Feature

MEMS sensors: past, present and future

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Abstract

Purpose – To describe the historical development of micro-electromechanical system (MEMS) sensor technology, to consider its current use in physical, gas and chemical sensing and to identify and discuss future technological trends and directions.

Design/methodology/approach – This paper identifies the early research which led to the development of MEMS sensors. It considers subsequent applications of MEMS to physical, gas and chemical sensing and discusses recent technological innovations.

Findings – This paper illustrates the greatly differing impacts exerted on physical, gas and chemical sensing by MEMS technology. More recent developments are discussed which suggest strong market prospects for MEMS devices with analytical capabilities such as microspectrometers, micro-GCs, microfluidics, lab-on-a-chip and BioMEMS. This view is supported by various market data and forecasts.

Originality/value – This paper provides a technical and commercial insight into the applications of MEMS technology to physical and molecular sensors from the 1960s to the present day. It also identifies high growth areas for innovative developments in the technology.

Keywords Sensors, Industrial engineering, MEMS

Paper type Technical paper

The origins of what we now know as micro-electromechanical system (MEMS) technology can arguably be traced back to 1 April 1954, when a paper by Smith (1954), then at the Bell Telephone Laboratories, was published in *Physical Review*. This described for the first time certain stress-sensitive effects in silicon and germanium termed piezoresistance. During the mid-1950s, researchers were starting to investigate whether the same technologies that had yielded the transistor, which subsequently revolutionised the fledgling electronics industry, could be applied to sensors. Might not the bulky electromechanical sensors of the day be replaced by small, rugged devices in the same way that the transistor had replaced the thermionic valve? Smith's paper was followed a year later by what is probably the first publication to consider this possibility (Paul and Pearson, 1955) and during the early 1960s, a series of papers from the Honeywell Research Centre and the Bell Labs described the first silicon diaphragm pressure sensors and strain gauges (Pfann and Thurston, 1961; Tufte *et al.*, 1962). Interest in silicon sensor technology grew dramatically and by the late 1960s a number of pioneering American companies had commercialised the first silicon pressure sensors. These were crude by today's standards (Figure 1) but in the early 1970s developments in micromachining, as it was then called and improvements to silicon processing led to pressure sensors with non-planar diaphragm geometries which yielded superior performance. These were arguably the first true MEMS sensors.

What exactly do we mean by MEMS? The term is something of a misnomer, as not all so-called MEMS devices are "electromechanical" and few are "systems". Nevertheless, the term is now widely applied to all manner of miniaturised devices, generally 3D microstructures of one sort or another, mostly fabricated from silicon and using techniques which are often derived from the microelectronics industry. These include isotropic and anisotropic etching ("microengineering"), various thin film deposition methods, anodic bonding and the well-known masking and doping techniques employed in IC manufacture. Today, silicon microsensors, "lab-on-a-chip" and micro-TAS (micro-total analytical systems) devices are all referred to as MEMS.

So what progress has been made during the half century that has passed since Smith's ground-breaking paper? MEMS technology has been outstandingly successful in the physical sensing context and has yielded a range of small, rugged and inexpensive devices such as accelerometers, strain gauges, microphones, air mass flow sensors, pressure sensors and more recently gyroscopes and yaw-rate sensors. Some have been developed to meet the demanding needs of the automotive industry and are used in their millions in engine management systems, to trigger air bags and in anti-rollover, vehicle stability control and GPS navigation systems (*Sensor Review*, Vol. 26, pp. 231-5). The impact on pressure sensing has been the greatest and almost all applications now use this technology, e.g. in the medical, aerospace, process control, automation and automotive industries. The sophistication of pressure sensors has increased dramatically: today's devices can be exceedingly small and exploit capacitive as well as piezoresistive effects; they are doped by ion implantation rather than diffusion and employ non-planar diaphragms; and, since the 1980s, many have featured on-chip signal processing and generate digital outputs. Figure 2 shows such a device. Accelerometers have undergone a similar technological evolution and many are fabricated by

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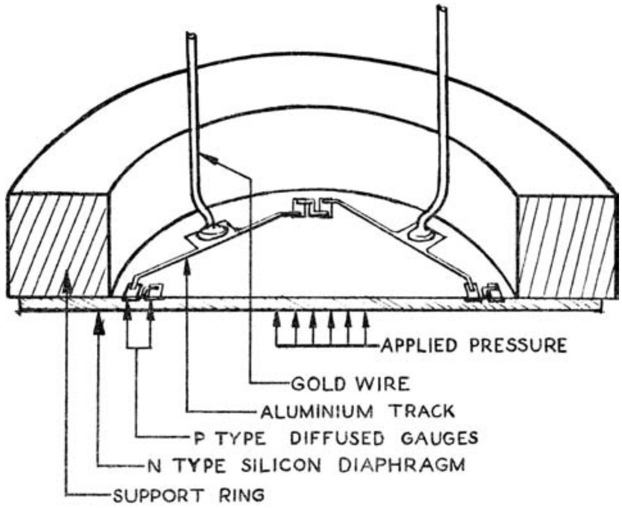
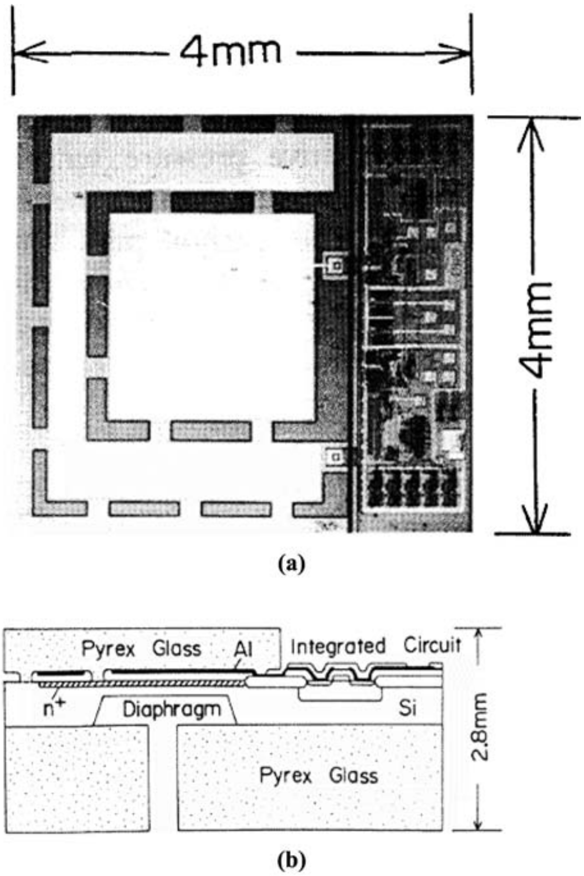
Figure 1 Schematic section of an early silicon pressure sensor



Note: The planar (non-microengineered) diaphragm mounted on the support ring and diffused rather than implanted "gauges" (piezoresistors)

Figure 2 Modern MEMS pressure sensor with integrated electronics, showing non-planar microengineered diaphragm



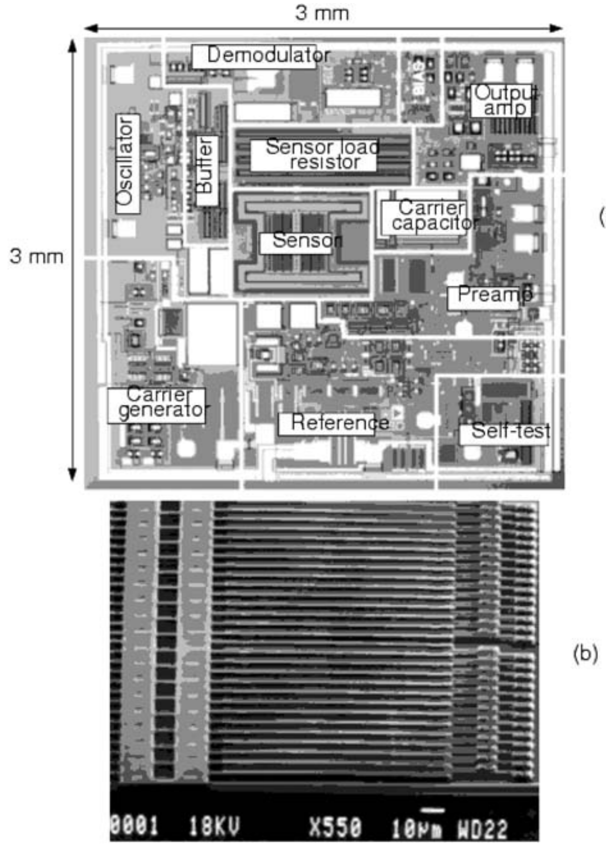
(a)

(b)

Notes: (a) Image of Sensor; (b) Schematic cross-section

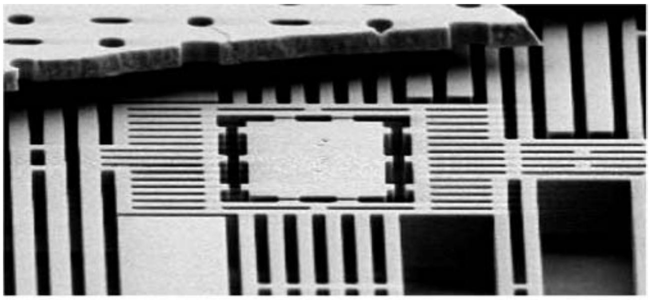
advanced surface micromachining techniques which allow them to sense in one, two or three axes (Figure 3). Many also feature on-chip electronics, over-range stops and self-test functions but the previously mentioned yaw-rate sensors, which feature very complex geometries, are probably the most sophisticated MEMS sensors yet to enjoy high volume production (Figure 4). However, these do not even approach the complexity of Texas Instrument's digital micromirror devices (DMDs). Although not sensors, they warrant mention

Figure 3 Surfaced micromachined MEMS accelerometer



Notes: (a) Overall chip structure showing sensor and electronics; (b) Micrograph of sensing element (Analog Devices, Inc.)

Figure 4 Micrograph of part of an automotive yaw-rate sensor showing complex MEMS microstructure



Source: Robert Bosch

as they are widely recognised as being the world's most complex MEMS products and are used in the company's digital light projection systems. Invented by Larry Hornbeck of Texas Instruments in 1987, DMD chips (Figure 5) comprise a rectangular array of up to two million hinge-mounted, individually addressable microscopic mirrors, each electrically coupled to the integral electronics. Figure 6 shows a schematic of a mirror and support structure and an electron micrograph of part of the structure is shown in Figure 7.

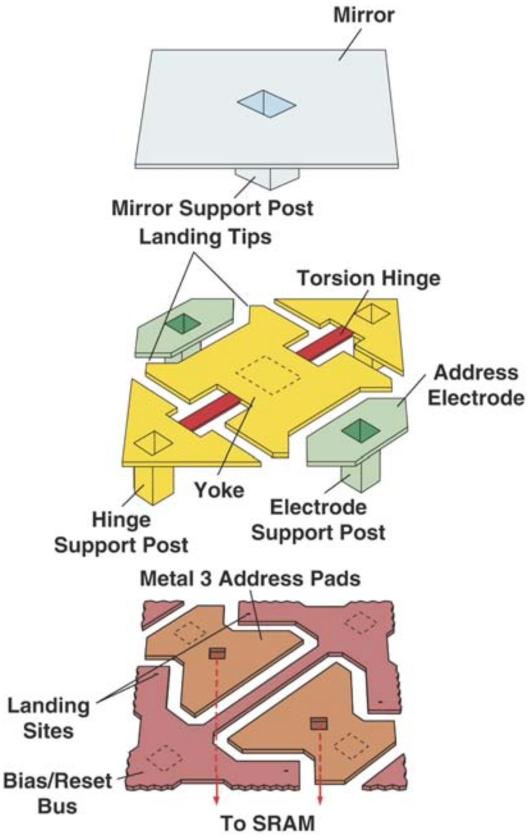
Following on from the early successes in physical sensing, during the 1970s the research community turned its attention towards the use of silicon technology in gas sensing. Here, the impact of MEMS has been far less dramatic, with very few products yet in high volume production. Silicon GasFETs (gas-responsive field effect transistors) where amongst the first to be investigated (Lundstrom *et al.*, 1975) and involve replacing the FET's aluminium gate with a gas-sensitive material such as platinum or palladium. However, despite three decades of research, these have so far failed to meet their early promise and still only satisfy niche applications. The major present-day gas sensing application of MEMS is the use of microengineered silicon substrates in metal oxide gas sensors, often termed "micro-hotplates". These are relatively simple devices but several more complex MEMS-based gas sensors based on techniques such as NDIR (non-dispersive IR absorption), thermal conductivity and photoacoustics, together with micro-spectrometers, have recently enjoyed a limited but growing degree of commercial success. However, a problem that often plagues such devices is that, whilst being small, rugged and potentially inexpensive, size reductions often lead to degraded performance. For example, miniaturised NDIR sensors suffer from low sensitivities due to the necessarily short optical path-lengths involved, restricting their use to applications involving relatively high gas concentrations.

At the same time as Lundström was investigating GasFETs, two researchers at Stanford University used the emerging micromachining technology to develop what was then the most complex silicon microstructure ever fabricated: a gas chromatograph, which featured an etched 1.5 m long separation column and injection valve and an integrated thermal conductivity detector (Figure 8). Despite being deployed on one of the Viking mission to Mars, "micro-GCs" (or μGCs) have still only enjoyed limited commercial success

Figure 5 The world's most complex MEMS structure? TI's DMDs contain up to two million micromirrors

Source: Texas Instruments

Figure 6 Schematic of an individual element within TI's digital micromirror device showing the three layers above the RAM

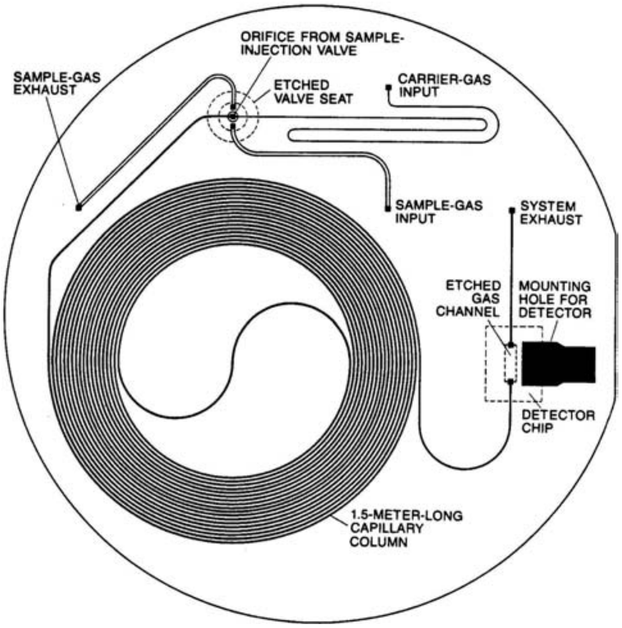


Source: Texas Instruments

Figure 7 Electron micrograph of part of TI's digital micromirror device

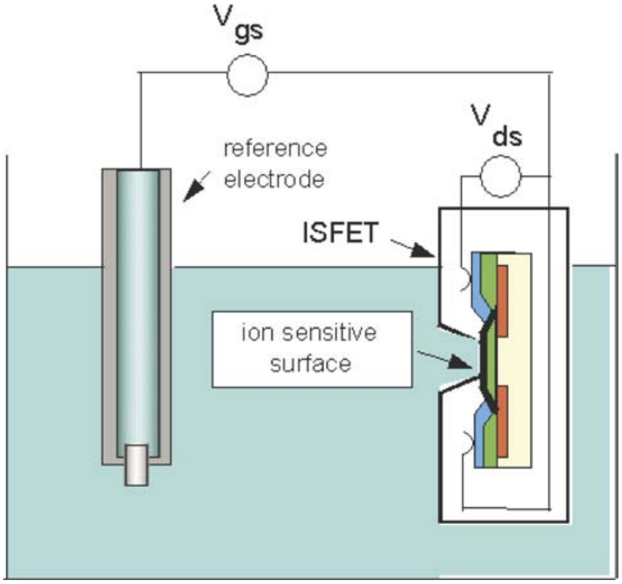
Source: Texas Instruments

Figure 8 Schematic of the silicon gas chromatograph fabricated at Stanford University in 1975



although this development paved the way for research into all manner of other miniaturised analytical instruments for both gases and liquids. These are variously referred to as lab-on-a-chip or micro-TAS devices. Before considering these, silicon ISFETs (ion-selective FET) warrant mention as these were reported even earlier than the GasFET (Bergveld, 1970) and represented the first attempt to apply silicon technology to the sensing of liquid chemicals. As with their gas-responsive counterparts, ISFETs involve modifying a conventional FET but no gate electrode is used and the gate's oxide is coated with a layer of an ion-selective material such as silicon nitride or a polymer (Figure 9). Research activities gained pace during the 1980s and around 30 years after Bergveld's publication, pH-responsive ISFETs became a commercial reality. Being small, rugged and inexpensive, they are progressively replacing their conventional glass counterparts in both portable instruments and fixed systems.

Figure 9 Schematic of an ISFET immersed in a liquid and showing an external reference electrode

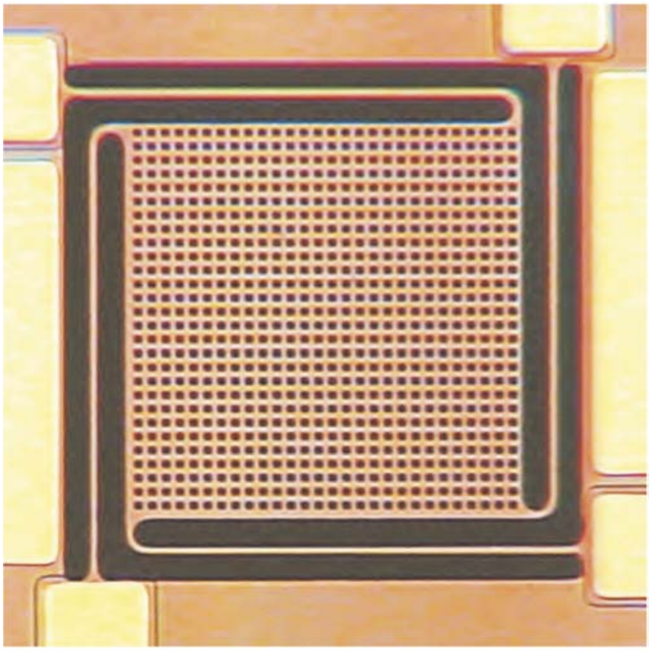


The present-day situation, then, is that MEMS technology has exerted a major impact on physical sensing, a small but growing impact on gas sensing and as yet a minimal impact on chemical sensing. So where is the technology going and will this situation change? As far as physical sensing is concerned, it appears that in the short to medium term at least, it will largely be a case of "more of the same", i.e. new or growing applications for existing sensor types. For example, the consumption of MEMS microphones has taken off dramatically since 2004 as they started to be used in mobile phones. Predictions are for more than 350 million units to be sold in 2008, rising from some 60 million in 2005. The MEMS gyroscope market is also expanding rapidly. In addition to established, but still growing applications in vehicles and defence, new, high volume market sectors are emerging, notably in consumer products. Examples of uses include camcorder, camera and cell phone stabilisation and position sensing in video games such as Nintendo Revolution or Sony Playstation 3. These applications are expected to account for tenth of millions of shipments during the next five years. By 2010, the MEMS gyroscope market is forecast to reach a value of around $800 million, although silicon will compete with both ceramic and quartz technology. The automotive industry's seemingly insatiable demand for MEMS sensors is such that consumption of pressure sensors, yaw sensors, gyroscopes and accelerometers will continue to rise for the foreseeable future.

The future prospects for MEMS in gas sensing are less clear: the market is dominated by many well entrenched optical, electrochemical and other techniques and MEMS faces strong competition. Nevertheless, MEMS gas sensors are the topic of a wide-ranging research effort and one potentially large application where the technology could exert a significant impact is in the automotive sector. Future legislation is expected to stipulate the monitoring of CO, NO_x and unburned fuel (hydrocarbons) in vehicle exhausts and MEMS is one of a number of technologies being investigated. Sensors developed to the prototype stage include silicon and silicon carbide (SiC) micro-hotplates with metal oxide coatings (Figure 10) and SiC GasFETs ("MISiCFETs" – metal insulator silicon carbide FET), which can operate at temperatures of up to 800°C. Often supported by the vehicle manufacturers, this research is underway in America, Europe and Japan but MEMS faces competition from other technologies such as solid electrolytes and thick film devices.

Another application where MEMS gas sensors may play a role is indoor air quality (IAQ) monitoring, particularly for volatile organic compounds (VOCs), and the allied field of detecting toxic organic vapours in the workplace. As yet, no inexpensive sensors exist which can selectively detect compounds such as benzene, toluene and butadiene and many research groups are investigating these applications. Coated micromachined resonators, such as beams and cantilevers, and resonator arrays have been fabricated from silicon and are attracting growing attention in this context. They can be extremely sensitive due to the low masses of the resonators – as little as 10 ng in some cases – and varying

Figure 10 Micro-hotplate gas sensor, micromachined from single crystal silicon carbide, designed in collaboration with MIT



Source: Boston MicroSystems

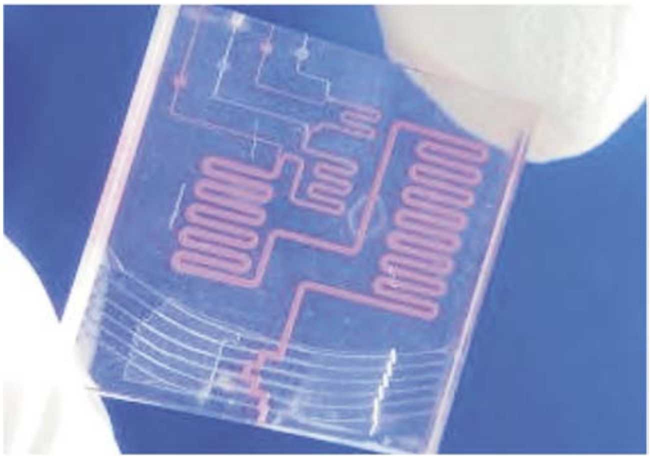
degrees of selectivity can be achieved through the use of appropriate coatings, generally polymers. Other MEMS-based sensors being developed for VOC detection include micro-hotplates and integrated sensor arrays (electronic nose chips) based on metal oxides, coated resonators and acoustic wave devices. Some commercial progress has been made here. For example, AppliedSensor has launched a family of IAQ sensors based on metal oxides and micromachined silicon substrates which can detect a range of oxidising and reducing gases and vapours.

Several other types of MEMS gas sensors are being investigated but to capitalise fully on one of the key capabilities of MEMS, the ability to fabricate sensors with very low unit costs, high volume applications need to be identified. Outside of the automotive industry there are very few examples of this, suggesting that the greatest prospects may arise from applying the technology to more complex gas detection instruments offering analytical capabilities. As noted above, miniaturised gas chromatographs were first developed during the 1970s but recent developments exploiting far more advanced fabrication technologies have yielded improved devices which are now exerting a real impact on the market. Key benefits include small size and rapid response times and some have been applied to IAQ applications and also offer prospects in the booming homeland security markets. Allied research is aimed at the development of all manner of other analytical devices such as mass spectrometers, ion mobility spectrometers, Michelson interferometers and optical spectrometers such as Fourier transform and other types. Some have already been commercialised but to exert a real impact, in many cases performance must be comparable to that of their conventional counterparts and prices must fall. This is something of a "chicken and egg" situation: prices will only fall if volumes increase. Indeed, a recent report (Anon., 2004), predicts that, by 2008, the global market for MEMS spectrometers will reach a relatively modest $96 million per annum. The report notes that "The spectrometer market appeared in 2000 and is growing slowly because current applications volumes are small and new high volume applications have to be found". In many ways, this comment is true for most of the devices listed above but with the ever-growing concern surrounding terrorism and homeland security, needs for portable instruments offering analytical capabilities are expected to stimulate rapid technological development and real market growth.

Analytical functions may also be the key that opens the door to MEMS in the chemical sensing context. Indeed, the capabilities offered by lab-on-a-chip and micro-TAS devices are already having an impact. These exploit analytical techniques such as liquid chromatography, spectrophotometry or electrophoresis in instruments fabricated in a miniaturised format. As a key function is the transport and manipulation of minute volumes of liquids, sometimes as little as a few nano-litres or even pico-litres, they utilise all manner of microfluidic components and sub-systems for sample and/or reagent delivery and mixing. These comprise often complex arrays of channels, pumps, nozzles and valves which can be etched into silicon, quartz, plastic or glass (Figure 11). Indeed, since the advent of the inkjet printer head, so far the most commercially successful MEMS-based microfluidic device, microfluidics has emerged as a technological discipline in its own right which is now being investigated at numerous national laboratories and universities. Its importance is well illustrated by the growing number of companies offering microfluidic components and recent market research which predicts that revenues for microfluidics will grow at a compound annual growth rate (CAGR) of 10.3 per cent, from nearly $1.7 billion in 2003 to more than $2.7 billion in 2008.

The perceived benefits of lab-on-a-chip devices are their portability, improved analytical speed, better separation efficiency, reduced sample and reagent consumption and lower costs. They are now becoming a commercial reality, although market development has been gradual rather than dramatic, with key applications emerging in

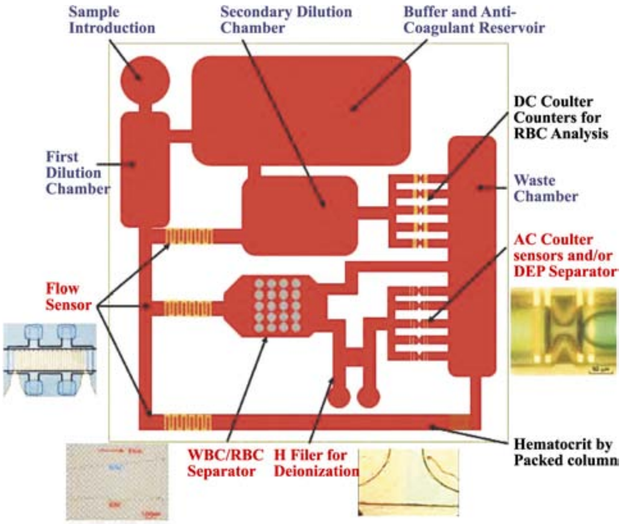
Figure 11 Microfluidic channels in a glass lab-on-a-chip device for the colorimetric monitoring of ammonia in water



point-of-care diagnostics and life science research such as genomics and drug screening. The market is forecast to grow at a CAGR of 31.3 per cent to 2008 and although devices for point-of-care applications (Figure 12) are expected to continue to dominate unit shipments during this period, recent security concerns involving liquid chemicals at airports suggests strong prospects in homeland security. The ability to analyse a single drop of liquid in minutes or even seconds by customs officials, first responders and forensic teams would clearly be of immense value.

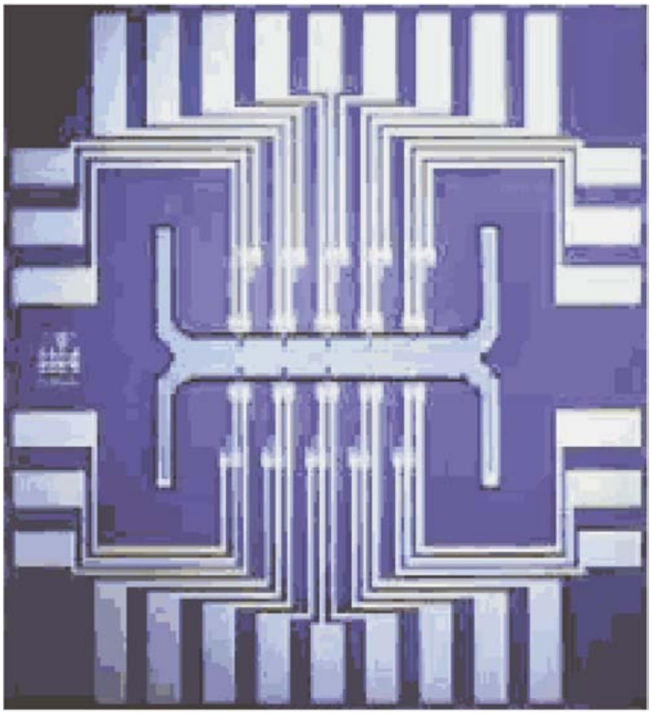
One of the most exciting and dynamic fields of MEMS technology is BioMEMS – biological micro-electromechanical systems. This is the application of MEMS to the biomedical and health sciences and involves incorporating biological sensing functions or materials into MEMS devices. One of the most significant BioMEMS applications is the miniaturised PCR (polymerase chain reaction) system and an example is the In-Check™ product developed by electronics giant ST Microelectronics. Based on silicon technology, this integrates all of the functions needed to identify a given oligonucleotide sequence in a sample and includes the microfluidic handling system, a miniaturized PCR reactor and a custom microarray. The chip is mounted on a 1 × 3 in. plastic slide that provides all of the necessary mechanical, thermal, electrical and fluidic connections. A fascinating BioMEMS development at the Technical University of Denmark involves the ubiquitous microengineered silicon cantilever structure, as used in both physical and gas sensing. Here, the cantilevers are functionalised so that specific molecules bind to one side of them, causing them to bend. The bending can be detected very precisely by integrated piezoresistors in exactly the same way as in a MEMS accelerometer and is proportional to the concentration of the bound molecules. The length of the cantilevers is 400 μm and the total dimension of the chip is a mere 6 × 5 mm, including the channel for the liquid transport (Figure 13).

Figure 12 Schematic of lab-on-a-chip device for point of care use. A single drop of blood can be analysed for red and white blood cells, lipids, proteins or oxygen molecules



Source: National Space Biomedical Research Institute

Figure 13 This prototype BioMEMS chip features ten cantilevers, with five on each side of the common liquid handling channel



Source: Technical University of Denmark

One of the problems facing BioMEMS technology is that microfabrication processes, especially those involving silicon, are not compatible with biomolecules. Silicon and metals have crystalline structures and are processed under harsh conditions with acids, bases and organic solvents at high temperatures. In comparison, biomolecules such as DNA and proteins have complex, three-dimensional structures and are sensitive to denaturation, oxidation, hydrolysis and thermal destruction. However, very recent and potentially ground-breaking research by a team from the Biotechnology Research Institute at the Hong Kong University of Science & Technology (Trau *et al.*, 2006) appears to have overcome this problem. For the first time a silicon/glass substrate was immobilised with DNA and protein molecules and then subjected to micro-fabrication processes. Silicon and oxide etching as well as metal deposition, lift-off process steps and mechanical manipulation were carried out, leaving the DNA molecules intact by using a novel passivation technique. It was shown that this preserves around 84 per cent of the bio-functionality of the DNA and 30 per cent of that of the protein. Most importantly, the process is photolithography-based and scalable for mass production, opening up all manner of interesting BioMEMS possibilities.

Overall, MEMS technology has exerted a significant impact on sensing practices and as more complex and sophisticated devices are developed in response to emerging needs in a wide range of industries, its future prospects look bright.

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