip, in B2, pp. 541 – 546.

146. Low profile, low power, uni and multi-axial strain transducers (LP2-UAST&MAST), Sarcos Research Corporation, DARPA funded project summary (06/09/2000):
http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_48.html

147. Jacobsen, S.C., Maclean, B.J., Whitaker, M., Olivier, M. and Mladejovsky, M.G., Multiregime MEMS sensor networks for smart structures, in B0, pp. 19 – 32.

148. Que, L., Li, M.-H., Chu, L.L. and Gianchandani, Y.B., A micromachined strain sensor with differential capacitive readout, in B3, pp. 552 – 557.

149. Hautamaki, C., Zurn, S., Mantell, S.C. and Polla, D.L., Experimental evaluation of MEMS strain sensors embedded in composites, JMEMS, **8(3)**, pp. 272 – 279 (1999).

150. Jain, V.K. and Jalwania, C.R., Uncooled IR-sensor array based on MEMS technology, in B15, pp. 206 – 215.

151. Socher, E., Bochobza-Degani, O. and Nemirovsky, Y., Optimal performance of CMOS compatible IR thermoelectric sensors, JMEMS, **9(1)**, pp. 38 – 46 (2000).

152. Kim, J.-K. and Han, C.-H., A new uncooled thermal IR detector using silicon diode, in B2, pp. 102 – 107.

153. Mao, M., Perazzo, T., Kwon, O., Majumdar, A., Varesi, J. and Norton, P., Direct-view uncooled micro-optomechanical infrared camera, in B3, pp. 100 – 105.

154. MEMS direct view infrared vision system, Sarnoff Corporation, DARPA funded project summary (06/09/2000):
http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_51.html

155. Hoshino, K., Mura, F. and Shimoyama, I., A micro-sized visual sensor based on the fly's compound eye with a scanning retina, in B3, pp. 429 – 434.

156. Hoshino, K., Mura, F. and Shimoyama, I., Design and performance of a micro-sized biomorphic compound eye with a scanning retina, JMEMS, **9(1)**, pp. 32 – 38 (2000).

157. Ikeda, M., Totani, H., Akiba, A., Goto, H., Matsumoto, M. and Yada, T., PZT thin-film actuator driven micro optical scanning sensor by 3D integration of optical and mechanical devices, in B3, pp. 435 – 440.

158. Niwa, T., Kato, K., Ichihara, S., Chiba, N., Mitsuoka, Y., Oumi, M., Shinogi, M., Nakajima, K., Muramatsu, H., Sakuhara, T., Shikida, M. and Sato, K., Fabrication of optical micro-cantilever consisting of channel waveguide for scanning near-field optical microscopy controlled by atomic force, in B3, pp. 355 – 359.

159. Phan, N.M., Ono, T. and Esashi, M., A novel fabrication method of the tiny aperture tip on silicon cantilever for near field scanning optical microscopy, in B3, pp. 360 – 365.

160. Lange, D., Akiyama, T., Hagleitner, C., Tonin, A., Hidber, H.R., Niedermann, P., Staufer, U., de Rooij, N.F., Brand, O. and Baltes, H., Parallel scanning AFM with on-chip circuitry in CMOS technology, in B3, pp. 447 – 452.

161. Hagleitner, C., Lange, D., Akiyama, T., Tonin, A., Vogt, R. and Baltes, H., On-chip circuitry for a CMOS parallel scanning AFM, in B26, pp. 240 – 248.

162. Chand, A., Viani, M.B., Schäffer, T.E. and Hansma, P.K., Microfabricated small metal cantilevers with silicon tip for atomic force microscopy, JMEMS, **9(1)**, pp. 112 – 116 (2000).

163. Schöning, M.J., Glück, O., Kordos, P., Lüth, H. and Emons, H., Thin film electrodes for trace metal analysis by d.c. resistance changes, in B48, pp. 135 - 143.

164. The polychromator: a MEMS-based optical correlation spectrometer, Honeywell Technology Center, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_32.html

165. Kerness, N., Koll, A., Schaufelbühl, A., Hagleitner, C., Hierlemann, A., Brand, O. and Baltes, H., N-well based CMOS calorimetric chemical sensors, in B0, pp. 96 - 101.

166. Koll, A., Schaufelbühl, A., Schneeberger, N., Münch, U., Brand, O., Baltes, H., Menolfi, C. and Huang, Q., Micromachined CMOS calorimetric chemical sensor with on-chip low noise amplifier, in B3, pp. 547 – 551.

167. Koll, A., Kummer, A., Brand, O. and Baltes, H., Discrimination of volatile organic compounds using CMOS capacitive chemical microsensors with thickness adjusted polymer coating, in B26, pp. 308– 317.

168. Nguyen, C.T.-C., Micromechanical filters for miniaturized low-power communications, in B26, pp. 55 – 66.

169. Xu, T., Wu, G., Zhang, G., Wang, W. and Li, T., A novel micro gas sensor with high selectivity based on both mass and conductivity measurement, in B2, pp. 108 - 113.

170. Briand, D., van der Schoot, B., de Rooij, N.F., Sundgren, H. and Lundström, I. A., low-power micromachined MOSFET gas sensor, JMEMS, **9(3)**, pp. 303 – 308 (2000).

171. Dokmeci, M. and Najafi, K., A high-sensitivity polyimide humidity sensor for monitoring hermetic micropackages, in B3, pp. 279 – 284.

172. Marowsky, G., Lewitzka, F., Karlitschek, P., Bünting, U. and Niederkrüger, M., A miniaturised laser-induced fluorescence system with a fiber-optic probe for the analysis of aromatic compounds, in B47, pp. 2 – 9.

173. Harris, R.D., Quigley, G.R., Wilkinson, J.S., Klotz, A., Barzen, C., Brecht, A., Gauglitz, G. and Abuknesha, R.A., Waveguide immunofluorescence sensor for water pollution analysis, in B47, pp. 27 – 35.

174. Ehlert, A. and Büttgenbach, S., Automatic sensor system for groundwater monitoring network, in B48, pp. 61 – 69.

175. Josse, F., Zhou, R., Patel, R. and Menon, A., Real-time, on-line detection of organic compounds in aqueous environments using polymer-coated QCRs, in B47, pp. 64 – 73.

176. Josse, F., Zhou, R., Altindal, A., Dabak, S. and Bekaroglu, Ö, Study of the sensitive properties of soluble dodecylsulfanyl phthalocyanines for organic vapors using impedance spectroscopy and QCR, in B47, pp. 74 – 84.

177. Josse, F., Dahint, R., Shah, S. and Houndegla, E., Metal ion solutions identification using acoustic plate mode sensors and principal component analysis, in B48, pp. 2 – 13.

178. Schneider, T.W., Frye-Mason, G.C., Martin, S.J., Spates, J.J., Bohuszewicz, T.V., Osbourn, G.C. and Bartholomew, J.W., Chemically selective coated quartz crystal

microbalance (QCM) array for detection of volatile organic chemicals, in B47, pp. 85 - 94.

179. Doll, T. and Eisele, I., Gas detection with work function sensors, in B47, pp. 96 - 105.

180. Bender, S. and Mokwa, W., Temperature stabilized silicon based surface-acoustic-wave gas sensors for the detection of solvent vapours, in B47, pp. 123 - 130.

181. Cernosek, R.W., Yelton, W.G., Colburn, C.W., Anderson, L.F., Staton, A.W., Osbourn, G.C., Bartholomew, J.W., Martinez, R.F., Ricco, A.J. and Crooks, R.M., Detection of volatile organics using a surface acoustic wave array system, in B48, pp. 146 – 157.

182. Grate, J.W. and Wise, B.M., Chemical information from polymer-coated acoustic wave sensor arrays, in B48, pp. 170 – 173.

183. Podgorsek, R., Franke, H., Woods, J. and Lessard, R.A., Selective detection of hydrocarbon vapors by ATR-leaky mode spectroscopy, in B49, pp. 173 – 181.

184. Fiaccabrino, G.C., van der Wal, P.D., de Rooij, N.F., Koudelka-Hep, M., Tercier, M., Belmont-Hébert, C., Buffle, J., Confalonieri, F., Riccardi, G. and Graziotin, F., Microfabricated voltametric sensors for trace metal analysis, in B47, pp. 157 – 160.

185. French, L.A., Schweyer, M.G., Foley, J.B., Andle, J.C., Watson, C., Bruce, M.R.M., Bruce, A.E. and Vetelino, J.F., Heavy metal detection combining stripping electrochemistry and piezoelectric sensor technology, in B47, pp. 161 – 169.

186. Lee, A., Miniature PbS sensor for NIR spectroscopy, in B48, pp. 92 – 97.

187. Kim, S.-H., Nam, S.M., Byun, G.S., Yun, S.Y., Hong, S. and Yoo, J.S., Determination of ammonia in a flow injection cell using the diode laser/fiber optic colorimetric spectrometer, in B49, pp. 166 – 172.

188. Krippner, P., Kühner, T., Mohr, J. and Saile, V., Microspectrometer system for the near infrared wavelength range based on the LIGA technology, in B49, pp. 141 - 149.

189. Dechow, J., Forchel, A., Lanz, T. and Haase, A., Development and characterization of an NMR microsensor for nanoliter sample volumes, in B48, pp. 98 – 103.

190. The enhanced mass imager on a chip: a micromechanical-based mass imaging spectrometer on a chip (MISOC) chemical sensor, DARPA funded project

summary (06/09/2000):
http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_45.html

191. Gardner, J.W. and Bartlett, P.N., Electronic noses: principles and applications, Oxford University Press, Oxford (1999).

192. Varadan, V.K. and Gardner, J.W., Smart tongue and nose, in B26, pp. 67 – 76.

193. Hierlemann, A., Koll, A., Lange, D., Hagleitner, C., Kerness, N., Brand, O. and Baltes, H., CMOS-based chemical microsensors: components of a micronose system, in B48, pp. 158 – 169.

194. Lang, H.P., Baller, M.K., Battiston, F.M., Fritz, J., Berger, R., Ramseyer, J.-P., Fornaro, P., Meyer, E., Güntherodt, H.-J., Brugger, J., Drechsler, U., Rothuizen, H., Despont, M., Vettiger, P., Gerber, Ch. and Gimzewski, J.K., The nanomechanical nose, in B3, pp. 9 – 13.

195. Savoy, S., Lavigne, J.J., Yoo, J.S.-J., Wright, J., Rodriguez, M., Goodey, A., McDoniel, B., McDevitt, J.T., Anslyn, E.V., Shear, J.B., Ellington, A. and Neikirk, D.P., Solution-based analysis of multiple analytes by a sensor array: toward the development of an "electronic tongue", in B47, pp. 17 – 26.

196. Cho, H.J. and Ahn, C.H., A novel bi-directional magnetic microactuator using electroplated permanent magnet arrays with vertical anisotropy, in B2, pp. 686 - 691.

197. Debéda, H., Freyhold, T.v., Mohr, J., Wallrabe, U. and Wengelink, J., Development of miniaturized piezoelectric actuators for optical applications realized using LIGA technology, JMEMS, **8(3)**, pp. 258 – 263 (1999).

198. Jonsmann, J., Sigmund, O. and Bouwstra, S., Compliant electro-thermal microactuators, in B3, pp. 588 – 593.

199. Park, J.-S., Chu, L.L., Siwapornsathain, E., Oliver, A.D. and Gianchandani, Y.B., Long throw and rotary output electro-thermal actuators based on bent-beam suspensions, in B2, pp. 680 – 685.

200. Que, L., Park, J.-S. and Gianchandani, Y.B., Bent-beam electro-thermal actuators for high force applications, in B3, pp. 31 – 36.

201. Bergamasco, M., Dario, P. and Salsedo, F., Shape memory alloy microactuators, Transducers '89, Proceedings of the 5th International Conference on Solid State Sensors and Actuators and Eurosensors III, 2, pp 253 – 257 (1990). Reproduced in B1, pp. 396 – 400.

202. Ma, C.C., Wang, R., Sun, Q.P., Zohar, Y. and Wong, M., Frequency response of TiNi shape memory alloy thin film micro-actuators, in B2, pp. 370 – 374.

203. Haga, Y., Esashi, M. and Maeda, S., Bending, torsional and extending active catheter assembled using electroplating, in B2, pp. 181 – 186.

204. Mineta, T., Mitsui, T., Watanabe, Y., Kobayashi, S., Haga, Y. and Esashi, M., Batch fabricated flat winding shape memory alloy actuator for active catheter, in B2, pp. 375 – 380.

205. Park, K.T. and Esashi, M., An active catheter with integrated circuit for communication and control, in B3, pp. 400 – 405.

206. Park, K.T. and Esashi, M., A multilink active catheter with polyimide-based integrated CMOS interface circuits, JMEMS, **8(4)**, pp. 349 – 357 (1999).

207. Takeuchi, S. and Shimoyama, I., Three dimensional SMA microelectrodes with clipping structure for insect neural recording, in B3, pp. 464 – 469.

208. Takeuchi, S. and Shimoyama, I., A three-dimensional shape memory alloy microelectrode with clipping structure for insect neural recording, JMEMS, **9(1)**, pp. 24 – 31 (2000).

209. Ebefors, T., Ulfstedt-Mattsson, J., Kälvesten, E. and Stemme, G., 3D micromachined devices based on polyimide joint technology, in B14, pp. 118 - 132.

210. Ebefors, T., Ulfstedt-Mattsson, J., Kälvesten, E. and Stemme, G., A robust micro conveyer realized by arrayed polyimide joint actuators, in B3, pp. 576 – 581.

211. Vdovin, G., Sarro, P.M. and Middelhoek, S., Technology and applications of micromachined adaptive mirrors, J. Micromech. Microeng., **9(2)**, pp. R8 – R20 (1999).

212. Micromechanical arrays for macroscopic actuation of deformable mirrors, Boston University, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_10.html

213. Aerogel MEMS for high acceleration and shock applications, University of California, Los Angeles, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_58.html

214. Camon, H. and Larnaudie, F., Fabrication, simulation and experiment of a rotating electrostatic silicon mirror with large angular deflection, in B2, pp. 645 - 650.

215. Nee, J.T., Conant, R.A., Hart, M.R., Muller, R.S. and Lau, K.Y., Stretched-film micromirrors for improved optical flatness, in B2, pp. 704 – 709.

216. Kim, C.-H. and Kim, Y.-K., Integration of a micro lens on a micro XY-stage, in B14, pp. 109 – 117.

217. Pan, L.-W., Lin, L. and Ni, J., Cylindrical plastic lens array fabricated by a micro intrusion process, in B3, pp. 217 – 221.

218. Yoon, H.-S. and Washington, G., Testing and development of doubly curved piezoceramic aperture antennas, in B26, pp. 173 – 180.

219. Yee, Y., Nam, H.-J., Lee, S.-H., Bu, J.U., Jeon, Y.-S. and Cho, S.-M., PZT actuated micromirror for nano-tracking of laser beam for high-density optical data storage, in B2, pp. 435 – 440.

220. Schenk, H., Dürr, P., Kunze, D., Lakner, H. and Kück, H., An electrostatically excited 2D-micro-scanning-mirror with an in-plane configuration of the driving electrodes, in B2, pp. 473 – 478.

221. Lin, W.-M., Schroth, A., Matsumoto, S., Lee, C. and Maeda, R., Two-dimensional microscanner actuated by PZT thin film, in B14, pp. 133 – 140.

222. Uchida, N., Uchimaru, K., Yonezawa, M. and Sekimura, M., Damping of micro electrostatic torsion mirror caused by air-film viscosity, in B2, pp. 449 – 454.

223. Chiou, J.C. and Lin, Y.C., A micromirror device with tilt and piston motions, in B9, pp. 298 – 303.

224. Ju, B.-K., Lee, Y.-H. and Oh, M.-H., Self-generated light emitting device using micromachined Si mirror arrays, in B3, pp. 371 – 375.

225. Vangbo, M., Karlsson, S. and Bäcklund, Y., Low cost micromachined mirrors for display systems, J. Micromech. Microeng., **9**, pp. 85 – 88 (1999).

226. Huja, M. and Husak, M., MEMS structure – micromirror array, in B10, pp. 556 - 567.

227. Chollet, F., Liu, A., Zheng, L., Asundi, A. and Lin, L., Improved silicon micromachined 3-D mirror for acceleration sensing using an extra-short external cavity laser self-mixing interferometer, in B17, pp. 98 – 108.

228. Tuantranont, A., Bright, V.M., Liew, L.-A., Zhang, W. and Lee, Y.C., Smart phase-only micromirror array fabricated by standard CMOS process, in B2, pp. 455 - 460.

229. Yokoyama, Y., Ota, H., Takeda, M., Matsuura, T., Chabloz, M., Kaneko, S.-i. and Uemura, A., Micro-optical switch with uni-directional I/O fibers, in B2, pp. 479 - 484.

230. Chen, R.T., Nguyen, H. and Wu, M.C., A low voltage micromachined optical switch by stress-induced bending, in B3, pp. 424 – 428.

231. Cugat, O., Mounaix, P., Basrour, S., Divoux, C., Reyne, G., Deformable magnetic mirror for adaptive optics: first results, in B2, pp. 485 – 490.

232. Carlen, E.T. and Mastrangelo, C.H., Paraffin actuated surface micromachined valves, in B2, pp. 381 – 385.

233. Messner, S., Müller, M., Burger, V., Schaible, J., Sandmaier, H. and Zengerle, R., A normally-closed, bimetallically actuated 3-way microvalve for pneumatic applications, in B4, pp. 40 – 44.

234. Rich, C.A. and Wise, K.D., An 8-bit microflow controller using pneumatically-actuated microvalves, in B3, pp. 130 – 134.

235. Capanu, M., Boyd IV, J.G. and Hesketh, P.J., Design, fabrication and testing of a bistable electromagnetically actuated microvalve, JMEMS, **9(2)**, pp. 181 – 189 (2000).

236. Grosjean, C., Yang, X. and Tai, Y.-C., A practical thermopneumatic valve, in B3, pp. 147 – 152.

237. Yang, X., Grosjean, C. and Tai, Y.-C., Design, fabrication, and testing of micromachined silicon rubber membrane valves, JMEMS, **8(4)**, 393 – 402 (1999).

238. Man, P.F., Mastrangelo, C.H., Burns, M.A. and Burke, D.T., Microfabricated capillarity-driven stop valve and sample injector, in B4, pp. 45 – 50.

239. Ikuta, K., Hasegawa, T., Adachi, T. and Maruo, S., Fluid drive chips containing multiple pumps and switching valves for biochemical family – Development of SMA 3D micro pumps and valves in leak-free polymer package, in B2, pp. 739 – 744.

240. van der Wijngaart, W., Andersson, H., Enoksson, P., Noren, K. and Stemme, G., The first self-priming and bi-directional valve-less diffuser micropump for both liquid and gas, in B2, pp. 674 – 679.

241. Olsson, A., Stemme, G. and Stemme, E., A numerical design study of the valveless diffuser pump using a lumped-mass model, J. Micromech. Microeng., **9(1)**, pp. 34 – 44 (1999).

242. Ahn, C.H. and Allen, M.G., Fluid micropumps based on rotary magnetic actuators, in B7, pp. 408 – 412.

243. Döpper, J., Clemens, M., Ehrfeld, W., Jung, S., Kämper, K.-P., and Lehr, H., Micro gear pumps for dosing of viscous fluids, J. Micromech. Microeng., 7, pp. 230 – 232 (1997).

244. Soerensen, O., Drese, K.S., Ehrfeld, W. and Hartmann, H.-J., Micromachined flow handling components - micropumps, in B48, pp. 52 – 60.

245. Matsumoto, S., Klein, A. and Maeda, R., Development of bi-directional valve-less micropump for liquid, in B3, pp. 141 – 146.

246. Maillefer, D., van Lintel, H., Rey-Mermet, G. and Hirschi, R., A high-performance silicon micropump for an implantable drug delivery system, in B3, pp. 541 – 546.

247. Tay., F.E.H., Xu, G.L., Choong, W.O. and Xue, H., A low cost metal micro-pump for drug delivery, in B9, pp. 234 – 240.

248. Büttgenbach, S. and Robohm, C., Microflow devices for miniaturized chemical analysis systems, in B47, pp. 51 – 61.

249. Hosokawa, K., Fujii, T. and Endo, I., Droplet-based nano/picoliter mixer using hydrophobic microcapillary vent, in B3, pp. 388 – 393.

250. Voldman, J., Gray, M.L. and Schmidt, M.A., An integrated liquid mixer/valve, JMEMS, **9(3)**, pp. 295 – 302 (2000).

251. Ikuta, K., Maruo, S., Fujisawa, T. and Yamada, A., Micro concentrator with opto-sense micro reactor for biochemical IC chip family – 3D composite structure and experimental verification, in B3, pp. 376 – 381.

252. Ikuta, K., Maruo, S., Fukaya, Y. and Fujisawa, T., Biochemical IC chip toward cell free DNA protein synthesis, in B4, pp. 131 – 136.

253. Electrokinetic microactuator arrays for control of vehicles, University of Michigan, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_68.html

254. Kumar, S.M., Reynolds, W.C. and Kenny, T.W., MEMS based transducers for boundary layer control, in B0, pp. 135 – 140.

255. Control of transition in swept-wing boundary layers using MEMS devices as distributed roughness, Arizona State University, DARPA funded project

summary (06/09/2000):
http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_3.html

256. Wong, J.E., Lang, J.H. and Schmidt, M.A., An electrostatically-actuated MEMS switch for power applications, in B2, pp. 633 – 638.

257. Kang, J.W. and Simonette, K., Surface micromachined multi-layer moving gate field effect transistor (MOGFET) pressure switch with integrated vacuum sealed cavity, in B3, pp. 499 – 504.

258. Tilmans, H.A.C., Fullin, E., Ziad, H., Van de Peer, M.D.J., Kesters, J., Van Geffen, E., Bergqvist, J., Pantus, M., Beyne, E., Baert, K. and Naso, F., A fully-packaged electromagnetic microrelay, in B3, pp. 25 – 30.

259. Sakata, M., Komura, Y., Seki, T., Kobayashi, K., Sano, K. and Horike, S., Micromachined relay which utilizes single crystal silicon electrostatic actuator, in B3, pp. 21 – 24.

260. Wallace, A.P., Howard, D.L., Sirota, J.S., Smith, R.L. and Collins, S.D., Long range translation actuator, in B49, pp. 158 – 165.

261. PolyMEMS actuator: a polymer-based MEMS microactuator with macroscopic action, Honeywell Technology Center, DARPA funded project summary (06/09/2000):
http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_31.html

262. Tadokoro, S., Yamagami, S., Ozawa, M., Kimura, T. and Takamori, T., Soft micromanipulation device with multiple degrees of freedom consisting of high polymer gel actuators, in B3, pp. 37 – 42.

263. Hirata, A., Machida, K., Kyuragi, H. and Maeda, M., A micromechanical switch as the logic elements for circuits in Multi Chip Module on Si (MCM-Si), in B3, pp. 582 – 587.

264. Edo, M., Watanabe, Y., Morita, O., Nakazawa, H. and Yonezawa, E., Two-dimensional micro conveyer with integrated electrostatic actuators, in B3, pp. 43 - 48.

265. Chan, E.K. and Dutton, R.W., Electrostatic micromechanical actuator with extended range of travel, JMEMS, **9(3)**, pp. 321 – 328 (2000).

266. Naniwa, I., Nakamura, S., Saegusa, S. and Sato, K., Low voltage driven piggy-back actuator of hard disk drives, in B3, pp. 49 – 52.

267. Kim, B.-H., Park, S., Kim, H.-C., Chun, K., Cho, D.-I.D., Lee, J.-W., Lee, H.-J., Kim, S.-H., Seong, W.-K. and An, Y.-J., MEMS fabrication of high aspect ratio track-

following micro actuator for hard disk drive using silicon on insulator, in B3, pp. 43 - 48.

268. Hirano, T., Fan, L.-S., Semba, T., Lee, W.Y., Hong, J., Pattanaik, S., Webb, P., Juan, W.-H. and Cahn, S., Micro-actuator for tera-storage, in B3, pp. 441 – 446.

269. Bobbio, S.M., Smith, S.W., Zara, J., Goodwin-Johansson, S., Hudak, J., DuBois, T., Leamy, H., Godwin, J. and Pennington, M., Microelectromechanical actuator with extended range and enhanced force: fabrication, test, and application as a mechanical scanner, in B26, pp. 210 – 218.

270. Bandyopadhyay, K., Smart materials and aerospace structures, in B15, pp. 312 - 324.

271. Demonstration of robust micromachined jet technology and its application to realistic flow control problems, Georgia Institute of Technology, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_26.html

272. A low altitude surveillance aircraft controlled by M^3 system, University of California, Los Angeles, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_60.html

273. Distributed turbulent flow control by MEMS integrated with neural-networks, University of California, Los Angeles, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_61.html

274. MEMS for micro air vehicles, University of Florida, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_66.html

275. Intelligent servo actuated surfaces (ISAS), Sarcos Research Corporation, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_49.html

276. MEMS based active control of macro-scale objects, Xerox Palo Alto Research Center, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_76.html

277. Smart dust, University of California, Berkeley, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_57.html

278. Low power wireless integrated microsensors (LWIM), University of California, Los Angeles, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_59.html

279. Asada, G., Bhatti, I., Lin, T.H., Natkunanthanan, S., Newberg, F., Rofougaran, R., Sipos, A., Valoff, S., Pottie, G.J. and Kaiser, W.J., Wireless integrated network sensors (WINS), in B26, pp. 11 – 18.

280. Suzuki, H., Kasagi, N., Suzuki, Y. and Shima, H., Manipulation of a round jet with electromagnetic flap actuators, in B3, pp. 534 – 540.

281. Schaible, J., Messner, S., Müller, M., Fuchs, N., Sandmaier, H. and Zengerle, R., A modular integrated pressure control unit for gases, in B3, pp. 77 – 81.

282. Saif, M.T.A., Alaca, B.E. and Sehitoglu, H., Analytical modeling of electrostatic membrane actuator for micro pumps, JMEMS, **8(3)**, pp. 335 – 345 (1999).

283. Accoto, D., Carrozza, M.C. and Dario, P., Modelling of micropumps using unimorph piezoelectric actuator and ball valves, J. Micromech. Microeng., **10(2)**, pp. 277 – 281 (2000).

284. Yeh, B.Y., Liang, Y.C. and Tay, F.E.H., Mathematical modelling on the quadrature error of low-rate microgyroscope for aerospace application, in B10, pp. 134 - 144.

285. Zhang, X.M., Chau, F.S., Quan, C. and Liu, A.Q., Modeling of the optical torsion micromirror, in B17, pp. 109 – 116.

286. Weinberg, M.S., Cunningham, B.T. and Clapp, C.W., Modeling flexural plate devices, JMEMS, **9(3)**, pp. 370 – 379 (2000).

287. Gardner, J.W., Udrea, F. and Milne, B., Numerical simulation of a new generation of high-temperature, micropower gas and odour sensors based on SOI technology, in B26, pp. 104 – 112.

288. Jie, D., Diao, X., Cheong, K.B. and Yong, L.K., Navier-Stokes simulations of gas flow in micro devices, J. Micromech. Microeng., **10(3)**, pp. 372 – 379 (2000).

289. Lin, L., Chu, H.-C. and Lu, Y.-W., A simulation program for the sensitivity and linearity of piezoresistive pressure sensors, JMEMS, **8(4)**, pp. 514 – 522 (1999).

290. Pan, L.S., Liu, G.R., Khoo, B.C. and Song, B., A modified direct simulation Monte Carlo method for low-speed microflows, J. Micromech. Microeng., **10(1)**, pp. 21 - 27 (2000).

291. Bousse, L., Minalla, A., Deshpande, M., Greiner, K.B. and Gilbert, J.R., Optimization of sample injection components in electrokinetic microfluidic systems, in B3, pp. 309 – 314.

292. Brynzari, V.I., Korotchenkov, G.S. and Schwank, J., Optimization of thin film gas sensors for environmental monitoring through theoretical monitoring, in B48, pp. 186 – 197.

293. Selvarajan, A. and Anand, S., Noise analysis and a comparative study of noise in MEMS and MOEMS, in B26, pp. 113 – 120.

294. Xu, B., Ooi, K.T., Wong, T.N. and Liu, C.Y., Study on the viscosity of the liquid flowing in microgeometry, J. Micromech. Microeng., **9(4)**, pp. 377 – 384 (1999).

295. Jones, A., Flamm, K., Gabriel, K., Van Atta, R. and Mareth, L., Microelectromechanical systems opportunities: a Department of Defense Dual-Use Technology Industrial Assessment, Office of the Director of Defense Research and Engineering, Washington DC, Report ADA304675 (December 1995).

296. Ruffieux, D., Dubois, M.A. and de Rooij, N.F., An ALN piezoelectric microactuator array, in B2, pp. 662 – 667.

297. Kladitis, P.E., Bright, V.M., Harsh, K.F. and Lee, Y.C., Prototype microrobots for micropositioning in a manufacturing process and micro unmanned vehicles, in B3, pp. 570 – 575.

298. Cox, A. and Garcia, E., Three-dimensional LIGA structures for use in tagging, in B26, pp. 122 – 126.

299. Miki, N. and Shimoyama, I., A micro-flight mechanism with rotational wings, in B2, pp. 158 – 163.

300. Miki, N. and Shimoyama, I., Flight performance of micro-wings rotating in and alternating magnetic field, in B3, pp. 153 – 158.

301. Pornsin-sirirak, T.N., Lee, S.W., Nassef, H., Grasmeyer, J., Tai, Y.C., Ho, C.M. and Keennon, M., MEMS wing technology for a battery-powered ornithopter, in B2, pp. 799 – 804.

302. DARPA-MEMS and microtechnology for space applications, Aerospace Corporation, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_1.html

303. Micromachined RF switches and tunable capacitors for higher performance secure communications systems, Rockwell International, DARPA funded project

summary (06/09/2000):
http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_47.html

304. Milanović, V., Maharbiz, M., Singh, A., Warneke, B., Zhou, N., Chan, H.K. and Pister, K.S.J., in B2, pp. 787 – 792.

305. Park, J.Y., Kim, G.H., Chung, K.W. and Bu, J.U., Electroplated RF MEMS capacitive switches, in B2, pp. 639 – 644.

306. MEMS for wireless communications, University of Michigan, DARPA funded project summary (06/09/2000):
http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_73.html

307. Wang, K., Yu, Y., Wong, A.-C. and Nguyen, C.T.-C., VHF free-free beam high-Q micromechanical resonators, in B3, pp. 453 – 458.

308. Wang, K., Wong, A.-C. and Nguyen, C.T.-C., VHF free-free beam high-Q micromechanical resonators, JMEMS, **9(3)**, pp. 347 – 360 (2000).

309. Nguyen, C.T.-C., Micromechanical filters for miniaturized low-power communications, in B26, pp. 55 – 66.

310. Submicron scale MEMS for ultralow power VHF/UHF applications, California Institute of Technology, DARPA funded project summary (06/09/2000):
http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_11.html

311. Ultra-high-density data cache for low-power communications, Carnegie Mellon University, DARPA funded project summary (06/09/2000):
http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_13.html

312. MBDS: MEMS-based data storage (MBDS), Hewlett Packard Laboratory, DARPA funded project summary (06/09/2000):
http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_29.html

313. 10 Gbyte personal multimedia MEMS ROM data storage card, Kionix Inc., DARPA funded project summary (06/09/2000):
http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_37.html

314. Despont, M., Brugger, J., Drechsler, U., Dürig, U., Häberle, W., Lutwyche, M., Rothuizen, H., Stutz, R., Widmer, R., Rohrer, H., Binnig, G. and Vettiger, P., VLSI-NEMS chip for AFM data storage, in B3, pp. 564 – 569.

315. Microscale combustor/evaporator development, Battelle, DARPA funded project summary (06/09/2000):
http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_6.html

316. Brooks, K.P., Martin, P.M., Drost, M.K. and Call, C.J., Mesoscale combustor/ evaporator development, ASME IMECE 1999 Conference, Nashville (Nov. 1999).

317. Brooks, K.P., Call, C.J. and Drost, M.K., Integrated microchannel combustor/ evaporator development, AIChE 1998 Spring National Meeting, New Orleans (1998).

318. Drost, M.K., Call, C.J., Cuta, J.M. and Wegeng, R.S., Microchannel integrated evaporator/combustor thermal processes, Journal of Microscale Thermophysics Engineering, 1(4), 321 – 333 (1997).

319. An integrated fuel cell and fuel processor for microscale power generation from liquid fuels, Battelle, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_7.html

320. A micro hydrogen-air fuel cell, Case Western Reserve University, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_16.html

321. Integrated chemical fuel microprocessor for power generation in MEMS applications, Massachusetts Institute of Technology, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_40.html

322. Srinivasan, R., Hsing, I.-M., Berger, P.E., Firebaugh, S.L., Harold, M.P., Ryley, J.F., Lerou, J.J., Jensen, K.F. and Schmidt, M.A., Micromachined chemical reactors for heterogeneously catalyzed partial oxidation reactions, AIChE Journal, **43**, 11 (1997).

323. Srinivasan, R., Firebaugh, S.L., Hsing, I.-M., Ryley, J.F., Harold, M.P., Jensen, K.F. and Schmidt, M.A., Chemical performance and high temperature characterization of micromachined chemical reactors, Technical Digest, International Conference on Solid State Sensors and Actuators, IEEE, 163 – 166 (1997).

324. Permanent magnet MEMS arrays and application to combustion-driven power generation, Georgia Institute of Technology, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_27.html

325. MEMS free-piston knock engine, Honeywell Technology Center, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_30.html

326. MEMS rotary internal combustion engine, University of California, Berkeley, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_56.html

327. A 3-d monolithically-fabricated thermoelectric microgenerator, University of Southern California, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_74.html

328. Flexible manufacturing of Application-Specific MEMS, BFGoodrich, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_8.html

329. S. Löbbecke, J. Antes, T. Türcke, E. Marioth, K. Schmid, H. Krause, The potential of microreactors for the synthesis of energetic materials, Int. Ann. Conf. ICT, 31, pp. 33-1 – 33-16 (2000).

330. W. Schweikert, T. Türcke, S. Löbbecke, Monitoring of nitration reactions in microreactors with FTIR microscopy, Int. Ann. Conf. ICT, 31, pp. 98-1 – 98-5 (2000).

331. Kaajakari, V., Rodgers, S. and Lal, A., Ultrasonically driven surface micromachined motor, in B2, pp. 40 – 45.

332. Dellman, L., Racine, G.-A. and de Rooij, N.F., Micromachined piezoelectric elastic force motor (EFM), in B2, pp. 52 – 55.

333. Lin, C.-C., Ghodssi, R., Ayon, A.A., Chen, D.-Z., Jacobson, S., Breuer, K., Epstein, A.H. and Schmidt, M.A., Fabrication and characterization of a micro turbine/bearing rig, in B3, pp. 529 – 533.

334. MEMS-based control for air breathing propulsion, Massachusetts Institute of Technology, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_42.html

335. Micromachined acoustic ejector arrays for propulsion, actuation, and control, University of Michigan, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_72.html

336. Parviz, B.A., Chou, T.-K., Zhang, C., Najafi, K., Muller, M.O., Bernal, L.P. and Washabaugh, P., A wafer-integrated array of micromachined electrostatically-driven ultrasonic resonators for microfluidic applications, in B2, pp. 34 – 39.

337. Turbine engine control using MEMS for reduction of high cycle fatigue, Virginia Polytechnical and State University, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_75.html

338. Harbrecht, D. (ed.), Pint-size satellites will soon be doing giant jobs, Business Week Online Daily Briefing (10/02/2000): http://www.businessweek.com/bwdaily/dnflash/feb2000/nf00210a.htm

339. MEMS microthruster propulsion system, TRW, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_53.html

340. DARPA/MTO/MEMS digital micro-propulsion project (06/09/2000): http://design.caltech.edu/micropropulsion/index.html

341. Amato, I., May the micro force be with you, Technology Review, pg 82 (Oct. 1999).

342. Stix, G., Little bangs – making thrusters for micromachines, Scientific American, pp 50-51 (Nov. 1998).

343. Iannotta, B., Pocket rocket, New Scientist, 162(2181), pg 38 (10 April 1999).

344. Lewis, Jr., D.H., Janson, S.W., Cohen, R.B. and Antonsson, E.K., Digital micropropulsion, pp. 517 – 522 in B3.

345. Lewis, Jr., D.H., Janson, S.W., Cohen, R.B. and Antonsson, E.K., Digital micropropulsion, Sensors and Actuators, **A80(2)**, pp. 143 – 154 (2000).

346. Small satellites home page, University of Surrey (26/09/00): http://www.ee.surrey.ac.uk/SSC/SSHP/nano/nano.html

347. Development and demonstration of a 20 mm safe and arming device, Armament Research Development and Engineering Center, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_4.html

348. Miniaturized explosive train and fireset for MEMS fuze/safety and arming, Naval Surface Warfare Center, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_44.html

349. Military applications of MEMS, George Washington University, DARPA funded project summary (06/09/2000): http://www.darpa.mil/MTO/MEMS/Summaries/Projects/individual_25.html

350. Krantz, D., Belk, J., Biermann, P.J., Dubow, J., Gause, L.W., Harjani, R., Mantell, S., Polla, D. and Troyk, P., Project update: applied research on remotely-queried embedded microsensors, in B26, pp. 157 – 164.

351. Dubow, J., Zhang, W., Lu, Y., Bingham, J., Syammach, F., Krantz, D.G., Belk, J.H., Bierman, P., Harjani, R., Mantell, S.C., Polla, D.L. and Troyk, P.R., Embedded cure monitor, strain gauge, and mechanical state estimator, in B26, pp. 336 – 349.

352. Gause, L.W., Krantz, D.G., Biermann, P.J. and Belk, J.H., Early demonstration of remotely queried microsensors, in B26, pp. 190 – 194.

353. Varadan, V.K. and Varadan, V.V., Microsensors and MEMS for health monitoring of composite and aircraft structures in flight, in B26, pp. 359 – 368.

354. White, A. and Macdowell, P.M., Potential applications of Microelectromechanical Systems (MEMS) in Propellant Service/Safe Life Monitoring, DSTO Technical Note (in preparation).

9. Bibliography

9.1 General Conferences and Reviews

B1. Trimmer, W.S. (ed.), Micromechanics and MEMS: Classic and Seminal Papers to 1990, IEEE, New York (1997).

B2. Proceedings of the 13th Annual International Conference on Micro Electro Mechanical Systems, Miyazaki, Japan, 23 - 27 January, 2000, IEEE, New York (2000).

B3. Proceedings of the 12th Annual International Conference on Micro Electro Mechanical Systems, Orlando, Florida, USA, 17 - 21 January 1999, IEEE, New York (1999).

B4. Proceedings of the 11th Annual International Conference on Micro Electro Mechanical Systems, Heidelberg, Germany, 25 - 29 January, 1998, IEEE, New York (1998).

B5. Proceedings of the 10th Annual International Conference on Micro Electro Mechanical Systems, Nagoya, Japan, 26 - 30 January, 1997, IEEE, New York (1997).

B6. Proceedings of the 9th Annual International Conference on Micro Electro Mechanical Systems, San Diego, California, 11 - 15 February 1996, IEEE, New York (1996).

B7. Proceedings of the 8th Annual International Conference on Micro Electro Mechanical Systems, Amsterdam, The Netherlands, 29 January - 2 February, 1995, IEEE, New York (1995).

9.2 Design, Structures, Fabrication, Packaging and Characterisation

B8. Courtois, B., Crary, S.B., Ehrfeld, W., Fujita, H., Karam, J.M. and Markus, K.W. (eds.), Design, Test, and Microfabrication of MEMS and MOEMS, Proceedings of SPIE Vol. 3680, SPIE, Bellingham (1999).

B9. Courtois, B. and Demidenko, S. (eds.), Design, Characterization, and Packaging for MEMS and Microelectronics, Proceedings of SPIE Vol. 3893, SPIE, Bellingham (1999).

B10. Courtois, B., Crary, S.B., Gabriel, K., Karam, J.M., Markus, K.W. and Tay, A. (eds.), Design, Test, Integration, and Packaging of MEMS/MOEMS, Proceedings of SPIE Vol. 4019, SPIE, Bellingham (2000).

B11. Smith, J.H. and Karam, J.M. (eds.), Micromachining and Microfabrication Process Technology V, Proceedings of SPIE Vol. 3874, SPIE, Bellingham (1999).

B12. Karam, J.M. and Yasaitis, J. (eds.), Micromachining and Microfabrication Process Technology VI, Proceedings of SPIE Vol. 4174, SPIE, Bellingham (2000).

B13. Bergmann, N.W., Reinhold, O. and Tien, N.C. (eds.), Electronics and Structures for MEMS, Proceedings of SPIE Vol. 3891, SPIE, Bellingham (1999).

B14. Chau, K. and Dimitrijev, S. (eds.), Device and Process Technologies for MEMS and Microelectronics, Proceedings of SPIE Vol. 3892, SPIE, Bellingham (1999).

9.3 Micromechanical Systems

B15. Pustovoy, V.I. and Jain, V.K. (eds.), Indo-Russian Workshop on Micromechanical Systems, Proceedings of SPIE Vol. 3903, SPIE, Bellingham (1999).

B16. French, P.J. and Peeters, E. (eds.), Micromachined Devices and Components V, Proceedings of SPIE Vol. 3876, SPIE, Bellingham (1999).

9.4 Micro-/Nano-structures

B17. Ho, S.T., Zhou, Y., Chow, W.W. and Arakawa, Y. (eds.), Photonics Technology into the 21st Century: Semiconductors, Microstructures, and Nanostructures, Proceedings of SPIE Vol. 3899, SPIE, Bellingham (1999).

9.5 Reliability

B18. Lawton, R.A., Miller, W.M., Lin, G. Ramesham, R. (eds.), MEMS Reliability for Critical and Space Applications, Proceedings of SPIE Vol. 3880, SPIE, Bellingham (1999).

B19. Lawton, R.A. (ed.), MEMS Reliability for Critical Applications, Proceedings of SPIE Vol. 4180, SPIE, Bellingham (2000).

9.6 Education, Training, Industry

B20. Payne, F. and Parameswaran, A.M. (eds.), Education in Microelectronics and MEMS, Proceedings of SPIE Vol. 3894, SPIE, Bellingham (1999).

9.7 Shape Memory Alloys, Smart Electronics, Structures and Materials

B21. Hariz, A., Varadan, V.K. and Reinhold, O. (eds.), Smart Electronics and MEMS, Proceedings of SPIE Vol. 3242, SPIE, Bellingham (1997).

B22. Varadan, V.K. and McWhorter, P.J. (eds.), Smart Structures and Materials 1996: Smart Electronics and MEMS, Proceedings of SPIE Vol. 2722, SPIE, Bellingham (1996).

B23. Varadan, V.K. and McWhorter, P.J. (eds.), Smart Structures and Materials 1997: Smart Electronics and MEMS, Proceedings of SPIE Vol. 3046, SPIE, Bellingham (1997).

B24. Aatre, V.K., Varadan, V.K. and Varadan, V.V. (eds.), Smart Materials, Structures and MEMS, Proceedings of SPIE Vol. 3321, SPIE, Bellingham (1998).

B25. Varadan, V.K. and McWhorter, P.J. (eds.), Smart Structures and Materials 1998: Smart Electronics and MEMS, Proceedings of SPIE Vol. 3328, SPIE, Bellingham (1998).

B26. Varadan, V.K. and McWhorter, P.J. (eds.), Smart Structures and Materials 1999: Smart Electronics and MEMS, Proceedings of SPIE Vol. 3673, SPIE, Bellingham (1999).

B27. Wereley, N.M. (ed.), Smart Structures and Materials 2000: Smart Structures and Integrated Systems, Proceedings of SPIE Vol. 3985, SPIE, Bellingham (2000).

B28. Lynch, C.S. (ed.), Smart Structures and Materials 2000: Active Materials: Behaviour and Mechanics, Proceedings of SPIE Vol. 3992, SPIE, Bellingham (2000).

9.8 Optics

B29. Motomedi, M.E. (ed.), Micro-optics/Micromechanics and laser scanning and shaping, Proceedings of SPIE Vol. 2383, SPIE, Bellingham (1995).

B30. Motamedi, M.E. and Bailey, W. (eds.), Microelectronic Structures and MEMS for Optical Processing II, Proceedings of SPIE Vol. 2881, SPIE, Bellingham (1996).

B31. Motomedi, M.E., Hornbeck, L.J. and Pister, K.S.J. (eds.), Miniaturized Systems with Micro-Optics and Micromechanics II, Proceedings of SPIE Vol. 3008, SPIE, Bellingham (1997).

B32. Motamedi, M.E. and Herzig, P. (eds.), Microelectronic Structures and MEMS for Optical Processing III, Proceedings of SPIE Vol. 3226, SPIE, Bellingham (1997).

B33. Motomedi, M.E. and Goering, R. (eds.), Miniaturized Systems with Micro-Optics and Micromechanics III, Proceedings of SPIE Vol. 3276, SPIE, Bellingham (1998).

B34. Motamedi, M.E. and Herzig, P. (eds.), Microelectronic Structures and MEMS for Optical Processing IV, Proceedings of SPIE Vol. 3513, SPIE, Bellingham (1998).

B35. Motomedi, M.E. and Goering, R. (eds.), Miniaturized Systems with Micro-Optics and MEMS, Proceedings of SPIE Vol. 3878, SPIE, Bellingham (1999).

9.9 Sensors

B36. Sze, S.M., Semiconductor Sensors, John Wiley and Sons (New York), (1994).

B37. Gardner, J.W., Microsensors: Principles and Applications, John Wiley and Sons (New York), (1994).

B38. Muller, R.S., Howe, R.T., Senturia, S.D., Smith, R.L. and White, R.M. (eds.), Microsensors, IEEE, New York (1990).

B39. Grattan, K.T.V. (ed.), Sensors: Technology, Systems and Applications, Adam Hilger, Bristol (1991).

B40. Göpel, W., Hesse, J. and Zemel, J.N. (eds.), Sensors - A Comprehensive Survey, Volume 1, Fundamentals and General Aspects, Grandke, T. and Ko, W.H. (volume editors), VCH Verlagsgesellschaft mbH, Weinheim (1995).

B41. Göpel, W., Hesse, J. and Zemel, J.N. (eds.), Sensors - A Comprehensive Survey, Volume 2/3, Chemical and Biochemical Sensors, Part I/II, Göpel, W., Jones, T.A., Kleitz, M., Lundström, I. and Seiyama, T. (volume editors), VCH Verlagsgesellschaft mbH, Weinheim (1995).

B42. Göpel, W., Hesse, J. and Zemel, J.N. (eds.), Sensors - A Comprehensive Survey, Volume 4, Thermal Sensors, Ricolfi, T. and Scholz, J. (volume editors), VCH Verlagsgesellschaft mbH, Weinheim (1995).

B43. Göpel, W., Hesse, J. and Zemel, J.N. (eds.), Sensors - A Comprehensive Survey, Volume 5, Magnetic Sensors, Boll, R. and Overshott, K.J. (volume editors), VCH Verlagsgesellschaft mbH, Weinheim (1995).

B44. Göpel, W., Hesse, J. and Zemel, J.N. (eds.), Sensors - A Comprehensive Survey, Volume 6, Optical Sensors, Wagner, E., Dändliker, R. and Spenner, K. (volume editors), VCH Verlagsgesellschaft mbH, Weinheim (1995).

B45. Göpel, W., Hesse, J. and Zemel, J.N. (eds.), Sensors - A Comprehensive Survey, Volume 7, Mechanical Sensors, Bau, H.H., deRooij, N.F. and Kloeck, B. (volume editors), VCH Verlagsgesellschaft mbH, Weinheim (1995).

B46. Göpel, W., Hesse, J. and Zemel, J.N. (eds.), Sensors - A Comprehensive Survey, Volume 8, Micro- and Nanosensor Technology / Trends in Sensor Markets, Meixner, H. and Jones, R. (volume editors), VCH Verlagsgesellschaft mbH, Weinheim (1995).

B47. Büttgenbach, S. (ed.), Chemical Microsensors and Applications, Proceedings of SPIE Vol. 3539, SPIE, Bellingham (1998).

B48. Büttgenbach, S. (ed.), Chemical Microsensors and Applications II, Proceedings of SPIE Vol. 3857, SPIE, Bellingham (1999).

9.10 Biomedical and Environmental Applications

B49. Mariella Jr., R.P. (ed.), Micro- and Nanotechnology for Biomedical and Environmental Applications, Proceedings of SPIE Vol. 3912, SPIE, Bellingham (2000).

9.11 Military Applications

B50. Brendley, K.W. and Steeb, R., Military Applications of Microelectromechanical Systems, MR-175-OSD/AF/A, Rand, Santa Monica (1993).

B51. Jones, A., Flamm, K., Gabriel, K., Van Atta, R. and Mareth, L., Microelectromechanical systems opportunities: a Department of Defense Dual-Use Technology Industrial Assessment, Office of the Director of Defense Research and Engineering, Washington DC, Report ADA304675 (December 1995).

B52. Nanotechnology and Microengineering for Future Guided Weapons, Royal Aeronautical Society, London (1999).

DISTRIBUTION LIST

A Review of Some Current Research in Microelectromechanical Systems (MEMS) with Defence Applications

A. White

AUSTRALIA

DEFENCE ORGANISATION

Task Sponsor
Director Ordnance Safety Group

S&T Program
Chief Defence Scientist } shared copy
FAS Science Policy } shared copy
AS Science Corporate Management } shared copy
Director General Science Policy Development } shared copy
Counsellor Defence Science, London (Doc Data Sheet)
Counsellor Defence Science, Washington (Doc Data Sheet)
Scientific Adviser to MRDC Thailand (Doc Data Sheet)
Scientific Adviser Joint
Navy Scientific Adviser (Doc Data Sheet and distribution list only)
Scientific Adviser - Army (Doc Data Sheet and distribution list only)
Air Force Scientific Adviser
Director Trials

Aeronautical and Maritime Research Laboratory
Director
Chief of Weapons Systems Division
Research Leader Joint and Intelligence
Head Propulsion Systems Technology
Head Explosives
Head Pyrotechnics
Mr P.M. Macdowell
Author(s):
Dr. A. White (5 copies)

DSTO Library and Archives
Library Fishermans Bend (Doc Data Sheet)
Library Maribyrnong (Doc Data Sheet)
Library Edinburgh
Australian Archives
Library, MOD, Pyrmont (Doc Data sheet only)
US Defense Technical Information Center, 2 copies
UK Defence Research Information Centre, 2 copies
Canada Defence Scientific Information Service, 1 copy
NZ Defence Information Centre, 1 copy
National Library of Australia, 1 copy

Capability Systems Staff

Director General Maritime Development (Doc Data Sheet only)
Director General Aerospace Development (Doc Data Sheet only)

Knowledge Staff

Director General Command, Control, Communications and Computers (DGC4) (Doc Data Sheet only)

Army

ABCA National Standardisation Officer (4 copies)
Land Warfare Development Sector
Tobruk Barracks
PUCKAPUNYAL VIC 3662

SO (Science), Deployable Joint Force Headquarters (DJFHQ) (L), MILPO Gallipoli Barracks, Enoggera QLD 4052 (Doc Data Sheet only)

NPOC QWG Engineer NBCD Combat Development Wing, Tobruk Barracks, Puckapunyal, 3662 (Doc Data Sheet relating to NBCD matters only)

Intelligence Program

DGSTA Defence Intelligence Organisation
Manager, Information Centre, Defence Intelligence Organisation

Corporate Support Program

Library Manager, DLS-Canberra

UNIVERSITIES AND COLLEGES

Australian Defence Force Academy
Library
Head of Aerospace and Mechanical Engineering
Serials Section (M list), Deakin University Library, Geelong, 3217
Hargrave Library, Monash University (Doc Data Sheet only)
Librarian, Flinders University

OTHER ORGANISATIONS

NASA (Canberra)
AusInfo

OUTSIDE AUSTRALIA

ABSTRACTING AND INFORMATION ORGANISATIONS

Library, Chemical Abstracts Reference Service
Engineering Societies Library, US
Materials Information, Cambridge Scientific Abstracts, US
Documents Librarian, The Center for Research Libraries, US

INFORMATION EXCHANGE AGREEMENT PARTNERS

Acquisitions Unit, Science Reference and Information Service, UK
Library - Exchange Desk, National Institute of Standards and Technology, US

SPARES (5 copies)

Total number of copies: **50**

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION DOCUMENT CONTROL DATA					
			1. PRIVACY MARKING/CAVEAT (OF DOCUMENT) n/a		
2. TITLE A Review of Some Current Research in Microelectromechanical Systems (MEMS) with Defence Applications			3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED REPORTS THAT ARE LIMITED RELEASE USE (L) NEXT TO DOCUMENT CLASSIFICATION) Document (U) Title (U) Abstract (U)		
4. AUTHOR(S) A. White			5. CORPORATE AUTHOR Aeronautical and Maritime Research Laboratory 506 Lorimer St Fishermans Bend Vic 3207 Australia		
6a. DSTO NUMBER DSTO-GD-0316	6b. AR NUMBER AR-012-138		6c. TYPE OF REPORT General Document	7. DOCUMENT DATE February 2002	
8. FILE NUMBER 9505-19-262	9. TASK NUMBER JNT 00/020	10. TASK SPONSOR Director- Ordnance Safety Group	11. NO. OF PAGES 68	12. NO. OF REFERENCES 354	
13. URL on the World Wide Web http://www.dsto.defence.gov.au/corporate/reports/ DSTO-GD-0316.pdf			14. RELEASE AUTHORITY Chief, Weapons Systems Division		
15. SECONDARY RELEASE STATEMENT OF THIS DOCUMENT *Approved for public release* OVERSEAS ENQUIRIES OUTSIDE STATED LIMITATIONS SHOULD BE REFERRED THROUGH DOCUMENT EXCHANGE, PO BOX 1500, SALISBURY, SA 5108					
16. DELIBERATE ANNOUNCEMENT No Limitations					
17. CASUAL ANNOUNCEMENT Yes					
18. DEFTEST DESCRIPTORS Microelectronics, Miniature electronic equipment, MEMS (Microelectromechanical systems), Military applications					

19. ABSTRACT

This report reviews some research in microelectromechanical systems (MEMS) published during the period 1999 - 2000. Research in defence applications of MEMS or MEMS research with potential applications for the Australian Defence Organisation are also discussed.