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Overview of MEMS sensors and the metrology requirements for their manufacture

NMS Programme for Engineering Measurement
2005 - 2008

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ABSTRACT

The MEMS sensor market is growing rapidly. However, the metrology that supports the fabrication of MEMS sensors is struggling to keep pace with the expanding limits of MEMS technology. The purpose of this report is to gauge the metrological requirements of the MEMS industry, review current MEMS manufacturing and metrology techniques, and highlight how metrology affects some of the key types of MEMS sensor (pressure sensors, accelerometers, gyroscopes, RF sensors and microfluidics). The metrology techniques reviewed include profilometry, micro co-ordinate measuring machines, electron microscopy, optical microscopy, white light interferometry and laser Doppler velocimetry. The emphasis is on dimensional metrology although other measurements are covered where appropriate. Finally, the report summarises the metrology requirements of the UK MEMS industry based on discussions with the key UK companies.

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1 INTRODUCTION

The development and manufacture of miniature mechanical structures has been carried out for hundreds of years, most notably by watchmakers. The manufacture of objects with very small dimensions and even smaller tolerances is often referred to as 'precision engineering'. Microengineering is a relatively new technology, only about twenty years old, which primarily utilises technology borrowed from the microelectronics industry. However, microelectronics generally makes use of two dimensional design and fabrication whereas microengineering requires precise manufacturing in three dimensions.

The acronym MEMS stands for microelectromechanical systems and was first used in the USA in the 1980s. In Europe the phrase MST (microsystems technology) is also used in place of MEMS and the Japanese use the term micromachines. For the purpose of this report we will use the acronym MEMS. In science and engineering the emergence of new technologies normally has two drivers. Firstly there is the discovery of a new technology or the drive to find a new technology. Secondly there is the need for a solution to solve a specific engineering problem. MEMS technology could be said to consist of both these factors as it is a relatively new technology and yet, on the other hand, it offers an improved way of manufacturing existing devices.

This report is part of a project funded under the DTI National Measurement System Engineering Measurement Programme 2005 – 2008 'Metrology for Advanced Sensors'. The principle reason for writing this report is to advise the formulation of the subsequent research and development parts of the project based upon these findings and discussions with the key industrial UK companies currently manufacturing MEMS sensors.

This report is in two sections: chapters 2 to 5 look at current MEMS sensor technologies, fabrication techniques and common failure modes. Some knowledge of this is required to appreciate chapters 6 onwards which concentrate on the limitations of current metrology for the MEMS industry and industrial requirements.

1.1 SENSORS

The field of sensors is very wide and there is some debate about the exact definition of a sensor. The Oxford English dictionary's definition is '*noun; a device which detects or measures a physical property and records, indicates or otherwise responds to it*'. This report will generally concentrate on the transduction elements of sensors and not the larger measurement system.

In the last twenty years or so there has been an enormous increase in the information processing capability of electronics; mostly due to the personal computer and the ready availability of inexpensive microprocessors for embedded systems. This has had a large effect on functionality of control systems and this control capability has expanded so has the requirement for accurate, inexpensive and easily embedded sensors. Note, however, that MEMS technology is also extensively used to manufacture actuators and many of the findings in this report relate to both sensors and actuators, indeed many active sensors require internal actuation

1.2 MEMS

It is evident that the number of microscale sensors in our environment is set to increase. In some markets they are well established such as pressure sensors, gyroscopes and ink jet nozzles, which currently account for two thirds of the MEMS sensors market (Nexus, 2005). One of the reasons for the success of MEMS technology is that the largest enabling technology, the integrated circuit industry, is already mature. Intel founder Gordon Moore's prediction, popularly known as Moore's law (Moore, 1965), which predicts that the number of transistors on a chip doubles every eighteen months is relevant to MEMS sensors in that, not only does manufacturing capability increase, but also the cost per sensor will reduce significantly making MEMS sensors an increasingly attractive option. MEMS are able to reduce the size, weight, power consumption, whilst increasing reliability and performance of existing macroscopic devices. Through MEMS it is also possible to make devices previously not possible at a macroscopic scale.

2 MEMS FABRICATION TECHNIQUES FOR SENSORS

The most popular fabrication techniques for MEMS sensors have already been used extensively in the semiconductor industry. These techniques are essentially two dimensional while the third dimension is created by layering. Micromachining techniques allow further structuring of devices in the third dimension, although this is limited and complex three-dimensional fabrication is still in its infancy (Beeby *et. al.*, 2005). This chapter will provide a brief introduction to the techniques used to fabricate MEMS devices and further reading can be found in the references cited in the text.

2.1 DEPOSITION TECHNIQUES

There are many deposition techniques in common use for MEMS manufacture. The selection of which technique would be most applicable is dependant on the type of material being processed, the thickness of the material and compatibility with previous or future steps in the manufacturing process.

2.1.1 Vacuum deposition

In the vacuum deposition process, a source material is placed in a deposition vacuum chamber with the sample. Ion bombardment or thermal evaporation then excites the atoms from the source material onto the sample. Precise thickness monitoring is possible through *in situ* monitoring.

As vacuum deposition is a line of sight technique there can be issues with shadowing effects. Vacuum deposition is commonly used for deposition of pure metals, however, low deposition rates mean vacuum deposition is seldom used for layers that are over 1 μm in thickness.

2.1.2 Chemical vapour deposition

In the chemical vapour deposition (CVD) process, gases are passed over the surface of a heated substrate and a film is formed by the reaction of the gas at the surface. CVD produces conformal coatings and is commonly used for films over 1 μm in thickness.

Low pressure CVD (LPCVD) is widely used in the semiconductor industry for the deposition of polysilicon. Residual stress can lead to deformation of the device, delamination or stress fractures. For MEMS devices annealing can be used to control the residual stress in amorphous silicon and polysilicon, deposited layer stresses can be as high as 400 MPa (Beeby *et. al.*, 2004) and can be tensile or compressive for amorphous silicon and polysilicon respectively. Annealing can be used to control the residual stress to ± 10 MPa. Alternatively, using opposing layers of polysilicon and amorphous silicon it is possible to balance the stress.

2.1.3 Epitaxy

Epitaxy is a specialised thin film deposition technique involving ordered crystalline growth on a single crystalline substrate. The technique of epitaxy can be used to deposit silicon with clearly defined doping levels that can then be used as an etch stop. For MEMS applications the most useful property of epitaxial silicon is that it can be grown selectively as silicon dioxide and silicon nitride. This can then be used to form three dimensional microstructures.

2.1.4 Silicon dioxide and silicon nitride deposition

LPCVD deposited silicon nitride is a good material for masking against potassium hydroxide wet etching. However, the deposition temperature is in the range of 700 °C to 800 °C, therefore, it cannot be used on aluminium wafers, which will melt at this temperature. Also intrinsic stresses in silicon nitride can reach 1 GPa and as a result layers of over about 200 nm are liable to crack or delaminate, while freestanding structures can be prone to fracture. Lower stress LPCVD films can be deposited by increasing the ratio of silicon to nitrogen or adding nitrogen oxide to the reaction gases and depositing silicon oxynitride.

Plasma enhanced chemical vapour deposition (PECVD) processes utilise plasma to enhance chemical reaction rates of the precursor materials. PECVD allows deposition at lower temperatures, which is often critical in the manufacture of semiconductors. When silicon nitride is deposited by PECVD, deposition typically occurs in the temperature range 250 °C to 350 °C allowing it to be used on wafers containing aluminium. However, if deposition is allowed to take place at higher temperatures then, at around 600 °C stress switches from compressive to tensile, allowing the deposition of very low stress films.

2.1.5 Spin coating

Spin coating is a procedure to apply thin films to flat substrates. Spin coating involves the placing of a material as a liquid on a substrate - upon spinning on a motorised chuck the liquid spreads into a thin layer. The deposition then solidifies through evaporation and polymerisation. This technique is often used for deposition of photoresist, spin coating can be used for silica-based glass *via* a sol gel process.

2.2 LITHOGRAPHY

Lithography is the imprinting of a pattern from a mask onto a layer of radiation sensitive resist. The resist is usually spin coated onto the wafer and a mask is placed above the wafer. Optical radiation then passes through the clear parts of the mask and changes the solubility of the resist; it can be either positive or negative depending on the resist. The majority of lithography in the IC industry uses optical rather than x-ray or electron beam techniques as masks are simpler. For optical lithography masks can be in contact with the wafer, known as shadow printing. This technique allows for higher resolution but often results in mask damage. The alternative is known as projection printing; resolution is not as high but mask damage is minimised. MEMS devices frequently require double sided processing which requires both sides of the wafer to be aligned to each other. Alignment equipment is available for double sided fabrication, the most accurate equipment available clamps to the wafer and uses an image featuring crosshairs on the wafer. Alignment can be achieved to around 1 μm. Grayscale lithography is an alternative technique that uses varying gray levels on the mask to vary the exposure at different points on the mask, this can then be used to create topographical features.

A rapid prototyping technique called stereolithography, also known as three dimensional (3D) layering or 3D printing, allows the creation of solid, plastic, 3D objects from CAD drawings. The 3D printer's laser 'paints' one of the layers, exposing the liquid polymer in the tank and hardening it. The platform drops down into the tank a fraction of a millimetre and the laser paints the next layer. This process repeats, layer by layer, until completion. Once the CAD model is complete, the object is rinsed with a solvent and then baked in an ultraviolet oven to cure the plastic.

Microstereolithography has evolved from the stereolithography technique, and is also based on light-induced layer-stacking manufacturing. Because the dimensional resolution of the microstereolithography technique is far greater than that for other rapid prototyping technologies, this technique is of particular interest in the MEMS domain where its 3D capability allows the production of components that no other microfabrication technique can create. The UV laser beam can be focused down to a spot size less than 1 μm. Overhanging features can also be realised by sacrificial support structures but removal of these supports can be challenging. Most microstereolithography systems build polymer parts but systems making ceramic parts have been developed. Microstereolithography systems can be divided into two groups: scanning and projection. Scanning systems move the laser beam over the whole work piece with an X-Y stage, which removes the need for scanning mirrors. Alternatively, in projection microstereolithography, each layer of the microstructure is exposed to a projected digital image of the layer design.

2.3 ETCHING

Wet etching is the dominant technique in MEMS manufacturing. Wet etchants for silicon dioxide, silicon nitride and aluminium are isotropic, whereas etchants for silicon can be either isotropic or anisotropic. Wet anisotropic silicon etching in particular is useful to MEMS fabrication. A crystalline material is immersed in a liquid that attacks particular planes of the crystal (mostly commonly etching of silicon by KOH or EDP). Dry etching is done in weak ionised plasma within low vacuum conditions. Dry etching is usually a combination of chemical and physical etching. When masked correctly these etching techniques can produce structures of the order of hundreds of micrometres with well-defined geometries and excellent surface quality.

2.4 LASER MICROMACHINING

The most common use of laser micromachining is micro drilling. Maskless drilling focuses the laser spot down to the required diameter, collimates it then a pulse laser ablates the required amount of material. For microdrilling using masks the material is ablated through apertures in the mask. Excimer lasers have been used to drill into polymers with diameters less than10 µm and aspect ratios of up to five to one.

2.5 WAFER BONDING

Wafer bonding is used extensively in the fabrication of MEMS devices. An example is bonding together wafers to form a vacuum cavity in an absolute pressure sensor. For all bonding techniques surface cleanliness and stress created by the bonding process is of importance. Therefore, thermally matching a bond will avoid stress within the device during temperature change.

Silicon fusion bonding is a technique that does not use any melting alloys or polymer glues and the silicon-to-silicon bonding technique means that there is negligible stress. After cleaning, two wafers can be joined together by van der Waals forces, the bond can then be strengthened to allow hermetic sealing by heat treating in a furnace or by radio frequency (RF) and microwave heating. Anodic bonding is used to bond silicon to glass using the electrostatic attraction between glass and silicon. Eutectic bonding uses the eutectic properties of each material having a lower combined melting point than individually. Joints formed using this technique are hermetically sealed although as different materials are used there is often a thermal expansion mismatch which can result in internal stresses. Adhesive bonding can also be used, although this technique is not suitable for hermetic sealing, it can provide some stress relief for the wafers. Bonding can be executed during the fabrication process to trap a vacuum in a cavity, which may contain a moving part and hence reduce damping. In this case bonding must be carried out within a vacuum although a getter is often required for anodic bonding.

2.6 ELECTROPLATING

Electroplating is a key technology in MEMS manufacturing for obtaining thick layers of metal and alloy. To produce a patterned electroplated layer on to silicon a resist pattern must be applied. Metal ions are deposited onto the conductive surfaces by passing a current through a suitable electrolytic bath.

2.7 LIGA

Lithographie Galvanoformung Abformung (LIGA) can be used to achieve high aspect ratio structures (Beeby *et. al.*, 2004). A sacrificial layer is selectively etched through a mask by synchrotron x-ray radiation, this forms a mould that electroplating fills. The remaining resist can then be etched leaving the electroplated parts attached to the substrate. The use of a highly collimated x-ray source allows structures to be manufactured with sidewalls with aspect ratios of over 100:1. LIGA is expensive and not well suited to mass production. However, it is possible to electroplate a metal master that can then be used for injection moulding mass production. UV based LIGA can be used to directly expose deep structures in resists such as SU-8.

3 MEMS PACKAGING

As with other MEMS technologies MEMS packaging is primarily derived from the IC industry. However, the requirements on MEMS packaging are more stringent than for microelectronics. This is because hermeticity, and stresses and strains are tolerable within microelectronics, providing they do not affect the device reliability. However, these parameters will directly affect the performance of a MEMS sensor. Therefore, MEMS packaging needs to be specific to its application, encompassing design, material selection and processes (Beeby *et. al.*, 2004, Reichl and Grosser, 2001), as this will directly dictate the functional performance and reliability requirements of the packaged device. Common technical challenges faced when packaging include: cost, size, package stresses, electrical shielding, tolerance to foreign particles and hermeticity.

MEMS packaging costs account for 70% to 90% of the device compared to 30% to 95% for an IC device (Evans, 2004). The primary drivers for increased cost in MEMS packaging include: package stress, particle protection during manufacturing, hermeticity requirements and lower production volumes. Design modelling of packaging will help designers remove redundant features in MEMS component packages and help drive cost down. However, accurately modelling total system performance is challenging when combining the package, components, adhesives, interconnections and possible effects on the package from board mounting, thermal conditions, *etc*.

3.1 PACKAGING MATERIALS

Material selection is critical to minimise package stress and outgas contamination of MEMS structures. Ceramic materials generally have excellent electrical, thermal and mechanical properties and can be hermetically sealed. Plastic packaging is a relatively low cost packaging material. The molding resins are a mixture of chemicals, specifically developed to obtain the required characteristics including viscosity, adhesion and ease of mold release, *etc*. Metal packaging generally offers the highest reliability. Electrical connections are often sealed with glass. Common metals used for packaging include Kovar, cold rolled steel, copper molybdenum and silicon reinforced aluminium.

Further reading on MEMS packaging materials can be found elsewhere (Menz and Dimov, 2005).

3.2 PACKAGING TECHNOLOGIES

Packaging technology can be divided into two separate classes: capped and non-capped. For example, an uncapped pressure sensor uses a diaphragm that is subject to strain as pressure is applied on both sides. A capped absolute pressure sensor has hermetically sealed pressure on one side of the diaphragm, while a differential pressure sensor has direct contact with the environment on both sides. Therefore, the packaging will vary dramatically between absolute and differential pressure sensors.

MEMS components can be fragile and so are typically sealed from the environment using a lid or cap. Capped product examples include accelerometers, gyroscopes and RF switches. Hermeticity is also a common requirement for capped devices. The lids/caps can be implemented using discrete assembly, wafer-to-wafer-level bonding and wafer processing techniques.

The discrete assembly of MEMS, electronics and lids/caps requires pick-and-place equipment that can handle a variety of bare die, substrate and lid components. Attachment materials must be compatible with the overall assembly and not outgas onto the fragile MEMS structures (Reichl and Grosser, 2001).

Wafer-to-wafer-level bonding has been applied to MEMS for capping (Sparks *et. al.*, 2001). It requires precise alignment of wafers, and then bonding of the wafers in a gas or vacuum environment. Components are subsequently processed and diced for final packaging.

Wafer processing techniques allow for a vacuum-sealed environment in a wafer-processing step, but are not compatible with all MEMS sensor products. This technique creates a hermetic seal with a lid that is strong enough to protect the microstructure during packaging process steps.

Non-capped product examples include pressure sensors and nozzles that require direct contact between the MEMS and the environment, therefore, they do not require a sealed lid/cap. An unsealed gel lid or cap may be used to protect other parts of the MEMS device.

4 MEMS SENSORS

This chapter gives an introduction to the various MEMS sensors currently in use, explains their principles of operation and indicates how improved metrology can enhance device performance, yield or reliability. The chapter covers pressure sensors, accelerometers, gyroscopes, force sensors, microfluidics and electrical sensors. It is evident that all these sensors are likely to increase their market share in the near future.

4.1 MEMS PRESSURE SENSORS

Pressure sensors are one of the most commonly used forms of MEMS sensor (Nexus, 2005). They are found in a wide and expanding area of applications ranging from blood pressure monitoring, washing machines, car exhausts to hydraulic systems and aeronautics. This section will discuss the most common designs of MEMS pressure sensors and summarise the metrology requirements. Generally, pressure sensor design can fall into three categories:

- Absolute pressure sensors that measure pressure relative to a vacuum reference.
- Gauge pressure sensors that measure relative to ambient pressure.
- Differential pressure sensors.

Pressure sensor selection and design needs to take into account which of these methods would be best suited to the sensor application along with other factors such as long term drift, linearity, sensitivity and temperature effects.

Along with accelerometers, pressure sensors are one of the most successful applications of MEMS devices - they account for a significant share of the MEMS market and the area of applications is further expanding. Traditional pressure sensing techniques, such as manometers, aneroid barometers and Bourdon tubes, are under increasing competition from MEMS based sensors. This is primarily because of the faster response time of MEMS based sensors making them more suitable for dynamic requirements and less invasive on the system application. MEMS pressure sensors are generally diaphragm based and there are several different established techniques for sensing the diaphragm deflection. Most common amongst these techniques are piezoresistors acting as strain gauges on the diaphragm surface and capacitance measurements between the diaphragm and a fixed electrode on the sensor housing.

4.1.1 Diaphragm pressure sensors

Diaphragm based pressure sensors are a well-established technique for MEMS pressure sensors. Research first began in the 1960's into diaphragm based solid-state pressure sensors (Sanchez, 1963). The principle of the design is that pressure deflects the diaphragm until it is balanced by the elastic reaction force of the diaphragm. The most common method of diaphragm fabrication is anisotropic wet silicon etching which allows a high degree of control of the diaphragm dimensions (Beeby *et. al.*, 2004). Wet potassium hydroxide etching produces sidewalls in parallel to the <111>

planes, *i.e.* 54.7° with a <100> wafer orientation. The diaphragm thickness is controlled by the etch time.

An advantage of using silicon is its durability - it does not become plastically deformed and returns to its original dimensions and tension. Also, silicon diaphragms usually only fail due to rupturing (Wilson, 2005). As a result pressure sensors are often designed to have a maximum range of one and a half times the pressure expected in a system. This is achieved by increasing the diaphragm thickness, but increasing thickness results in a loss of sensitivity by a factor of four for every doubling of diaphragm thickness. Devices are, therefore, regularly shielded in a stainless steel enclosure as a protective measure against rupturing. Bossed diaphragms (Figure 1) are also used extensively to increase the device sensitivity by increasing the rigidity of the diaphragm, therefore, inducing higher stresses than a non-bossed diaphragm for an equal deflection. Bossed diaphragms also enable improved linearity in the sensor (Di Giovanni, 1982).

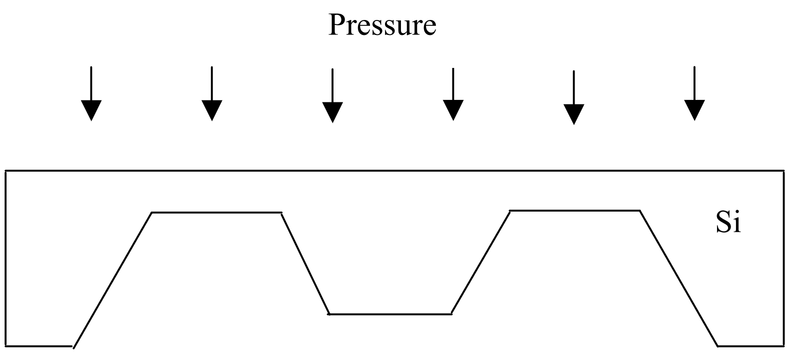

Figure 1 Schema of a cross section of a bossed diaphragm

4.1.2 Piezoresistive pressure sensors

Piezoresistive pressure sensors use diffused or implanted resistors that measure the strain on a silicon diaphragm. This type of piezoresistive pressure sensor is widely available and is commonly used for applications in the automotive industry on, for example, manifold pressure sensors (Goldman, 1998) or monitoring diesel injection pressure (Marek and Illing, 2002). A layout with the resistors placed on the edge of the diaphragm, orientated in the same direction and in a bridge configuration around a boss results in each resistor experiencing an equal and opposite force, improving linearity and minimising temperature cross-sensitivity. Because manufacturing tolerances on the resistors are relatively large, piezoresistive based devices often require the use of a temperature sensor and require calibrating or the use of a dummy bridge (Akbar and Shanblatt, 1993). In 1992 Honeywell designed a bossed and ribbed diaphragm with piezoresistors (Johnson, 1992). The resistors were located on the top of the rib, therefore, magnifying the stress. The basic layout of a piezoresistive bridge diaphragm is shown in Figure 2.

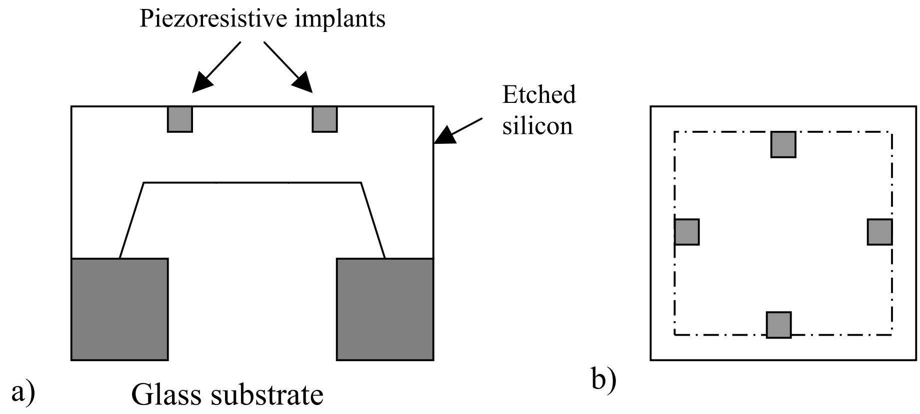

Figure 2 a) Side view of etched silicon anodically bonded on glass substrate b) piezoresistors viewed from above on a square diaphragm

A further method, now commonly used, for improving device performance is the use of meandering resistor patterns (Dziuban, 1994). Meander resistors incorporate different levels of doping in each direction, improving the strain sensitivity and also the length of the resistor is increased resulting in improved sensitivity. Silicon on insulator (SOI) wafers offer a number of benefits to MEMS pressure sensors, primarily because the buried insulator can act as an etch stop allowing precise control of the diaphragm thickness (Diem, 1995). SOI has also been used for high temperature sensor applications as an electrical insulator on a pressure sensor that has been demonstrated up to 600 $^{\circ}$C (Ned *et. al.*, 1998).

Diaphragms can be made from a range of materials using surface micromachining techniques. For the fabrication of a polysilicon diaphragm (Guckel, 1991) a wet etch is used to remove a sacrificial silicon dioxide layer, while the lateral dimensions are defined by the oxide layering. This process allows vacuum sealing during fabrication, resulting in a device that can be used as an absolute pressure sensor. Silicon nitride diaphragms have been fabricated with a polysilicon sacrificial layer by Sugiyama (1986). A side view of this device is shown in Figure 3.

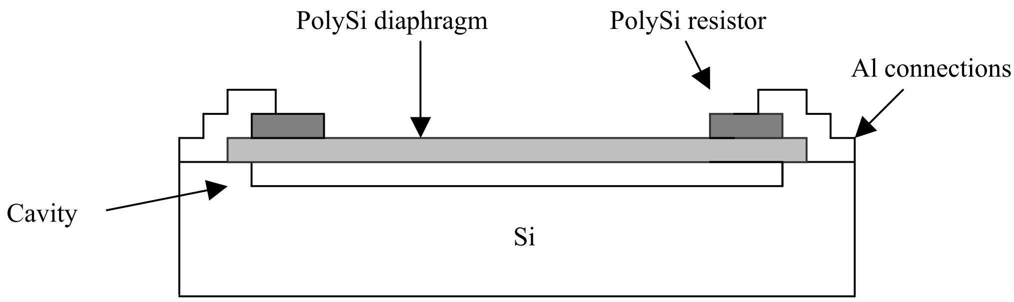

Figure 3 Cross section through a polysilicon diaphragm sensor

More elaborate pressure sensing structures can be realised using surface micromachining techniques. For example, a dual beam pressure sensor has been developed (Melvas *et. al.*, 2002) that uses a cantilever attached to the underside of a diaphragm acting as a mechanical lever that amplifies the strain. A cross section of a cantilever pressure sensor is shown in Figure 4. The sensor is temperature compensated by a dummy cantilever with a piezoresistor that is not coupled to the diaphragm.

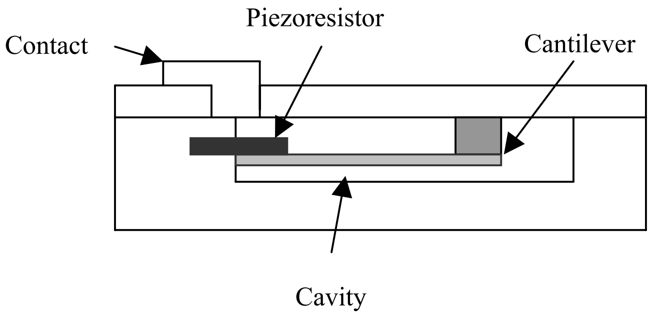

Figure 4 Cross section through a cantilever beam pressure sensor

4.1.3 Capacitive pressure sensors

Capacitive MEMS pressure sensors were first developed in the 1970's (Sander *et. al.*, 1980). Capacitive sensors have high sensitivity, low power consumption and low temperature sensitivity. A cross section through a typical capacitive pressure sensor (Lee and Wise, 1982) is shown in Figure 5.

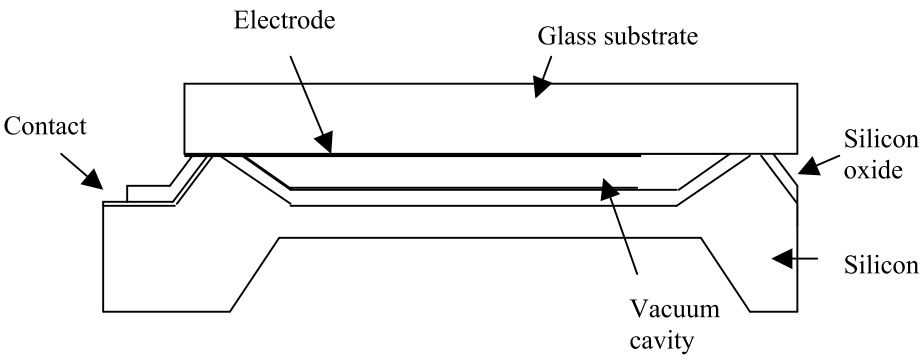

Figure 5 Cross section through a capacitance based pressure sensor

Capacitive sensors can suffer from cross sensitivity to acceleration. However, this problem can be overcome by employing an extra electrode on an additional diaphragm. Between the two diaphragms the capacitance electrodes will pickup pressure but not acceleration due to the fact it is in a sealed cavity (Mulkins and Pogany, 1989). Capacitive sensors also suffer from non-linear output. This can be moderated to a certain extent by the use of bossed diaphragms (Beeby, 2000) or measuring the capacitance at a point offset from the centre of the diaphragm; this improves nonlinearity but leads to a loss of sensitivity (Hyeonchol, 1997). Another technique is to constrain the diaphragm at its centre point; this improves linearity of the sensor but again at the loss of sensitivity (Omni, 1997). If the diaphragm is pressurised to contact with the fixed electrode, the sensor is relatively linear as pressure increases from that point. This has been used as a method of reducing nonlinearity, but the device is then susceptible to stiction and hysteresis (Wang and Ko, 1999). Capacitive sensor arrays are easily fabricated in a range of different sensitivities across the wafer and can then be deployed in an array, thus extending the sensing range of the system. This type of array has been applied to medical sensor systems for intravascular blood pressure measurements (Kandler, 1992). The advantages and disadvantages of capacitive against piezoresistive techniques are summarised in Table 1.

Table 1 Comparison of piezoresistive and capacitance based pressure sensor techniques

	Disadvantages	**Advantages**
Piezoresistive	Temperature sensitive	Smaller structure
Capacitive	More complex electronics	Higher sensitivity

4.1.4 Resonant pressure sensors

Resonant pressure sensors use a resonant mechanical mechanism working as a strain gauge to sense the deflection of the diaphragm. Resonant pressure sensors often offer a higher specification than piezoresistive or capacitive designs. However, they are generally more challenging to fabricate for several reasons: the mechanical resonator needs to be engineered onto the diaphragm, the inclusion of an excitation and detection mechanism for the resonator and vacuum sealing of the cavity. The earliest MEMS resonant pressure sensors appeared in the 1980’s (Greenwood, 1984) and were brought to market by Druck, now GE Sensing (Druck RPT). A cross sectional view of the sensor and plan view of the resonator is shown in Figure 6.

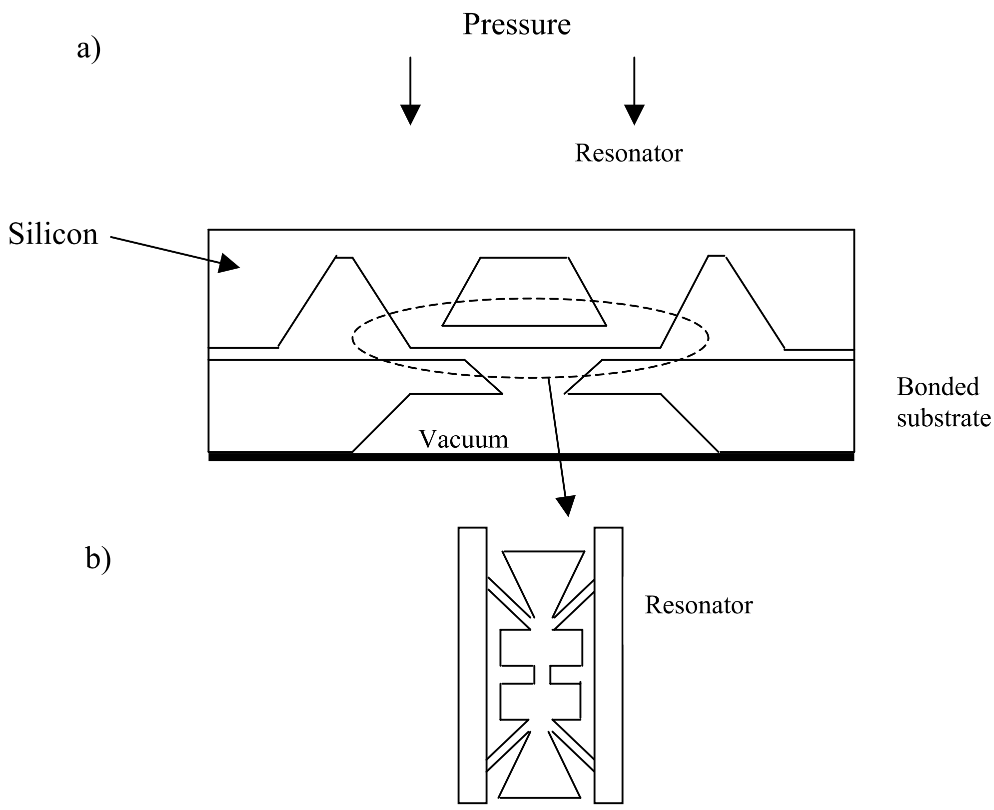

Figure 6 a) Cross section and b) plan of a resonant pressure sensor

The arms of the sensor (shown in Figure 6) attach the resonating structure to the diaphragm and are positioned at node points at twice the fundamental frequency of the resonator. As the diaphragm deflects, the arms of the resonator are put in tension and the natural frequency of the resonator changes. The resonator has a Q factor of 40 000 and is excited electrostatically; its vibrations are detected by electrodes located on the housing substrate (Greenwood and Wray, 1993). Yokogawa Corporation have also produced a resonating pressure sensor that uses two electromagnetically excited resonators on a diaphragm. The resonators are vacuum-sealed at around 1 Pa and have a Q factor of 50 000. To maximise the differential reading between the resonators, one resonator is positioned in the centre of the diaphragm and the other at the edge. Surface micromachining techniques can facilitate the fabrication of comb drive structures that can laterally drive resonating structures. The advantage of lateral resonating structures is the energy of the resonance is not coupled into the diaphragm, resulting in damping. This technique is being developed by GE Sensing in their TERPS (Trench Etched Resonant Pressure Sensor). Quartz has also been used as a resonating structure as it is easily actuated and is particularly suited to high pressure applications. However, lack of micromachining options has limited its use (Wagner *et. al.*, 1993).

4.1.5 Further MEMS pressure sensing techniques

The three previous sections describe the most commonly used MEMS pressure sensor designs, however, there are a number of alternative designs. Microthermopiles are used as thermal conductivity gauges as they have better pressure sensitivity than membranes at lower pressures. Optical techniques have been demonstrated in which the movement of the pressure sensing diaphragm perturbs the optical signal path or a measurement is made on a cavity formed between a fibre end and a diaphragm (Kim and Neikirk, 1995). Surface acoustic wave resonators can be placed on one end of a pressure sensitive structure. The benefit of this technique is that RF electromagnetic waves allow the sensor to operate remotely (Buff, 1997). Inductive coils have also been used with one coil suspended beneath the diaphragm and the other attached to the diaphragm (Okojie and Carr, 1993).

4.1.6 Metrology for MEMS pressure sensors

MEMS pressure sensor performance relies on accurate diaphragm thickness fabrication. Of secondary importance are the physical properties of the diaphragm material, such as Young’s modulus, which affect device sensitivity. Resonant structures often require characterising with a vibrometer to ensure the resonator has been fabricated correctly. Diaphragm bow is also of importance as substrate bonding may result in bow which can then introduce non-linearity into the sensor performance. A problem that has been identified in manufacture is outgassing into the vacuum within the MEMS device, lowering the vacuum and affecting device performance. Often the sensors are sealed inside a vacuum chamber, however, the device cavity may not be at the same pressure as the chamber due to outgassing from surfaces near the device, due to gas generated during the bonding process or due to restricted pumping paths. Applied Microengineering Limited have proposed a solution with their AWB04 wafer bonder and aligner (Rogers *et. al.*, 2005) which allows a greater distance between wafers before alignment hence allowing wafers to be aligned after pump down, avoiding outgassing from nearby surfaces and allowing a good vacuum in the device cavity.

4.1.7 MEMS pressure sensors market

The growing requirement for information and monitoring is creating continued interest and demand for pressure sensors. Aiding this market growth has been the technological advancements that have made pressure sensors more versatile and reliable (Frost and Sullivan, 2006). Current pressure sensors are incorporated with added functionality and along with pressure measurement, can also monitor temperature, detect leaks and provide feedback to a control system. However, the pressure sensor market is nearing maturity and price is the foremost competitive factor cited as being key to product success.

Total revenues in the European pressure sensors and transmitters market stood at \$1484.8 million in 2005 and are set to reach \$2069.6 million by 2012 (Frost and Sullivan, 2006).

4.2 MEMS ACCELEROMETERS

Accelerometers or inertial sensors are widely used within the aerospace, defence, automotive, medical and marine industries. In the aerospace industry they are used for flight stabilisation of aircraft and rockets and navigation. Automotive applications include vehicle stability systems, rollover prevention systems and aids to navigation. Naval and marine applications include ship stabilisation and navigation. Medical applications include monitoring of patients who have suffered for example from a stroke or suffer from Parkinson’s disease. The most common MEMS accelerometer designs fall into three categories:

- Piezoresistive.
- Capacitive.
- Resonant.

Each category has its own benefits and drawbacks that will be discussed in the following sections. As the size and cost of inertial sensors decreases, the number of applications they are used for has increased significantly. Also, as the accuracy and stability of these devices increases, high performance systems are being introduced into lower cost items and consumer goods such as cars; enhancing safety and functionality. However, as illustrated by Table 2 (Beeby *et. al.*, 2004), many of these applications have significant range and resolution requirements, implying that no single design is suitable for all applications. Inertial sensors are normally part of a larger control system as opposed to many of the other sensors discussed in this report, therefore, a display of the measurand is seldom of interest.

Table 2 Required specification for accelerometer applications, g is the acceleration due to gravity

Application	**Resolution**	**Bandwidth**	**Range**
Automotive airbag release	<500 mg	0-0.5 kHz	± 100 g
Automobile stability control	<10 mg	0-0.5 kHz	± 2 g
Inertial navigation	<5 μg	0-100 Hz	± 1 g
Active suspension	<10 mg	0-1 kHz	± 100 g
Shipping of fragile artefacts	<100 mg	0-1 kHz	± 1 kg
Space microgravity measurement	<1 μg	0-10 Hz	± 1 g
Medical measurements	<10 mg	0-100 Hz	± 100 g
Vibration monitoring	<100 mg	0-100 kHz	± 10 kg
Missiles	<1 g	10-100 kHz	± 100 kg

Inertial sensors were first reported in the late 1970's (Roylance *et. al.*, 1979) and have been developed extensively over the past twenty years. There have been many different designs - the majority use a suspended proof mass attached to a reference frame. The displacement of the proof mass is measured by a position detector system and converted into an electrical signal. A variety of sensing mechanisms have been used including piezoresistive, piezoelectric, tunneling current and optical. These techniques will be discussed in the following sections.

4.2.1 Piezoresistive accelerometers

The first reported MEMS accelerometer used a bulk silicon micromachined wafer as a proof mass and a cantilever as the suspension system (Roylance *et. al.*, 1979). The silicon wafer was bonded between two glass substrates, allowing clearance for movement of the mass while also acting as a protective element. Piezoresistors were implanted into the device on the cantilever suspension. The advantage of piezoresistive techniques was the ease of fabrication and the technology was easily developed from pressure sensors. However, applications were restricted as piezoresistors produce thermal noise and have a relatively weak output signal (Allen *et. al.*, 1989). Piezoresistive devices typically operate in the range 5 g to 50 g and have a temperature coefficient of 0.2% K^{-1}. A diagram of a piezoresistive accelerometer developed by Siedel (1995) is shown in Figure 7. The sensing element is a bulk micromachined proof mass attached to the frame by three cantilevers, one of which has four piezoresistors forming a Wheatstone bridge. The top and bottom wafers are bonded on to the middle layer and air gaps, for damping, are formed by dry etching.

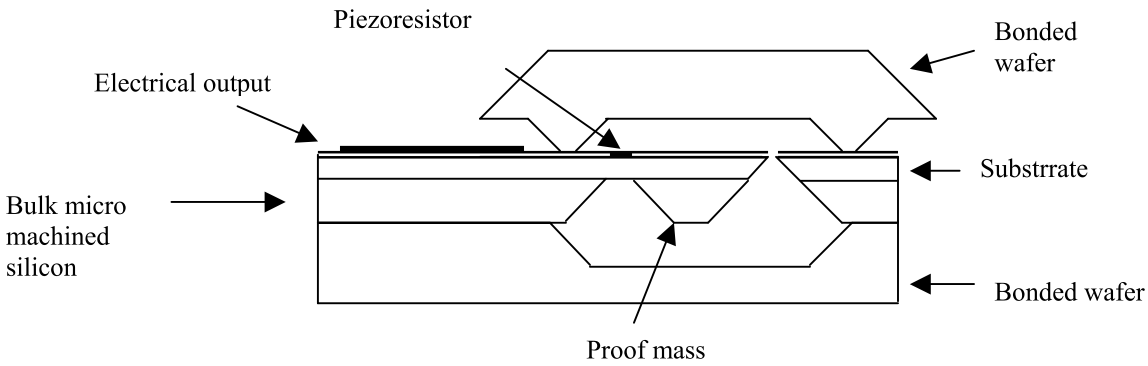

Figure 7 Schematic of a piezoresistive accelerometer

4.2.2 Capacitive accelerometers

As with MEMS pressure sensors, capacitive accelerometers offer improved sensitivity and a good steady state response. However, they can be susceptible to electromagnetic interference and often need shielding. As the inertial force moves the proof mass, the change in capacitance of the device is proportional to acceleration for a given small range of deflection. For higher precision accelerometers, which require a large dynamic range, closed loop techniques can be used to keep the deflection of the proof mass to a minimum. Similar to piezoresistive devices, early capacitance based accelerometers (Rudolf *et. al.*, 1990) were bulk micromachined and the axis of sensitivity was out of the plane of the wafer. The top and bottom wafers acted as electrodes. One problem with capacitive accelerometers is that the proof mass should ideally remain parallel to the electrodes. However, using cantilever suspension systems non-linearities are introduced for larger deflections. This requires the fabrication of more sophisticated suspension techniques, such as folded beams, which can minimize cross sensitivity between the axes (Siedel, 1990).

The automotive sector began to require cheap and reliable accelerometers around the mid 1990's. Initially bulk micromachined accelerometers were used (Mcdonald, 1990). Soon surface micromachined sensors started to appear with electronics integrated on the chip. Analog Devices (1993) produced accelerometers with the axis of sensitivity in-plane with the wafer. The proof mass was smaller than bulk micromachined devices but integrated electronics allowed greater sensitivity – partially offsetting the loss of sensitivity from having a smaller mass. Figure 8 (Mukherjee *et. al.*, 1999) shows a typical surface micromachined in-plane device.

Yazdi and Najafi (2000) developed a highly sensitive capacitive accelerometer using a combination of surface and bulk micromachining. The device has the sensing element on a single wafer but uses the full thickness of the wafer thus having a larger proof mass. A cross section of the device is shown in Figure 9.

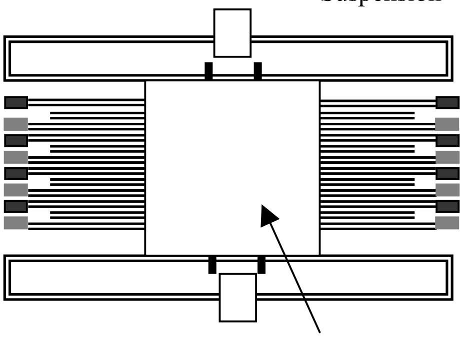

Figure 8 Diagram of a surface micromachined in-plane accelerometer

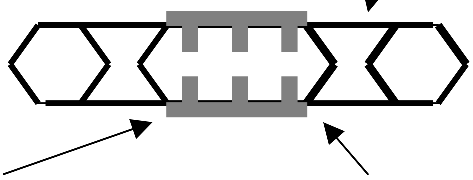

Figure 9 Cross section of a large proof mass bulk and surface micromachined accelerometer

4.2.3 Piezoelectric accelerometers

Chen *et. al.*, (1983) developed the earliest piezoelectric accelerometers. Their accelerometers featured a cantilever beam with sputtered zinc oxide. However, lead zirconium titanate (PZT) has been used more recently to create higher sensitivity devices such as the sensor designed by Beeby *et. al.*, (2001) which utilised PZT and thick film screen printing techniques.

4.2.4 Resonant accelerometers

Resonant accelerometers use a proof mass that changes the strain in an attached resonator when the mass is subject to an inertial force in the sensitive axis. The change in strain then changes the resonant frequency of the resonator. The advantage of the resonant technique is that a frequency measurement can be readily converted into a digital format that has good immunity to noise (Beeby *et. al.*, 2004). A resonator designed by Burns (1996) used three wafers bonded together with the proof mass in the centre. Earlier resonators were formed by surface micromachining two beams on the flexures at the point where the stress is greatest. Such resonators are excited electrostatically to vibrate out-of-plane in a vacuum enclosure, with a Q factor of 20 000. Implanted piezoresistors are used to detect the resonant frequency; two resonators are used in differential mode while a third resonator is used as a temperature sensor.

4.2.5 Multi-axis accelerometers

For a multi-axis sensor it is possible to use three single axis sensors orientated in orthogonal directions to each other. However, a single multi-axis device has advantages in cost and size. Lemkin *et. al.*, (1997) have reported a three axis device, along four of the sides of the sensing element there are interdigited comb fingers, allowing a displacement measurement in both in-plane directions while the out-of-plane motion is measured using an air gap capacitor formed between the proof mass and an electrode. The same authors also developed a three axis sensor (Lemkin and Boser, 1999) with three proof masses on the same chip. Performance was improved over the single mass device, largely due to a lower resonant frequency and the large capacitance of the three mass device.

4.2.6 Commercially available MEMS accelerometers

Several companies offer MEMS accelerometers. Analog Devices offer a range of products including the ADXL range. Launched in 1991 the ADXL range is based on a surface micromachined in-plane proof mass in a feedback loop with interdigited capacitative actuators and sensors. Other designs in the ADXL range use folding suspension arms and external tuning. Multi axis versions and on-chip temperature sensors are also available. Bosch and Motorola offer similar surface micromachined accelerometers, while many companies offer bulk micromachined devices. A list of manufacturers and contact details is included in Table 3.

4.2.7 Accelerometer metrology issues

MEMS accelerometer performance relies on many of the same parameters as MEMS pressure sensors. The primary metrology issues are accurate diaphragm thickness control and accurate dimensional manufacturing of the proof mass. Of secondary importance are the material properties, such as Young's modulus, which affect device sensitivity, particularly in suspension beams. Resonant structures often require characterising with a vibrometer to ensure the resonator and actuator have been fabricated correctly. Sidewall orthogonality and paralellism is also an issue for accelerometers as deviations from parallel sidewalls can lead to device non-linearity and failure.

Table 3 Accelerometer manufacturers

Company	Details	URL
Analog Devices	First and largest provider of commercial accelerometers	www.analog.com
Colibrys	Custom devices available from 1 *g* to 100 *g*. Now specialising in military equipment.	www.colibrys.com
Bosch	Third largest supplier of MEMS products. They supply to the automotive sector and are planning to move into the consumer market.	www.bosch.com
Honeywell	Supply a resonating beam accelerometer and quartz flexure based accelerometers. Applications include aerospace and energy exploration.	www.inertialsensor.com
Kistler	Specialise in low frequency accelerometers and supply three axis accelerometers.	www.kistler.com
Motorola	Surface micromachined capacitance based sensors. Single and dual axis available.	www.motorola.com
Sensornor	Control management systems. Piezoresistive sensors used for airbags.	www.sensornor.com
STMicroelectronics	Two or three axis accelerometers.	www.st.com

4.3 MEMS GYROSCOPES

As with accelerometers, gyroscopes are increasingly being used in consumer products. In parallel to this, applications in the traditional gyroscope markets, such as aeronautics and defence, are expanding. Market researchers (InStat, 2004) predict that the MEMS gyroscope market will be worth $396 million in 2007. The wide range of gyroscope applications is shown in Table 4 (Beeby *et. al.*, 2004).

4.3.1 MEMS gyroscope technologies

Macro-scale gyroscopes normally use a large mass flywheel rotating at high speed, however, frictional forces prevent this technique being viable for microdevices. As a result, most micromachined gyroscopes use a mechanical structure that is driven into resonance and rotation excites a second resonance due to the Coriolis force. A closed feedback loop is then often used to null the oscillation in the second axis. However, an obstacle to this technology is the small size of the Coriolis force compared to the driving force that is applied in an orthogonal direction. One way of countering this is using high-*Q* structures vibrating at the resonance of the sensing axis. Active tuning using electrostatics is also normally required to fine-tune the resonance due to the difficulty achieving the required manufacturing tolerances (Clark *et. al.*, 1996). Unsatisfactory alignment of the drive mechanism with the axis of freedom can also result in cross-talk, which can overshadow the relatively small Coriolis force. Early MEMS gyroscopes were based on double ended tuning forks; rotation causing the tines to resonate along the perpendicular axis while actuation was achieved by either electromagnetic (Hashimoto, 1995) or piezoelectric techniques (Voss, 1997). To detect the sensing axis of the gyroscope piezoresistive, optical and tunnelling techniques have been employed but the capacitive technique is the most common.

Table 4 Required specification for gyroscope applications

Application	Resolution / $^{\circ}s^{-1}$	Bandwidth / Hz	Range / $^{\circ}s^{-1}$
Automotive rollover protection	< 1	0-100	± 100
Automobile stability control	< 0.1	0-100	± 100
Inertial navigation	< 10^{-4}	0-10	± 10
Platform stabilisation	< 0.1	0-100	± 100
Computer controlled pointing devices	< 0.1	0-10	± 100
Robotics	< 0.01	0-100	± 10

Charles Stark Draper Laboratory developed the earliest MEMS gyroscope suitable for batch processing (Grieff, 1997). The device, shown in Figure 10, consists of a double gimbal structure and is supported by torsional flexures. Rotational forces couple the vibration from the outer gimbal to the inner gimbal, while a closed loop control system ensures the oscillation is kept constant. Maximum sensitivity of the device is achieved when the outer gimbal is driven at the resonant frequency of the inner gimbal.

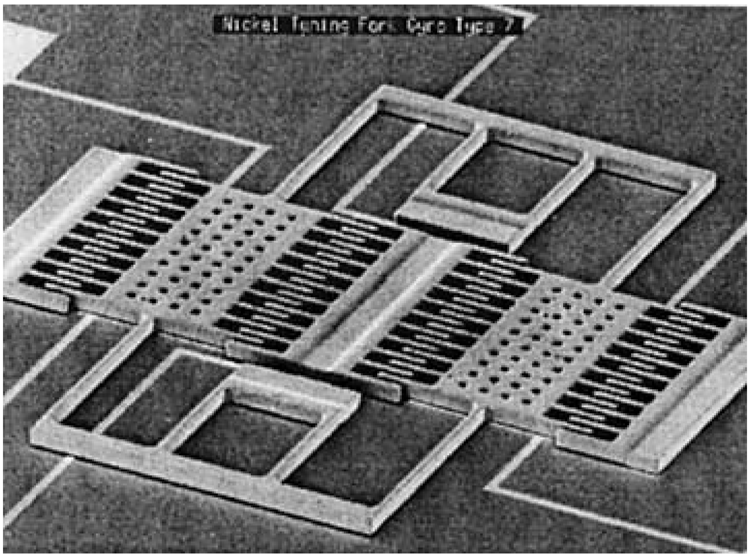

Figure 10 SEM image of the Draper Laboratory comb drive tuning fork gyroscope (courtesy of Draper Laboratory)

The earliest surface micromachined gyroscope (Clark and Howe, 1996) used two electrostatic comb drives operating perpendicular to each other; one comb as the actuator the other as the sensing capacitor. Another common implementation is the vibrating ring structure. The ring is set to oscillate elliptically but rotational forces couple this vibration to a secondary resonance at 45^{o} to the primary mode. Electrodes placed at 45^{o} are then used to capacitively measure the amplitude of the second mode which is proportional to the angular rate (Putty and Najafi, 1994). A schematic of the vibrating ring gyroscope is shown in Figure 11.

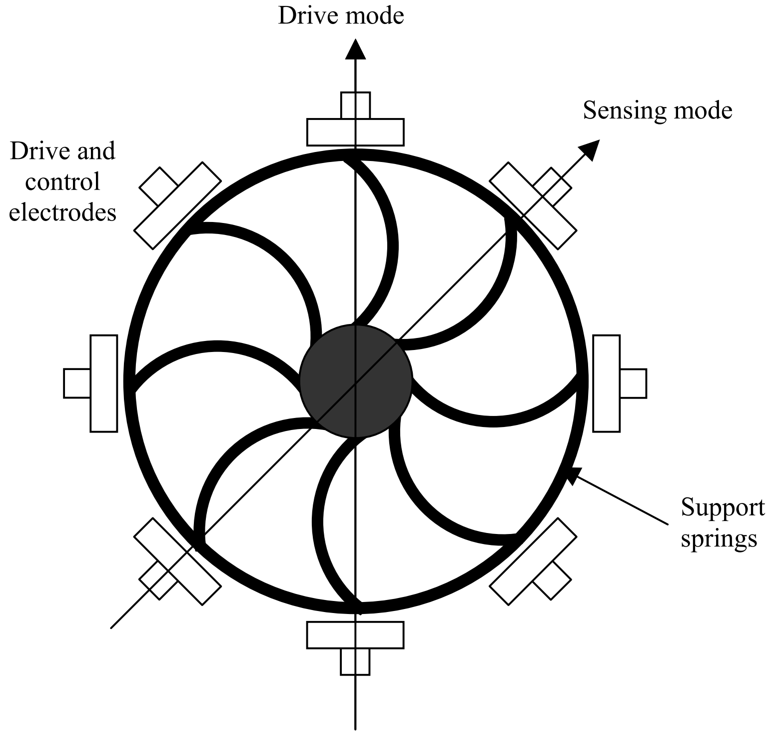

Figure 11 Schematic of vibrating ring structure gyroscope

4.3.2 Commercially available MEMS gyroscopes

BAE Systems and Sumitomo Precision Products have produced a successful ring structure gyroscope (Hopkin, 1997). The sensor uses electromagnetic actuation and detection; the resonator ring is of 6 mm diameter and is supported by eight compliant beams. The device is shown in Figure 12. BAE Systems and Sumitomo Precision Products have also developed a capacitive based version of the ring gyroscope (Fell *et. al.*, 1999).

Analog Devices have produced the integrated ADXRS range of sensors. This range is based on a resonant tuning fork design. Two polysilicon sensing structures each contain a frame that is driven to resonance. Rotation about the vertical axis introduces a Coriolis force that moves the inner frame perpendicular to the driven axis and capacitive sensors then detect this motion. A schematic of the device is shown in Figure 13. The sensor units each contain two matching structures used to sense differentially and, therefore, eliminating environmental shock and vibration (Analog Devices, 2005).

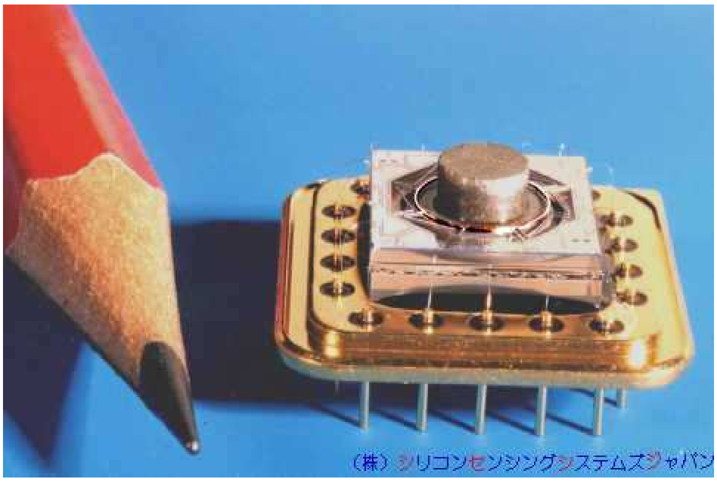

Figure 12 Silicon Sensing Systems vibrating ring gyroscope (courtesy BAE Systems)

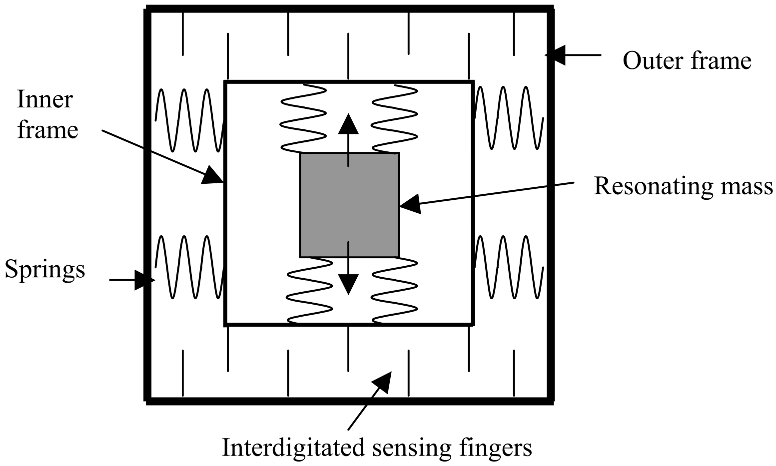

Figure 13 Schematic diagram of a gyroscope element

4.3.3 MEMS gyroscope market

Nearly all MEMS gyroscope sales are to the automotive and military markets, with 99% of the gyroscopes sold as part of an inertial measurement unit. However, according to market research company In-Stat (2003) supply of stand-alone gyroscopes into consumer applications will increase if the average selling price can drop below $10 per sensor.

MEMS gyroscopes are making significant gains on more established gyroscopic technologies, particularly ring laser gyroscopes and fibre optic gyroscopes. Ten of the top twelve inertial measurement unit suppliers are either currently offering or actively developing MEMS based gyroscopes.

4.3.4 MEMS gyroscope metrology issues

MEMS gyroscope performance relies on many parameters including the dimensional and material properties of the resonators and the suspension beams. Resonant frequencies of the gyroscopes are often measured with vibrometers, as extra modes can cross talk with Coriolis induced modes. Suspension beams require dimensional measurements including sidewall verticality and thickness measurement.

4.4 MEMS FORCE SENSORS

Force is normally measured by monitoring the change in length of a spring device, therefore, strain gauges are dominant in force metrology. However, as in many other sensing technologies the requirement is for devices with lower power consumption, greater range, non-contact operation and wireless deployment (Beeby *et. al.*, 2004). Traditional metallic strain gauges used in force measurement can be labour intensive to calibrate, require amplification and have a limited range. The advantage silicon based strain sensors have over metal devices is increased sensitivity. The drawbacks of silicon sensors are that they are non-linear and temperature dependant (Kanda, 1982).

4.4.1 Markets for MEMS force sensors

Unlike inertial and pressure sensors MEMS force and torque sensors have yet to dominate the marketplace, although the technology is receiving growing interest. Examples have been reported using piezoresistance (Vass, 1994) and capacitance (Elwenspoek and Wiegerink, 2001) techniques. Resonance based force sensors have also been demonstrated. Resonant sensors are highly sensitive and operate over a wide dynamic range. Tilmans *et. al.*, (1992) realised a force sensor using bulk micromachining while Roesing *et. al.*, (1995) used surface micromachining to produce a double ended tuning fork design - the dimensions of the fork determine the sensors range and sensitivity. Figure 14 shows a schematic of the device.

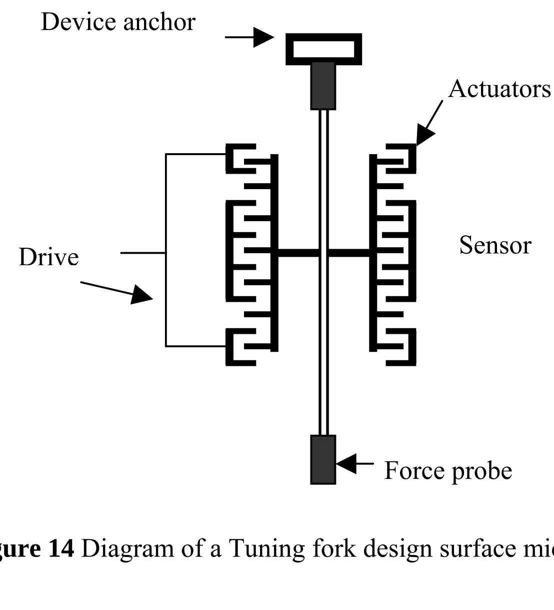

Figure 14 Diagram of a Tuning fork design surface micromachined force sensor

Silicon micromachining has been used to fabricate a differential force sensor based on capacitance techniques (Despont, 1993). The device, shown in Figure 15, is engineered from two electrically isolated plates, so that if one capacitance increases then the other proportionally decreases. This differential technique improves linearity and sensitivity.

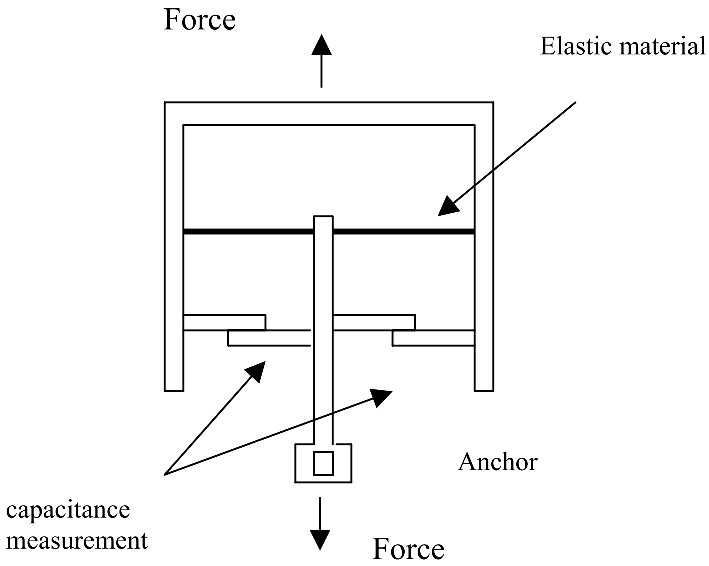

Figure 15 Differential force sensor based on capacitance techniques

Capacitive force sensors have been used to build an array that can measure masses of up to 1000 kg (Wiegrink, 1999). Force and torque sensors have been used in a number of other applications such as atomic force microscopy (Cumpson *et, al,*, 2003), manipulation with microgrippers (Greitmann and Buser, 1996) and robotics (Engel, 2003).

The MEMS force market is much smaller than the inertial sensors market and no analysis can be found in the literature. Low force metrology is, however, becoming increasingly important. Probing forces are critical for dimensional metrology particularly at the lower end of the force scale. NPL has developed an electrostatic force balance operating in the range from 1 nN to 10 μN and is now developing the associated transfer artefacts (Leach *et. al.*, 2006).

4.5 MEMS DEVICES FOR ELECTRICAL MEASUREMENT

MEMS for electrical measurement is a broad area, covering a diverse range of devices and systems. Generally, electrical MEMS can be considered to consist of three main categories concerned with:

- Generation of electromagnetic fields.
- Transmission of electromagnetic fields.
- Detection of electromagnetic fields.

In addition, in this report we limit the definition of electrical MEMS devices to cover the frequency domain from DC to 100 GHz. The dimensions of typical electrical MEMS devices can vary from 1 μm to several millimetres.

4.5.1 MEMS Structures for the generation of electromagnetic fields

The generation of electromagnetic fields at the on-chip or micro- and nano-scale can be achieved using traditional concepts of passive devices and systems, such as capacitors, inductors, resistors and transformers but scaled using microfabrication techniques. Only some of these devices will be discussed in detail. There are several key benefits of scaling such devices and systems to the micrometre region, such as operation at much higher frequencies (where their self-resonance frequencies lie well into the gigahertz region), higher *Q* of the devices, integration with CMOS electronics to enable novel applications and investigation of electromagnetic material properties at the micrometre scale.

4.5.2 MEMS inductors

Inductors are used for important circuit functions in wireless applications (< 10 GHz) and are typically in the range 1nH to 5 nH with a high *Q* factor and a self-resonance frequency (SRF) above 10 GHz (Tilman, 2003). In standard, low-cost CMOS or bipolar technologies the *Q*-factor of spiral inductors is limited to about ten and SRFs of 5 GHz to 20 GHz. The low *Q*-factor arises from substrate and metallic losses in the inductor. MEMS technology is one of the routes to improving inductor characteristics, by employing out-of-plane self-assembly 3D micromachining (Dahlman, 2001), or etching away the substrate beneath the inductor to minimise conductive losses (Tilman, 1996). These two types of inductors are illustrated in Figures 16 and 17. *Q*-factors of up to 17 at 3.5 GHz for a 1.5 nH inductor have been reported (Dahlman, 2001). However, self-assembled or suspended inductors are prone to vibration and shock and, therefore, are limited to applications where alternative solutions do not exist such as when low resistivity substrates are used for high *Q*-factors. The concept of micro-machined inductors is also being extended to develop coils for a number of applications, such as field generation, miniature motors and MRI coils (Martincic, 2004).

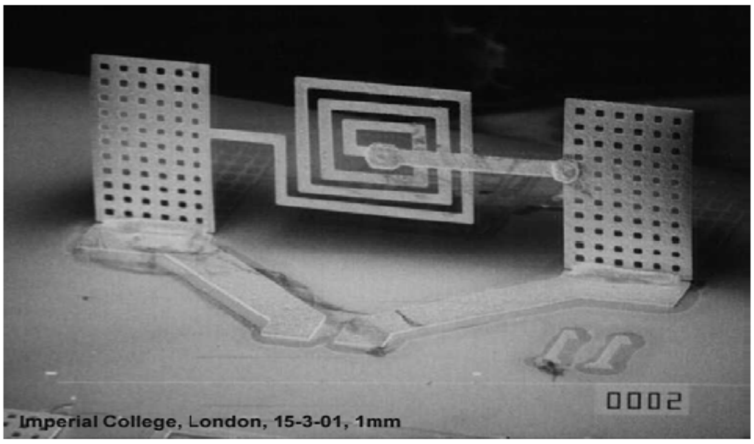

Figure 16 Photograph of a self-assembled out-of-plane three turn spiral inductor of 1.5 nH (coil dimensions 350 mm by 350 mm) (Dahlman, 2001)

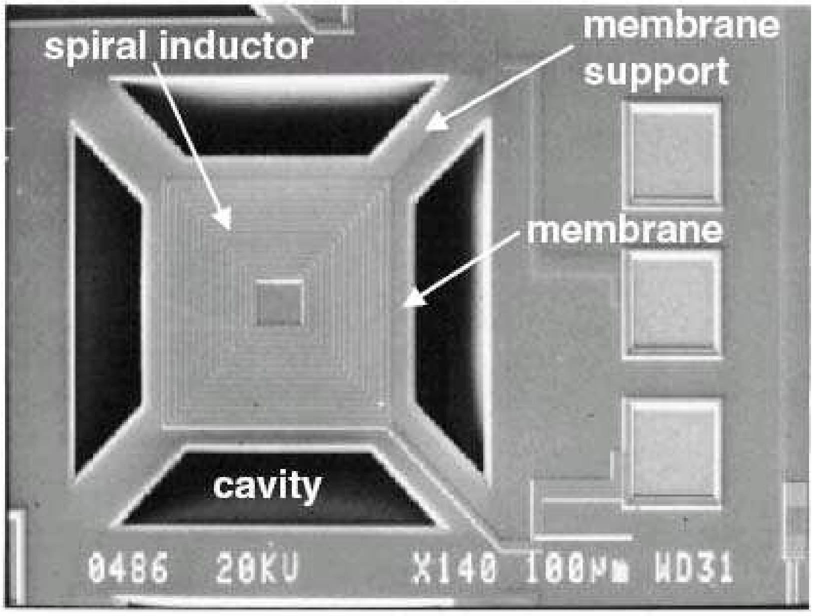

Figure 17 Membrane suspended spiral inductor integrated into a 0.7 µm CMOS process (Tilman, 1996)

4.5.3 MEMS capacitors

Micro-machined capacitors are also employed in a variety of shapes, sizes and configurations in a number of practical applications. One of the major applications is in an RF-MEMS switch that is based on a parallel plate design. A typical design of a MEMS capacitive switch is shown in Figure 18.

High frequency switches are used in wireless communications and radar systems for switching between the transmit and receive paths, for routing signals to the different blocks in multi-band/standard telephones, for RF signal routing in phase shifters used in phased-array antennas, and numerous other applications. The main performance characteristics of a RF-MEMS switch are the insertion loss in the on-state, the isolation in the off-state, the return loss in both states, power consumption, bandwidth, power handling capability and linearity. At present, RF switching is often realised using a PIN diode and GaAs MESFET or JFET-based semiconductor switches. RF-MEMS switches offer significant benefits over semiconductor switches in terms of high isolation (in particular over 30 GHz), low loss over a wide frequency range, extremely low standby power consumption and excellent linearity characteristics (Rebeiz and Muldavin, 2001). However, the main drawbacks remain the relatively high drive voltages and slow response. Nevertheless, RF-MEMS switches based on capacitive designs offer significant potential benefits for a wide range of applications. At present, the effects and complexity of packaging and reliability issues remain largely unknown and require further investigations.

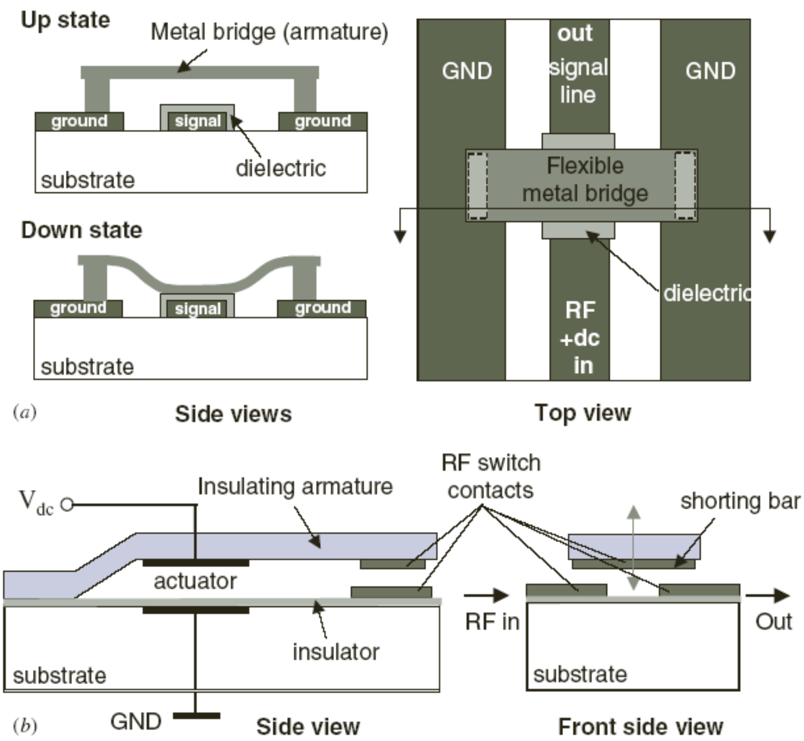

Figure 18 Schematic of the operational principle of a RF-MEMS switch (Tilman, 1996)

Figure 19 shows another type of micro-machined capacitor, which has recently been devised at NPL, referred to as the cross-capacitor, it is based on the original macroscopic design discovered by Thompson and Lampard for realising the SI unit of Farad in terms of a single length measurement (Thompson and Lampard, 1956). The MEMS cross-capacitor was designed at NPL and fabricated by Microfabrica, USA, using their EFAB process. The operation of the MEMS cross-capacitor is such that the capacitance between any pair of opposing electrodes is calculable using the Thompson-Lampard theorem, with the remaining two electrodes connected to the shield potential.

Finally, it is worth noting that there are a great variety of MEMS capacitor designs, intended for various applications, which are covered extensively in the literature (Sun *et. al.*, 1996, Young 1996, Yao 1996) In particular, tuneable or comb structures are widely employed in a range of applications, such as matching networks, tuneable filters, phase shifters and frequency controlling elements in an inductive capacitive tank of a voltage controlled oscillator (Dahlman, 2001). For micro-machined resistors and transformers the reader is referred to Varadan, (2003).

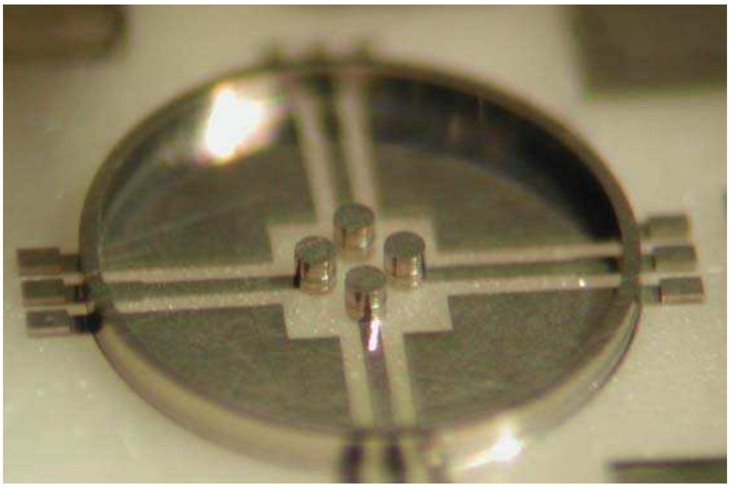

Figure 19 MEMS cross-capacitor based on the macroscopic Calculable Capacitor (Thompson and Lampard, 1956). The diameter and height of the device is approximately 1 mm and 0.14 mm, respectively (Awan *et. al.*, 2005)

4.5.4 MEMS structures for transmission of electromagnetic fields

In this section we restrict our discussions to the so-called ‘guided wave’ region of the electromagnetic spectrum, *i.e.* frequencies up to 100 GHz. Most of the electromagnetic transmission lines based on MEMS technology are typically co-planar waveguides (CPW) or microstrips (Varadan, 2003). However, recently micro-machined coaxial transmission lines have also been developed at NPL and elsewhere (Awan *et. al.*, 2005, Microfabrica).

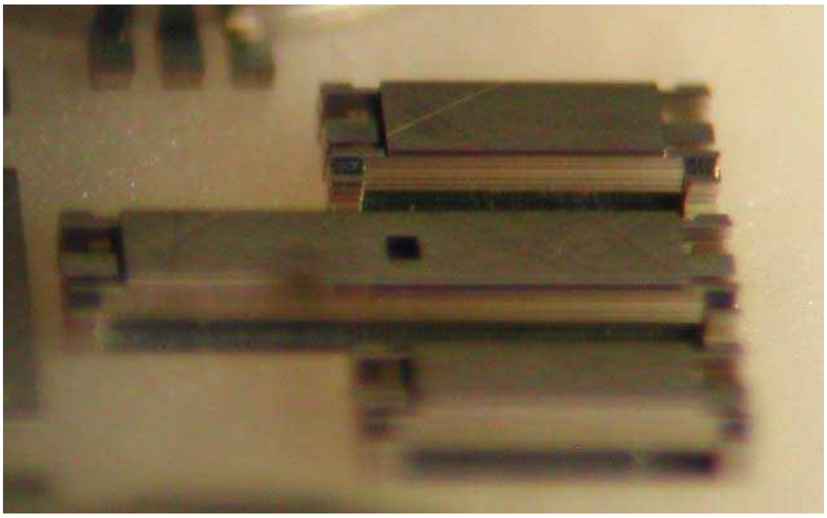

Figure 20 Micro-machined 3D coaxial transmission lines. The central coaxial line is approximately 1 mm in length and 0.14 mm in height (Awan, 2005)

The theory and practice of CPW and microstrips is well understood since they are employed extensively in a great number of applications, as is clear from existing literature. However, this is not the case for the micro-machined coaxial transmission lines that have only recently begun to be investigated. One reason for the lack of complete understanding of the micro-machined coaxial transmission lines is that they are difficult to employ in practice, in fact the range of their applications is limited (at the on-chip scale) and mostly related to specific precision measurements requiring fully shielded transmission media. In addition, the non-standard cross-sectional geometry (rectangular) of the transmission lines also makes their modelling and measurements difficult to quantify accurately. Figure 20 shows the coaxial lines recently developed at NPL *via* Microfabrica.

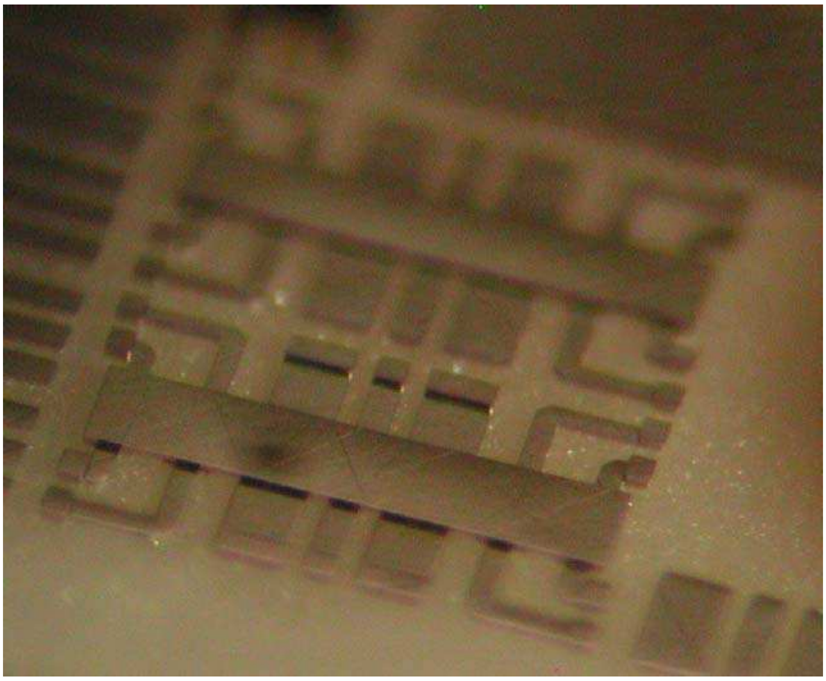

Figure 21 Two MEMS RF and microwave power sensors. The length and width of the sensors is approximately 0.6 mm and 1 mm, whereas the membranes are suspended 4 µm above the CPW

4.5.5 MEMS structures for detection of electromagnetic fields

Precision or sensitive detection of electromagnetic fields, based on MEMS as well as micro-machined devices and systems, is an area of research that covers a large number of applications. It is not possible to cover these in any detail here, but some examples include RF and microwave power sensors, voltage dividers, AC/DC voltage references, antennae, phase shifters and couplers (Seppa, 2001). In addition, electromagnetic field detection sensors are often employed as transducers that allow sensitive detection of a whole range of other physical parameters, such as, pressure, force, acoustic vibrations, thermal, mechanical, as well as biological and chemical activities. An example of an electromagnetic field detector is the RF and microwave power sensor that NPL has been recently developing, shown in Figure 21). Here the electromagnetic signal transmitted *via* the CPW is detected using a thin membrane placed above the CPW. When the RF and microwave power is applied to the CPW an attractive electrostatic force is generated between the CPW and the membrane. Since the membrane is designed to have a small mechanical spring constant, forces in the sub nanonewton range are sufficient to displace the membrane towards the CPW. This displacement can be detected using capacitive sense electrodes placed beneath the membrane (and outside of the CPW), using a precision 1 kHz capacitance bridge.

4.5.6 Markets for electrical MEMS

The electrical MEMS and microsystems market is expected to reach $1 billion worldwide by 2009 according to a NEXUS (European Microsystems Network) commissioned market analysis report by Wicht Technologie Consulting (WTC). The report also highlights possible future growth markets for micro- and nano-technology (MNT) in consumer electronics, telecommunications, industrial process control, transport, aerospace, medical and defence applications. The electrical MEMS devices and systems include BAW (bulk acoustic wave) duplexers and filters, micromechanical resonators, MEMS switches for automatic test equipment, RF test and phased array antennae.

4.6 MICROFLUIDIC MEMS

Microfluidics is the science of developing miniaturised devices, which can sense, separate, and control small volumes of fluids. Microfluidic systems hold promise for the large-scale automation of chemistry and biology, suggesting the possibility of numerous experiments performed rapidly and in parallel, while consuming little reagent. While it is too early to tell whether such a vision will be realised, significant progress has been achieved recently and the underlying physics is sufficiently understood to allow new applications to be developed by engineers (Squires and Oak, 2005).

A micro-scale total analytical system, sometimes called lab-on-a-chip, contains all the elements typically found in larger analytical instrumentation including a sampling system, a separation system and a detection system, see (Clayton, 2005) for a review of the latest biomedical applications. Due to the demand for small-scale instrumentation, there is a great need for compatible sensors and detectors.

4.6.1 Microactuators

Microvalves and micro-pumps are important building blocks for control in fluidic systems. MEMS technique can fabricate micro actuators that can be incorporated as fluid delivery devices. The design and fabrication of thermopneumatic devices, micro-valves and micro-pumps, have been reported in two papers (Kwang and Chong, 2006, Laser and Santiago, 2004).

Microfabricated electromechanical valves are an important area of research and key requirements are a low dead-volume, rapid actuation, and low power consumption. For integration, it may be important that the valves are on silicon; because the temperature processing tolerance is low for general microfluidic devices. A typical valve would consist of an actuator (around 1 mm in diameter) and comprises a permanent magnet defined on a movable Permalloy membrane, approximately 400 µm in diameter, supported by two cantilever beams. When a current is applied to the coil a magnetic field is generated which attracts the membrane, closing off the flow channel. Once closed, the permanent magnet is strong enough to maintain the valve in the closed condition without current applied to the coil allowing a low energy consumption of only 3 mJ.

4.6.2 Microsensors

Electric detectors are capable of providing effective measurements in microfluidic systems through electrochemical methods such as amperometry, potentiometry and conductometry. An example of such a technique is the conductivity detector for microchip capillary electrophoresis. However, despite the electric detectors' effectiveness the cost of fabrication is extremely high due to integration issues. MEMS based capacitive sensors have been applied to microfluidic applications in the form of pressure sensors and flow sensors based on a differential pressure principle. Capacitive sensing has also been utilised for fluid level sensing, determination of ion concentration, and for measuring the makeup of mixtures. All these sensors are academic one-offs and their integration and price make them out of reach for the mass market at the moment.

Optical fluorescence is the most commonly used analytical tools in biology and medicine. Several bulk fluorescence techniques with near single molecule sensitivity exist, including confocal microscopy, epifluorescence, near-field scanning microscopy and evanescent field detection. A fully integrated approach to single molecule spectroscopy is desirable, but as yet to be developed for microfluidic systems.

4.6.3 Sensirion

As an example of a company involved in this area, Sensirion, a Swiss SME produce MEMS-based liquid flow sensors for microfluidic systems. The sensor can be integrated into analytical instruments and medical devices. The device is based on thermal mass flow measurements using coils around a steel capillary. The liquid is totally isolated by polymer or fused silica channels and the semiconductor sensor chip is mounted on the outside of the flow path and senses through the wall of the channel. The high level of on-chip integration results in reductions in cost, size and weight. The key feature of the sensors is merging the sensor element with digital intelligence for linearisation and temperature compensation on the same microchip. The device enables measurement of liquid flow rates down to 8 nl per minute with a repeatability of 0.6%. Response times are of the order of milliseconds and the total device mass is 6 g.

4.6.4 Metrology issues in the field

Metrology issues for microfluidics include the following:

- Surface roughness and 3D dimension of microfluidic channels.
- Flow and pressure measurement at the micrometre scale.
- Surface energy and adhesive properties for integration of microfluidic devices in complex system.
- Temperature measurement in the microchannel.

- Identification of small defects, micrometre in size or smaller, over large areas, (microfluidic channels can be over a metre long).

5 MEMS SENSOR FAILURE MODES

One of the biggest challenges facing manufacturers of MEMS sensors is device reliability which is key for several reasons:

- Many of the applications of MEMS will be in critical systems where the cost of failure is high.
- MEMS are a new technology with potentially new and poorly understood failure mechanisms.
- Design tradeoffs must account for reliability, often against cost.
- Multiple technologies on the same chip results in many failure modes.

Although MEMS fabrication is relatively complex, both MEMS and IC fabrication have similarities such as mass-production, low cost and products fabricated completely without separate parts. While the IC industry has used test structures for over thirty years, in the MEMS industry test structures are still in their infancy (Lavu *et. al.*, 2005).

5.1 COMMON MEMS FAILURE MODES

MEMS device failure can be broadly categorised into three classes: failure during fabrication, failure during operation and failure due to environmental effects. The most common forms of failure modes for MEMS devices have been summarised by Miller (1998) and are presented briefly in this section.

5.1.1 External particles

External particles can be expected to have a detrimental mechanical or electrical effect, particularly on devices where small gaps exist between bearing surfaces or elements with large potential differences. External particle contamination can be considered a minor problem, however, as the particles which are the primary problem are internally generated, for example, by outgassing, wear, or present at fabrication in despite of clean room conditions.

5.1.2 Fused components due to overdriving

Components can become attached due to electrical overdriving, leading to inadvertent contact of structural and electrical members - this has been observed in springs and in comb fingers.

5.1.3 Stiction

Stiction occurs between contacting surfaces and can affect elements that are actuated or unactuated. For example, stiction may occur on cantilevers or diaphragms that are under more strain than they are designed for. Of all the failure modes observed, stiction and friction are of the most concern. The most common route to failure observed for all rotating devices involves sticking of structures that are in sliding contact.

5.1.4 Static overload

Many MEMS sensors operate at stress levels in the vicinity of 1 GPa. These stress levels are usually higher by at least one order of magnitude than is the case for macroscopic structures. High stress levels can induce critical cracks from small defects that are introduced during etching, polishing or rough handling.

5.1.5 Delamination

Delamination can be caused by thermal or epitaxial mismatch that may lead to high stresses associated with multilayer films. The adhesion between layers depends strongly on their chemical and mechanical compatibility. Thermal cycling over the lifetime of a MEMS device can slowly lead to degradation and delamination.

5.1.6 Creep

High stresses and stress gradients introduce the possibility of mass transfer through glide and diffusion mechanisms. These effects may be negligible for macroscale devices but they can be significant on the scale of MEMS devices. The use of metal as a structural material in MEMS, where room temperature creep exists, can result in those devices being susceptible to creep.

5.1.7 Environment

MEMS devices are used for a variety of applications where environmental effects can be important. This includes valves, pumps and manifolds, where the contacting fluids, can be corrosive. Also, experiments have shown that crack growth can be a function of moisture, resulting in MEMS failure (Brown, 1997).

5.1.8 Fatigue

A process that causes irreversible repositioning of atoms within a material can contribute to fatigue. Fatigue is of particular interest in devices such as RF switches that operate under cyclic loading at high frequencies (kilo- to gigahertz). Cyclic loading can cause behaviour evolution over as few as one hundred cycles due to strain hardening or softening, thereby causing device performance to change well before failure is reached. Research has also shown that the fatigue life of polysilicon is a function of stress (Brown, 1997).

5.2 CAUSES OF MEMS FAILURE

The causes of the failure modes observed in MEMS devices can differ significantly from those commonly found in macroscopic devices. For example, gravitational forces are negligible at the micrometre level and the dominant forces are those associated with contacting or near-contacting surfaces. This section outlines the causes of typical MEMS failure modes.

5.2.1 Capillary forces

Often the final step in fabricating surface micromachined MEMS sensors is a wet chemical etch, removing the silicon dioxide that encapsulates the moveable mechanical structures. Removal of the wafer from the liquid etchant results in a liquid-air interface that often pulls moveable structures into contact via capillary forces. Once in contact, and even after drying, the surfaces often remain in contact due to various types of adhesion forces (for example, capillary, van der Waals and electrostatic forces).

5.2.2 Operational methods

Actuation of a MEMS device is often provided by an electrical drive signal. If excessive signals are applied, excessive constraint forces can result to compensate for overdriving. Experiments show that MEMS actuators driven by model-based drive signals have five orders of magnitude longer life than square wave signals. Therefore, the operation signals must be carefully considered when developing MEMS devices where high constraint forces are likely to occur.

5.2.3 Mechanical instabilities

Electrical actuation forces depend on the geometry of the attracting electrodes and this must be carefully considered when designing active MEMS devices. Undesired forces (for example, lateral or out-of-plane forces) can result in mechanical instabilities causing both performance degradation and premature failure. For devices such as comb drives, in addition to the degradation in performance, a second failure mode may occur when an individual finger deflects sufficiently to contact an adjacent finger. The two fingers typically fuse together, causing immediate and abrupt failure of the comb drive.

5.3 TECHNIQUES TO IMPROVE RELIABILITY

When a failure mode of a MEMS sensor has been identified, there are techniques designed to alleviate the problems and to improve the reliability of MEMS devices. This section summarises such techniques.

5.3.1 Chemical surface treatments

As has been stated, stiction is a major failure mode of MEMS devices. Typically a liquid etchant used in the fabrication process can cause moving parts to stick when dried. Hydrophobic coatings, improved release etches and drying schemes, such as super-critical carbon dioxide drying, can be used to lessen the affect of stiction. The development of fabrication friendly methods to stabilise the anti-stiction properties of surfaces is important to the commercialisation of MEMS products.

5.3.2 Model-based operational modes

Improper operational methods, i.e. those that do not use model-based drive signals designed to minimise parasitic constraint forces and part-wear, can significantly degrade the performance of MEMS devices. Consequently, the method of operation must be considered when developing active MEMS that are designed for reliability.

5.3.3 Design modifications

Modifications to the parts that fail frequently can improve sensor reliability and prolong their life. Thickness, stiffness and shape are typical factors of concern. For example, the gaps at the ends of electrostatic comb fingers when they are fully engaged may need to be redesigned to be large enough so that the parasitic force due to the end fringing fields is negligible for a particular application. Table 5 (next page) summarises the typical MEMS failure modes and possible causes.

Table 5 Summary of many of the failure modes and possible causes

Failures during fabrication	**Effects**
Breaks in suspended parts	Oxide residues preventing sufficient etching, reformation of etched materials
Stiction	Caused during release by capillary forces, van der Waals forces, *etc*. Geometric variations left after etching
Surface undulations	Particle contamination during etching can leave hillocks – affecting diaphragm/cantilever performance
Buckling	Residual stresses when etching sacrificial underlayer
Failures during operation	**Effects**
Stiction	Out of range input signals, electro-mechanical instabilities
Creep	High residual stress
Wear	Decay of material caused by long term use
Delamination	Temperature cycling between structures that have different thermal expansion coefficients
Particle contamination	Caused by debris from parts wear or residues after etching. Can result in electrical bridging or stiction by lodging between mechanical parts. Outgassing in microfluidics devices can also be a pollutant to the measurand
Electromigration	Gradual displacement of metal atoms during high current densities resulting in a change of conductor characteristics
Environmental causes of failure	**Effects**
Particle contamination	Potential electrical shorts
Vibration	Inducing surface adhesion or fatigue
Humidity	Increased stiction forces, increased wear in polysilicon
Pressure	Affects Q factor in resonant structures, changes in thermal resistance
Ambient temperature	Vary internal stresses resulting in delamination and deformation
Radiation	Dielectric layer may trap charged particles and create a permanent electric field

5.4 MEMS RELIABILITY TESTING

There has been some limited work done to experimentally evaluate the reliability of MEMS devices. Sandia Labs have developed a MEMS reliability testing system referred to as SHiMMeR (Sandia High-Volume Micromachine Measurement of Reliability) (Tanner *et. al.*, 1997). SHiMMeR features a Plexiglas enclosure that contains a base for testing 256 MEMS devices at a time, and an optical microscope and video camera to observe and record the failures. Each MEMS device under test is attached to electrical cables through which signals are sent to activate the devices. Humidity, a major factor in MEMS failure, can also be controlled. During the experiments the MEMS devices, initially microengines, were run until failure and then a cross-section was cut through the gears with a focused ion beam and inspection carried out under a microscope. Sandia focused on adhesive wear, which involves parts rubbing and causing small pieces of debris to drop off. These pieces attract and stick to each other, particularly in high humidity environments, resulting in regions where the micromachines begin to catch and fail. Simultaneously, Sandia developed a numerical-based model which included strength, adhesive wear, critical volume, pin joint radius, applied force, resonant frequency and quality factor. The Sandia model predicted when parts fail and the results were in agreement with test data from SHiMMeR, potentially allowing MEMS reliability to be tested without extensive experimental testing. Reliability and failure mode analysis of MEMS devices are key for the future success of MEMS sensors. Particularly as markets mature and sensors are increasingly found in safety critical applications this analysis should be underpinned by sound metrology to ensure all devices under physical test are exposed to equivalent conditions.

6 CURRENT MEMS METROLOGY TECHNIQUES

When measuring any physical quantity it is desirable that the measurement be traceable. Traceability is defined as “the property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties” (PD 6461-1: 1995). Traceability ensures consistency of measurement from one manufacturer to another and ultimately from one nation to another. This is essential when any interchangeability of parts is required. It is trivial to prove the traceability route for a single length measurement (for example *via* gauge blocks that have been calibrated by interferometry, the laser source of which is calibrated against the primary laser at NPL, which realises the definition of the metre) but not so trivial to prove the traceability when measuring the complex dimensions of a typical MEMS structure. In addition, only surface profile measurements and macro-scale co-ordinate measurements are currently covered by specification standards. Furthermore, although the route to traceability for surface profile measurements is well established, that for areal surface measurements is only just being developed in the National Measurement Institutes (see Leach 2004 for a further discussion on these issues). There is still a great deal of work required to establish traceability for MEMS metrology, although in the interim, manufacturers of MEMS devices can apply measurement good practice and ensure that they understand the limitations of the instruments they are using.

As has been discussed in the previous sections of this report MEMS structures, and devices incorporating MEMS structures can have complex geometries and dynamic behaviours. MEMS structures may have high aspect ratios, for example those manufactured using LIGA and DRIE techniques, there can be a number of different materials present in a single structure and there may be re-entrant or hidden features. This makes the dimensional metrology of MEMS structures very difficult and has meant that many companies only undertake functional testing of the final device. This “scrap mentality” can be very costly, especially when one considers that 70% to 90% of the cost of a MEMS device can be down to the packaging. In many cases it would be much better to measure a component’s geometry directly after manufacture and before packaging.

To determine the geometry of MEMS structures most MEMS manufacturers use instrumentation that was originally designed to measure surface texture. These instruments, such as stylus profilometers and vertical scanning interferometers, essentially “measure from above” and are not capable of measuring the high slope angles generally encountered in a MEMS structure. Surface measuring instruments are only capable of measuring planar structures whereas many MEMS structures are truly three-dimensional. Also, the size of the probe (in the cases above the physical size and shape of a stylus and the spot size of the optical beam respectively) critically limits the size of features that can be measured. Figure 22 and Figure 23 show examples of MEMS structures that are impossible to measure using surface measuring instrumentation. Scanning electron microscopy is also used for imaging MEMS structures and in many cases it is necessary to destructively cut a sample to image hidden features. Instrumentation to measure the dynamic performance of MEMS structures is also extensively used by MEMS manufacturers – often with retrofitted optical surface texture measuring instruments.

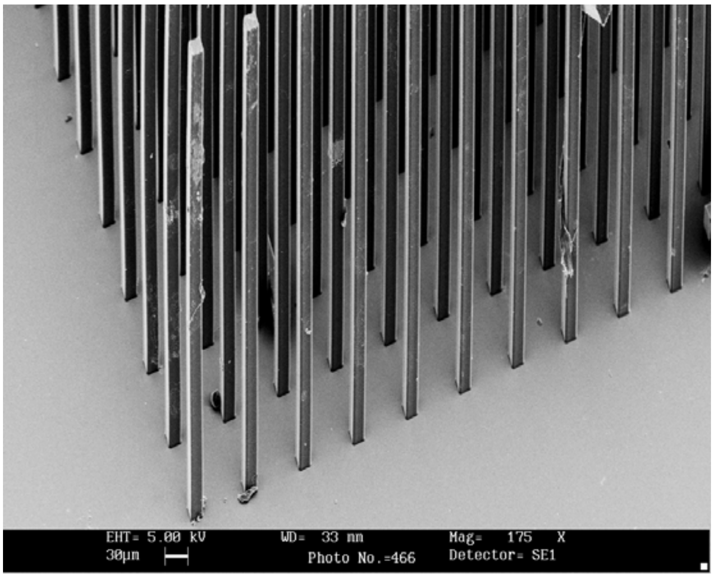

Figure 22 LIGA structures produced by x-ray lithography with pillars 20 μm by 20 μm, courtesy of RAL

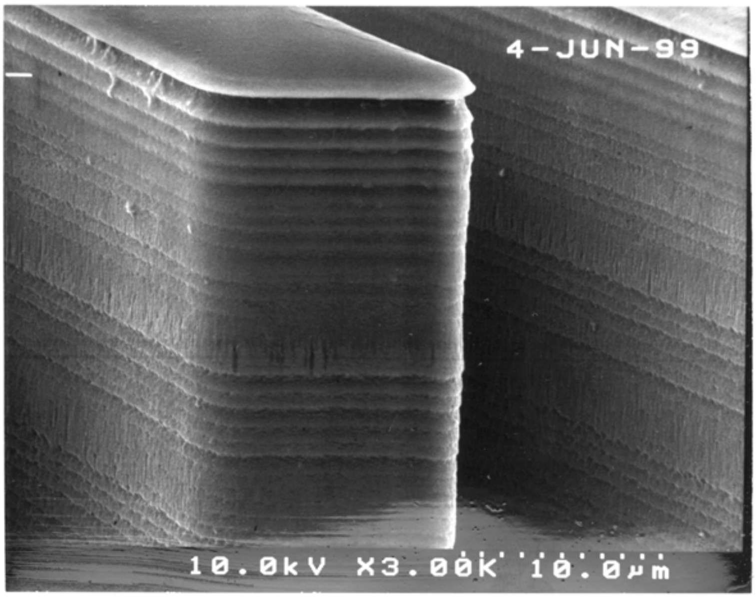

Figure 23 A deep DRIE structure, courtesy of RAL. Note that RAL's requirement was to measure the surface texture of the sidewalls

Measurement of materials properties, for example Young's modulus or Poisson's ratio, is also very important to MEMS manufacturers. However, this report will concentrate on dimensional metrology (static and dynamic measurands) chiefly because corresponding stress and strain measurements can be performed by measuring the dimensions and changes in the dimensions of a structure. The measurement of other materials properties such as elastic modulae and hardness are also of importance, however, materials metrology is not covered in this report as an extensive review is given in an earlier roadmap (Cui *et. al.*, 2003) and in a recent survey (Heeren *et. al.*, 2004).

The following sections in this chapter will discuss the capabilities and limitations of the most extensively used dimensional metrology tools for measuring the geometry, surface texture and dynamic behaviour of MEMS structures.

6.1 MECHANICAL PROFILOMETERS

Mechanical profilometers have been used to measure surface texture, and form, for many decades and can have sub-nanometre vertical resolution. A typical stylus instrument consists of a stylus that physically contacts the surface being measured and a transducer to convert its vertical movement into an electrical signal. Other components can be seen in Figure 24 and include: a pickup, driven by a motor and gearbox, which draws the stylus over the surface at a constant speed; an electronic amplifier to boost the signal from the stylus transducer to a useful level; and a device, also driven at a constant speed for recording the amplified signal. The part of the stylus in contact with the surface is usually a diamond tip with a carefully manufactured shape. Its limitation is that owing to the finite shape of the stylus it will not always penetrate into valleys and will give a distorted or filtered measure of the surface texture. The measurement of surface texture using stylus instruments is described in detail elsewhere (Leach 2001, Thomas 1999).

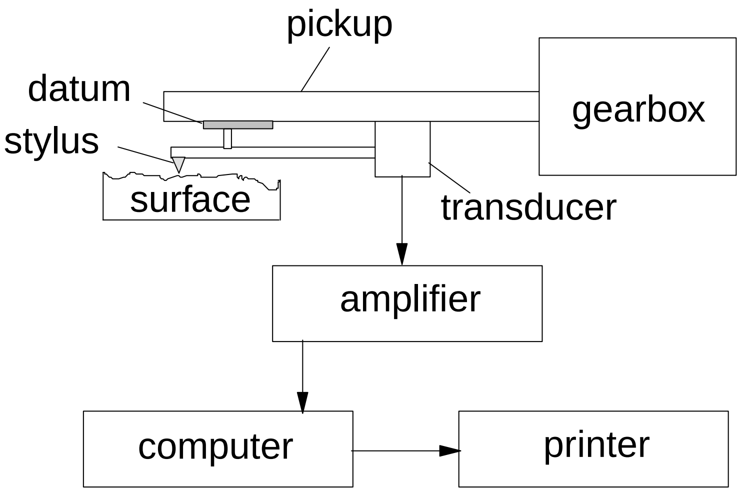

Figure 24 Schema of a typical stylus instrument

A recent advance with stylus instruments is the ability to measure three dimensional or areal surface texture by raster scanning the stylus. This makes the measurement of MEMS structures possible but the stylus can cause unwanted effects at high slope angles, for example when traversing a step. Also, compared to optical methods, the measurement can be very slow. It is not uncommon for measurement times to be several hours. More importantly, there is currently no definitive traceability route for areal stylus instruments and there are no specification standards in place (although these are being drafted by ISO technical committee 213). The development of a traceability route for areal stylus instruments is discussed elsewhere (Leach *et. al.*, 2006).

In conclusion, stylus instruments are very useful devices for measuring two dimensional surface texture (surface profile) or planar areal surface texture but have limitations when applied to three-dimensional MEMS structures. Typical stylus instruments have ranges over several millimetres, vertical resolutions down to sub-nanometre (although this is rare and a more typical value is around 10 nm) and micrometre lateral resolution.

6.2 SCANNING PROBE MICROSCOPY

There are many types of scanning probe microscopes but the device that is used in most cases by MEMS manufacturers is the atomic force microscope (AFM, see Danzebrink *et. al.*, 2006 for a recent review on AFMs). The AFM is a form of profilometer that can image all types of surface with potentially sub-nanometre vertical resolution and nanometre lateral resolution. AFM images are obtained by measurement of the force on a sharp tip created by the proximity to the surface of a sample. The tip is usually at the end of a micro-machined cantilever arm, the deflections of which can be measured using optical means (see Figure 25 for a schema of a typical AFM). As the tip is raster scanned over the surface the force is kept constant with a feedback network and the tip follows the contours of the surface.

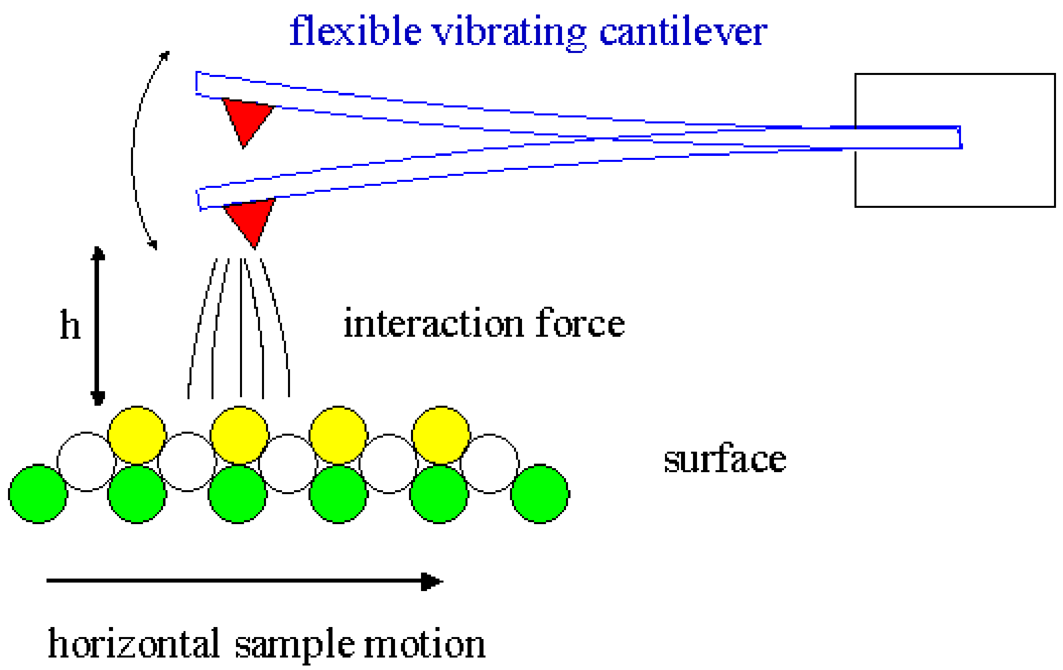

Figure 25 Schema of an AFM cantilever measuring a surface

The AFM image scales are usually derived from the voltages that drive the piezoelectric actuators that scan either the AFM tip or the sample. These scales can be calibrated from images of calibration transfer standard samples. However, calibration of the scales is not straightforward because the piezoelectric actuators suffer from hysteresis, creep and ageing effects and are often configured to scan in a bending mode that introduces distortion to the image. For metrology applications the accuracy that can be achieved through calibration of the scales derived from the piezoelectric scanners may not be sufficient; in this case it is necessary to add displacement transducers to the scanning axes of the instruments and many commercial AFMs now have metrology built in using linear scales or capacitive displacement sensors.

Whilst AFMs have extremely high resolutions they do not have long range compared to conventional stylus profilometers and optical instruments, and are normally restricted to a planar scan of around 100 µm by 100 µm with 10 µm in the vertical axis. The range of an AFM can be extended to several millimetres using an AFM in conjunction with a co-ordinate measuring machine (see section 6.3 and Dai *et. al.*, 2005). However, AFM scanning is relatively slow and even over 100 µm by 100 µm the scan time can be measured in minutes. Over millimetres of range scan times can be up to several hours (note that recent advances have been investigating significantly increasing the speed of AFMs – see Humphris *et. al.,* 2005). Conventional AFMs also lack the ability to measure high aspect ratio structures due to the design of the cantilever, although recent developments use inverted cantilever designs to measure sidewalls (Dai *et. al.*, 2006).

In conclusion, AFMs (and other scanning probe microscopes) are useful for measuring short range (compared to stylus profilometers) planar structures or surface texture but significant advances are required for them to be able to measure the high aspect ratio, high slope angle structures encountered in MEMS (see Weckenmann and Wiedenhöfer, 2004).

6.3 MINIATURE CO-ORDINATE MEASURING MACHINES

A co-ordinate measuring machine (CMM) is a programmable, versatile instrument that is used to measure dimensional data for many types of manufactured component. CMMs have three or more measurement axes, usually linear or rotary or a combination of the two. The measurement axes are combined in series so that a unique combination of axes positions defines a single point in space. Measuring an object using a CMM is achieved by moving a measuring probe to a number of points on the object surface in sequence and measuring the position of the probe at each point *via* the machine scales. Figure 26 shows an example of a conventional CMM.

Over the last decade there has been a great deal of research effort directed towards the development of CMMs that can measure miniature components. NPL designed and built a CMM with a 50 mm x 50 mm x 50 mm working volume and a target measurement uncertainty of 50 nm (Lewis 2003 and see Figure 27). This instrument could be used to measure small features on small components, to measure soft materials, or to measure complex shapes with small uncertainty, for example, aspheric optical surfaces. All of the metrology systems of the NPL small CMM are calibrated *in situ*. Therefore, not only can small uncertainties be achieved, but all measurements are directly traceable to the realisation of the metre. The NPL small CMM was one of the first in a series of metrology instruments designed to bridge the gap between the conventional and the micro-scale worlds. Commercial small CMMs are now available from IBS Precision Engineering (the Isara 3D-CMM, see Ruijl, 2001a, Ruiji *et. al.*, 2001b), Mitutoyo (the UMAP Vision System Hyper 302, see Masuzawa *et. al.*, 1993), SIOS (the NMM1, see Jaeger *et. al.*, 2005) and Zeiss (the F25 3D CMM). The Technical University of Eindhoven have also recently developed a system with reduced range (4 mm) in the *z* axis (van Seggelen *et. al.*, 2005).

Figure 26 A typical bridge type CMM

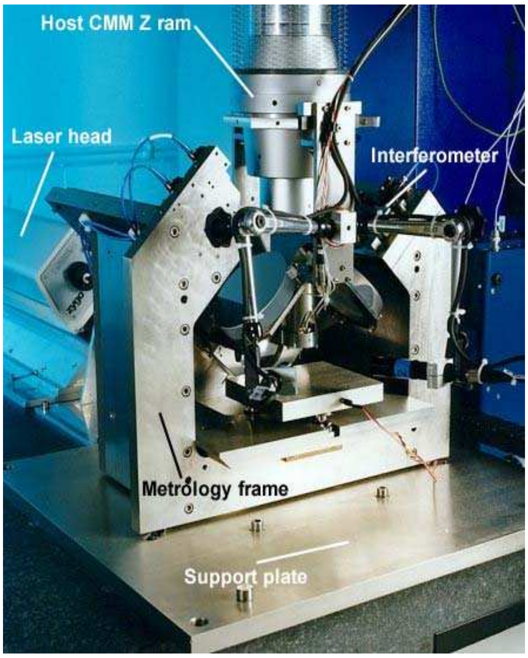

Figure 27 The NPL small CMM

The most challenging part of shrinking the size of a CMM is shrinking the measuring probe. A thorough review of the techniques used to produce probes for measuring miniature components is presented elsewhere (Wechenmann *et. al.*, 2004). However, most of the probes developed to date have a minimum tip diameter of around 0.1 mm – too large to be able to measure the MEMS structures encountered in modern advanced sensors. The smallest commercially available tip to date is the PTB-designed opto-tactile sensor (Schwenke *et. al.*, 2001) which has a minimum tip diameter of 25 μm with stem lengths of a few millimetres (although only a two dimensional probe is available commercially). NPL have also reported on further development work towards smaller probes using electro-discharge machining to produce the stem and ball, lithography to produce the elastic sensing element and an optical measurement system (Leach and Murphy, 2004). The University of North Carolina, Charlotte have developed a "virtual probe" concept that uses a standing wave set up in a high aspect ratio rod (Bauza *et. al.*, 2005). Thus the probe does not require a spherical ball and simply uses the contact diameter of the free end of the oscillating rod. A minimum diameter of 7 μm has been achieved in first prototypes with an aspect ratio of 700:1. PTB are also developing effectively "inverted" high aspect ratio AFM cantilevers that are specifically designed to measure sidewall roughness and form (Dai *et. al.* 2006).

There are many problems associated with manufacturing and using miniature probes. These include:

- The high aspect ratios mean that the stylus stem will bend significantly compared to conventional sized probes.
- Whilst most probes are designed to have a very low probing force, the tiny size of the probe can lead to high pressures and the possibility of damage to the surface and/or the probe ball (Meli and Küng, 2006).
- The tiny stylus tip will tend to adhere or "snap to" the surface being measured due to capillary forces caused by fluid contamination on the surface being measured or electrostatic forces.
- It is difficult to control dirt and other contaminants on the stylus or the surface being measured.
- To give good fidelity the probing speed must be slow. This has led to a number of advances in dithering the probe to speed up its measurement time (this also has advantages in minimising some of the other problems listed here).
- It is difficult for the user to know where the stylus tip is on the workpiece. This has led to the incorporation of non-contact optical systems that can locate the probe and surface.
- It is difficult to measure the form of the ball. When using a conventional CMM it is usually only necessary to measure the radius of the ball and subtract that from a co-ordinate measurement. As the ball size decreases the measurement of the form of the ball becomes increasingly important and difficult to achieve.

NPL is now active in procuring a commercial miniature CMM to use as a platform to develop the next range of probes for measuring the geometry of MEMS structures, including sidewall roughness, form and angle, and hole or nozzle geometry. The probe will consist of a vision system to find the areas on a part to be measured and a high aspect ratio mechanical probe to measure such areas.

6.4 ELECTRON MICROSCOPY

Electron microscopy is extensively used for imaging MEMS structures. To gain three-dimensional images using an electron microscope, the sample can be tilted to a number of angles and geometrical relationships used to calculate three-dimensional images (this is known as stereo electron microscopy, see Piazzesi, 1973 and de Chiffre *et. al.*, 2004). A major drawback with electron microscopes is that the probing of the test surface must take place in a vacuum. In addition, in the case of scanning electron microscopes (SEMs), the surface under test must be conducting (or at least be semiconducting). Kris *et. al.*, (2004) discuss the limitations of SEM for height and sidewall angle measurement. There are two main types of electron microscopy that are used to image MEMS structures and these are described below.

6.4.1 Transmission electron microscope

The transmission electron microscope (TEM) operates on the same basic principle as a light microscope but uses electrons instead of photons. The active components that comprise the TEM are arranged in a column, within a vacuum chamber. An electron gun at the top of the microscope emits electrons that travel down through the vacuum towards the specimen stage. Electromagnetic lenses focus the electrons into a narrow beam and direct it onto the test specimen. The majority of the electrons in the beam travel through the specimen. However, depending on the density of the material present, some of the electrons in the beam are scattered and are removed from the beam. At the base of the microscope the unscattered electrons hit a fluorescent viewing screen and produce a shadow image of the test specimen with its different parts displayed in varied intensity according to their density.

Using suitable electromagnetic lenses, TEMs can achieve image magnifications of over $\times 300\,000$ and have extremely high resolutions; a typical TEM can have a resolution of better than 0.5 nm (compared to light microscope magnifications of $\times 1000$ and resolutions of 0.2 μm). However, a TEM only produces a two dimensional image of a test specimen. In addition, electrons have very little penetrating power, so the test specimen must be very thin to allow the electrons to pass through.

6.4.2 Scanning electron microscope

An image of a test specimen can be obtained using a SEM. This microscope uses a very fine beam of electrons, which is made to scan the specimen under test as a raster of parallel contiguous lines. Upon hitting the specimen electrons will be backscattered or emitted (secondary electrons) from the test surface. The specimen is usually a solid object and the number of secondary electrons emitted by the surface will depend upon its topography or chemical/physical nature. The image resembles that seen through an optical lens but at a much higher resolution. Typical SEMs can achieve image magnifications of $\times 200\,000$ and have a resolution of around 5 nm.

6.5 OPTICAL SCANNING MICROSCOPY

There are a number of commercially available variations on the theme of a conventional optical microscope that are specifically designed for measuring areal surface texture (in the context of this report). The confocal microscope produces images that are formed with light from a limited zone around the focal plane of the microscope (Bunning *et. al.*, 1974). These images are optical slices or sections through the surface that can be processed to provide non-contact three-dimensional information. Another variation on the confocal theme uses an objective lens that has chromatic aberration purposely built in to it, essentially to reflect a spectrum of light onto the surface. Spectroscopic techniques are then used to again produce optical slices through the surface and determine the areal surface texture.

The highest accuracy systems can have a vertical resolution of a few nanometres but all systems based on optical microscopes have certain fundamental limitations. For example, the numerical aperture (NA) of the objective lens and the wavelength of the optical source determine the lateral resolution (with low NA objective lenses the lateral resolution limit is more likely to be determined by the pixel spacing of the camera used to detect the light). Most systems cannot measure features that are spaced less than around 1 μm. The NA also limits the slope angle that can be measured which can be a severe limitation when measuring many MEMS structures. Different materials present at a surface will cause different phase changes on reflection and this can lead to errors in the vertical axis of some tens of nanometres. All the systems discussed in this section can be fast compared to a stylus profilometer when only measuring over the field of view of the objective lens (typically 100 μm to a few millimetres depending on the NA) but to measure over a larger lateral range they have to be mechanically scanned using a two-axis displacement stage. This will increase the measurement time and decrease accuracy significantly.

A recently developed instrument that combines the small depth of focus of an optical system with vertical scanning to provide topographical and colour information, can increase the slope sensitivity by the use of ring lights (Danzl and Helmi, 2006). However, this instrument is limited to surfaces that are not too smooth (Rq greater than 25 nm) which can limit its applicability for MEMS structures.

Optical microscope based instruments are very versatile tools for measuring areal surface texture but do have limitations when attempting to measure MEMS structures.

6.6 VERTICAL SCANNING WHITE LIGHT INTERFEROMETRY AND PHASE STEPPING INTERFEROMETRY

Vertical scanning white light interferometry (VSWLI) combined with phase stepping interferometry (PSI) is now widely used in industry for measuring areal surface texture with sub-nanometre vertical resolution. A vertical scanning white light interferometer involves the use of a broadband light source and the measurement of the degree of modulation contrast as a function of path difference. Because of the large spectral bandwidth of the source, the temporal coherence length of the source is short, so high contrast fringes will only be obtained when the two paths in the interferometer are closely matched in length. By looking at the sample position for which the fringe contrast is a maximum while the optical path difference is varied, the height variations across the surface can be determined. Figure 28 is a schema of a typical VSWLI.

Despite the relatively simple theory behind the operation of the VSWLI, there are many problems that can occur in practice that are not always obvious to the user. Some examples include the effects of different materials present on the surface (phase change effects) (Harasaki *et. al.*, 2001), edge diffraction or batwinging (Harasaki and Wyant, 2000), the sensitivity to slopes at the surface due to the finite numerical aperture (Creath, 1989) of the interferometer and dispersion in the optical components (Pförtner and Schwider, 2001). Whilst it may be possible to explain such effects with *a priori* knowledge of the nominal surface structure, it is not easy to explain such effects for an unknown sample. Added to this is the need to use different objective lenses for different surfaces, and the multiple settings on an instrument that, all taken together, make it very difficult to validate traceable measurements.

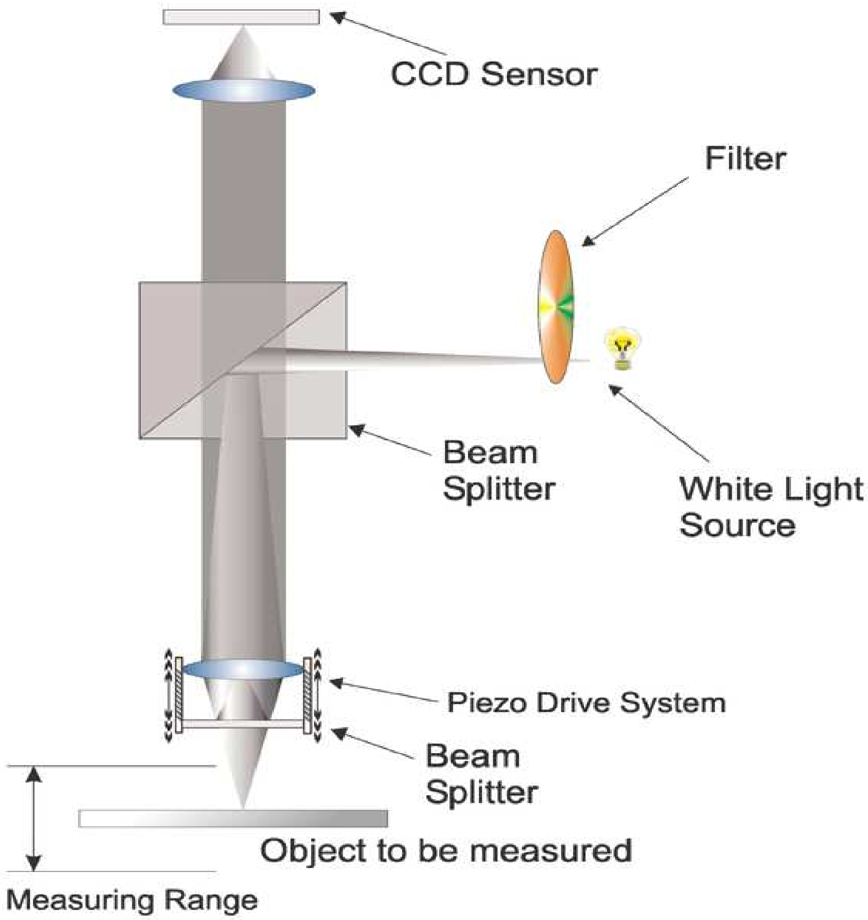

Figure 28 Schema of a typical VSWLI

Phase stepping interferometry is a well-known technique in many areas of optical metrology and, more recently, MEMS metrology. In PSI the reference mirror is stepped to a number, *n*, (commonly five) of positions to obtain *n* phase maps that can be analysed to calculate the heights at a surface. The method is limited in range – if a surface height change is greater than a fringe, there can be ambiguity in the fringe order determination. The method usually employs a piezoelectric actuator to translate the reference mirror to the step positions during a measurement. It is common to combine VSWLI with PSI in a single instrument (Harasaki *et. al.*, 2000). This is usually done to exploit the ability of a VSWLI to unambiguously determine heights larger than one fringe spacing and the high-accuracy capabilities of the PSI technique.

A recent comparison of the VSWLI and PSI techniques has illustrated some interesting problems (Rhee *et. al.*, 2005). Generally both techniques agree well (within a nanometre or so) for simple step heights (after some subsequent filtering to remove batwinging effects). However, considerable differences were discovered when comparing measurements of periodic structures and rough surfaces. Rhee *et. al.*, (2005) used diffraction theory in an attempt to explain the discrepancies but did not get good agreement with measurements. They attribute the discrepancies to the error sources described above and encourage the combination of phase and coherence information as described elsewhere (Harasaki *et. al.*, 2000, de Groot *et. al.*, 2002).

In conclusion, VSWLI and PSI (or the combination of the two) are widely used in a number of applications where nanometre vertical resolution and micrometre lateral resolution are required. However, one must be very careful when interpreting the results from these instruments. It is always benficial to have a good idea of what the surface should look like, for example from CAD files or a prior measurement with a mechanical profiler. NPL and Loughborough University are currently producing a measurement good practice guide for the use of VSWLI that will be available in 2007. Note that VSWLI can also be used to measure film thickness thus increasing VSWLI’s versatility (see Kim and Kim, 1999, Mansfield, 2006).

6.7 DYNAMIC MEASUREMENTS OF MEMS STRUCTURES

Typical MEMS devices are produced to operate in a variety of ways, such as in accelerometers, gyroscopes and micropumps. As such, there is a need to study the dynamic properties of these devices. Depending upon the MEMS device of interest it is possible to study the dynamic response either by shaking the system (using a small piezoelectric element for example) or through direct electrical AC biasing of an active structure.

6.7.1 Laser Doppler vibrometry

Laser Doppler vibrometry (LDV) is the most common method used for studying the dynamic behaviour of MEMS. LDV is a non-invasive method, which can be used to obtain both in- and out-of-plane vibrational information. Conventional LDV works on the priciple of optical interference. In practice, a beamsplitter splits a laser into a reference beam and measurement beam, which are recombined and directed to the detector. The Doppler shift of the laser, having been scattered from a vibrating area, is detected. This then gives the velocity of that region along the axis of the laser light. In order to determine whether the sample is moving towards or away from the laser source, an optical frequency shift is inserted in to one arm of the interferometer. A schematic of this set up is shown in Figure 29.

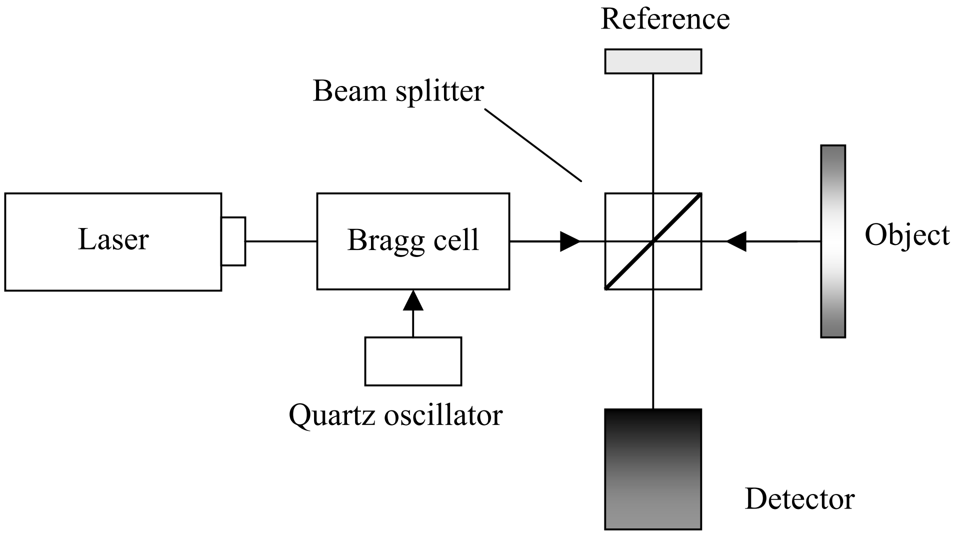

Figure 29 Schematic of the heterodyne interferometer set-up

For a sample surface oriented normal to the axis of the incident laser it is usual to maximise the signal being returned from the sample, and this is best achieved by taking measurements from the highly reflective surfaces typical of MEMS devices. If, however, the sample is oriented off-normal, then a more diffuse scattering surface is of benefit for increasing the laser intensity reaching the detector.

LDV is usually a technique that measures the local vibrations of a point, but it is also possible to scan across a feature of interest and build up a map of the dynamic response of the sample. This may be achieved by either scanning the sample or the laser point. For MEMS structures, the measurement signal is focussed onto the surface through a microscope. Using a microscope can result in the spot size being reduced to around 1 μm in size (dependent upon the objective lens used), whilst maintaining sub-nanometre displacement resolution. When performing scanning LDV measurements, small mirrors are driven to position the laser beam at different regions. NPL use a commercial dual fibre vibrometer system with a custom built vacuum chamber for low-pressure LDV measurements of MEMS structures, as well as optional humidity and temperature control. This vibrometer is limited to vibration frequencies up to 1.5 MHz, although it is possible to purchase a system that may detect motion at frequencies above 20 MHz. A photograph of the NPL system is shown in Figure 30.

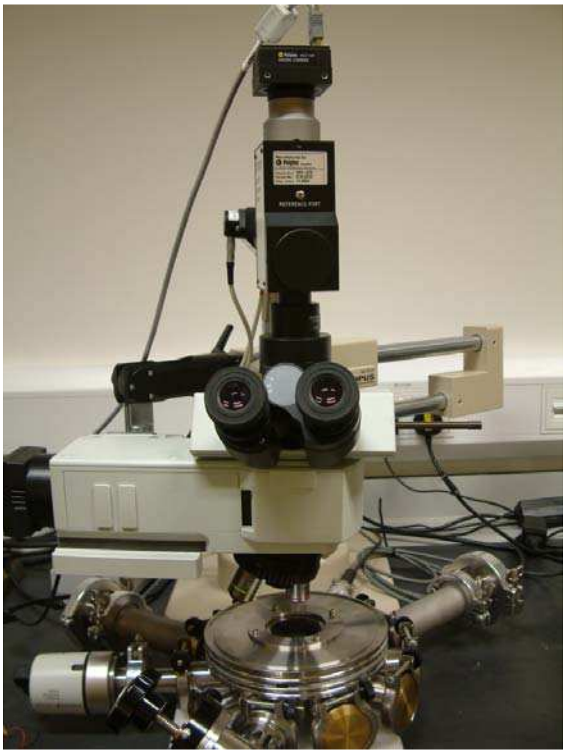

Figure 30 Photograph of the vibrometer system in use at NPL. The scanning LDV unit is positioned on top of the microscope, with the vacuum chamber beneath the microscope objective lens

The LDV set-up described above is used to obtain out-of-plane vibrational information. However, there is growing need to be able to characterise in-plane displacements. This can be achieved using a conventional LDV system by either tilting the sample approximately 90°, or by using a 45° mirror to change the incident angle of the measuring laser. This set-up is not ideal though, requiring careful alignment and not being suited to full scanning of the vibrating sample. One way of overcoming this is to use stroboscopic methods to periodically flash the surface and record the displacement. Polytec have developed such a system, which can trace the in-plane vibrations of devices with a lateral resolution of as low as 2 nm. This technique relies on the instrument software being able to pick out features of a sample and is only suitable for certain MEMS systems.

LDV has been used to study a variety of MEMS devices, including micromirrors (Lee *et. al.*, 2002, Cheng *et. al.*, 2005, Ji *et. al.*, 2006), micromechanical oscillators (Liu *et. al.*, 2001, Liu *et. al.,* 2005), micro-membranes (Držík *et. al.,* 2006), microcantilevers (Kang *et. al.*, 2006), gyroscopes (Acar and Shkel, 2004) and (piezoelectric) microactuators (Mou *et. al.*, 2004, Su *et. al.*, 2005).

6.7.2 Stroboscopic optical profilometry

Veeco have developed a technique for dynamic measurements based on optical profilometry (Zecchino and Novak, 2003). This technique relies on the fact that the motion is periodic with a constant frequency, typical of most MEMS devices. In the dynamic measurement, a low intensity light source provides a strobed illumination. Data frames can then be combined to generate a video of the sample in motion, for both in- and out-of-plane analysis.

A similar system has also been developed by Zygo Corporation (Zygo, 2005), which can be used for non-contact static and dynamic measurements, with sub-nanometre out-of-plane resolution.

6.7.3 Other solutions

Various research groups have attempted to characterise the motion of MEMS devices using other techniques. One inexpensive method that could be used to measure dynamic properties in air or in liquid used a DVD optical head (see Scuor *et. al.*, 2006). Test samples were fabricated using a conventional polysilicon surface micromachining process and were electrostatically actuated. The system was able to resolve out-of-plane displacement on the nanometre scale, with experimental results agreeing with those from a simple theoretical, one degree-of-freedom model. However, the system was limited to measuring up to 20 kHz in water and approximately 70 kHz in air.

Other techniques are also available that have been used to characterise 3D structures and may be applied to MEMS devices. Multi-pulse digital holography is one such technique where several laser pulses are used to record image plane holograms (Mendoza Santoyo *et. al.*, 1999). These are subsequently digitally reconstructed to give a 3D displacement profile.

Another technique based on holography for dynamic studies of MEMS devices is electro-optic holographic microscopy (Brown and Pryputniewicz, 1998), which uses the principles of time-averaged holographic interferometry. This technique has been developed to study samples vibrating at up to 2 MHz, whilst resolving the motion of samples with dimensions of 5 μm by 18 μm.

7 RESULTS OF COMPANY VISITS

For the purposes of this report the majority of the key UK MEMS manufacturers and MEMS fabrication system manufacturers were consulted between November 2005 and May 2006. The metrology requirements of the companies were obtained through visits, phone calls, email correspondence and face-to-face meetings at conferences.

7.1 APPLIED MICROENGINEERING

Applied Microengineering (AML) is an independent company owned by its directors. AML was founded in 1992 and they were one of the first companies to exploit MEMS technology. They are based on the Harwell International Business Centre site within walking distance of the Central Microstructure Facility of the Rutherford Appleton Laboratory at which they also has offices and equipment. AML has two roles, firstly as a MEMS equipment supplier, notably wafer bonding machines and polymer emboss tools, and secondly, as a designer and low volume manufacturer of MEMS devices and wafer scale packaging techniques. AML are interested in speaking to NPL about metrology requirements but do not envisage that they will get involved in any collaborative projects at the moment.

7.1.1 Metrology wish list

- Standardised measurement for quantifying surface flatness – standardisation of surface roughness, waviness, peak-to-valley values, *etc*.

- Measurement of surface moisture levels and attraction of like materials to surfaces.

- Electrical measurement of direct bonded and fusion bonded wafer interfaces, and changes in time – does the capacitance or resistance across bond interface alter with time?

- A non-destructive test to measure bond strength between wafers (existing techniques rely on breaking the bond or fracturing the material).

7.2 BAE SYSTEMS

The BAE Systems Advanced Technology Centre in Filton, Bristol offers a comprehensive capability in MEMS from concept through detailed design to fabrication and evaluation. They have been involved with MEMS technology since 1982 and have developed devices that are recognised as world leading, notably the BAE Systems Silicon Gyro which has been transferred to a high volume manufacturing line delivering several million devices per annum into the automotive industry. Their portfolio of developed devices covers display, inertial, optical, RF, aerodynamic, biological, chemical and electromagnetic functionality. Their MEMS fabrication staff work alongside specialists in other engineering areas to form optimised project teams. They see their niche market as producing devices in volumes somewhere between hundreds to 50 000. When they move into mass production the manufacturing is carried out elsewhere, in the case of the gyro by Silicon Sensing Systems in Japan (a joint venture between BAE Systems and Sumitomo Precision Products).

Most of their metrology problems are short term, when customer's timescales are so short that they are not able to measure against the specification on manufacturing, so they have to use functional testing. They can only test hermetic sealing by testing the functionality of fully manufactured and packaged devices at high cost.

They would like to see standards in MEMS manufacturing but they believe this would be extremely challenging given all the different processing techniques and materials used.

They have comprehensive MEMS measuring equipment including a Zygo interferometer which they have recently had upgraded to enable dynamic characterisation.

7.2.1 Metrology wish list

- They would like to measure wafer thickness variations to sub-micrometre accuracy across a complete wafer, of typical thickness between 100 μm and 500 μm. They believe that being unable to make such measurements limits the development of future products.
- They are keen to use a vibrometer/interferometer in vacuum for testing of their resonant gyro sensors.
- Measuring of high aspect ratio structures is a problem for them and they are interested in any developments at NPL in the future.
- They would like to automate line width measurements and are concerned with repeatability of measurements. They believe their present line width measurement equipment, whilst adequate for today's devices needs improving by an order of magnitude for future developments.
- They are interested in NPL's confocal microsopes and would like to visit NPL in the future.

7.3 EPIGEM

Epigem was established in 1995, following a management buy-out from ICI Materials by a group of ICI research and development staff. In 1999 they moved to a purpose-built research and development clean room manufacturing facility with key processes operated under class 100 clean room conditions. Epigem offer R&D to product manufacture; they specialise in polymer based microengineering and microfluidics.

7.3.1 Metrology requirements

Their quality control measurements on their microfluidic devices include searching for missing features, debris in the microfluidic channel, excessive channel wall roughness and misplaced drill holes. A recurring metrology problem for Epigem is that the defects are only micrometres in size but the channel may be metres in length. They find optical inspection techniques challenging as the fluid circuit is transparent on a transparent background, features are small and the channels are embedded. Their approach to optical inspection at the moment is to borrow techniques from the high-resolution printed circuit board industry but the smallest feature size normally inspected for on PCBs is about 20 µm. Semiconductor wafer inspection equipment can also be used but it is expensive and cannot cope with the large range of feature depths involved (debris may be at the bottom of a channel as well as near the top of the wall).

Epigem measure the physical characteristics of the microfluidic chip as this relates to device performance. Surface energy needs to be measured, which can be controlled by plasma treatment prior to bonding or by a post bonding liquid treatment. Current measurement methods involve a water drop contact angle measurement prior to bonding but they would like a non destructive in-chip (after bonding) method.

Surface chemistry measurements are important as Epigem want to control the binding of chemical and biological species in the micro channels at a particular position in the chip. However, measurement of the thickness and uniformity of coatings inside channel walls is challenging. Refractive index normally matches quite closely to the channel wall and the coating is often less than micrometres thick. They have used fluorescent labelled DNA in the past and measured the drop in fluorescence of a solution passed through the channels.

For measurements on liquid within the microchannels they have used techniques such as fluorescence microscopy, absorption and emission spectroscopy, impedance spectroscopy and other electrochemical methods. They have developed a microfluidic spectroscopy delivery device using fibre and a grating to increase light/fluid interaction and increase the signal to noise ratio in the spectrometer.

Epigem would like to make on chip measurements of pressure and flow rate, they have looked into doing this with venturi tubes but they require the pressure tap pipes to be a much smaller diameter than the main pipes and the dead volume of the pressure sensor needs to be minimised. MEMS devices are a possible solution but the sensors need to have a range of 0 to 100 bar.

Flow visualisation is an important measurement as Epigem would like to identify points of stationary flow. Foreign particles such as fluorescent beads can be used to image the flow velocity lines. However, in micro-mixing, for example, it is the rate of reaction between two components that needs to be determined. There are some techniques which are promising, such as micro particle imaging velocimetry and fluorescence lifetime imaging where the fluorescence lifetime of the dye depends on its environment and as the mix progresses the fluorescence lifetime changes.

Temperature measurement is an issue for Epigem. Within polymerase chain reaction (PCR) chips, for example, there are three zones of heating and the only methods currently available for monitoring the temperature are embedding a thermocouple or thermal imaging. However, these techniques are not as accurate as they would like.

7.3.2 Metrology wish list

- They would like a method of measuring surface roughness of microfluidic channels *in situ.*
- They would like to measure the surface energy when the chip is bonded together.
- They would like to measure the surface chemical functionality after the chip has been bonded together and treated with a liquid solution run through.
- They would like a more accurate method of temperature measurement in the microchannels.
- A recurring metrology problem for Epigem is that the defects are only micrometres in size but the channel may be metres in length.
- A non invasive pressure measurement would be desirable.

7.4 EUROPEAN TECHNOLOGY FOR BUSINESS LTD

Founded in 1997, European Technology for Business Ltd (ETB) are an SME which specialises in the design of microsystems, with the focus on physical sensors, resonating structures and piezoelectric based devices. They are currently developing a three-axis silicon accelerometer and single axis angular rate sensor made from bulk PZT.

7.4.1 Metrology requirements

During the testing and characterisation of their angular rate devices they found systematic anomalies and subsequently approached NPL under the Measurement For Innovators scheme. They used NPL's vibrometer as they suspected there were irregularities about operational mode of vibration within the angular rate sensor, due to irregularity of the sensors output electrical signals. The vibrometer uncovered many superfluous modes of vibration not detectable using ETB's in-house testing method. Extensive measurements of the operational mode of vibration revealed a degree of coupling with a second mode of vibration, but it was determined this did not directly affect device performance. There are many possible sources of irregularities within the vibratory device. There are possible causes of the irregularity, including surface flatness and material non-uniformities, of either electrical or material properties. However, as yet they are unable to ascertain the cause of the problem. They plan to return to NPL within months to use a Polytec vibrometer which can measure in- and out-of-plane, this will help them further characterise their sensor.

7.4.2 Metrology wish list

- ETB currently have little metrology equipment but envisage they may need to regularly make functional, dimensional and materials measurements on their products.

7.5 GE SENSING

GE Sensing, formerly Druck, are the UK's foremost MEMS manufacturer. Their products range from low cost devices to very high accuracy resonant silicon barometric sensors measuring pressures from less than 2 μPa to 2 Pa. They also supply a range of portable field calibrators coupled with supporting software. In addition, the GE Sensing product range includes Air Data Test Sets used to calibrate aircraft static instruments.

7.5.1 Metrology requirements

GE is currently developing the Trench Etched Resonant Pressure Sensor (TERPS). There has been a shift from piezoresistive into resonant structures as resonant devices suffer less hysteresis and less drift. Their earlier generation of resonant sensor, the RPT, is excited electrostatically at 30 kHz. The RPT uses a closed loop feedback system and the supply voltage is monitored to keep the device at resonance from which the pressure measurement is derived. However, the RTP resonates out-of-plane with the diaphragm so vibrational energy is easily coupled between the resonating structure and the diaphragm, effectively damping it. The new generation of resonant MEMS pressure sensors in development (TERPS) are designed to combat this by using in-plane resonance, reducing the damping, increasing the *Q* factor and thus increasing sensitivity. The in-plane design also allows more control over the critical dimensions of the device. TERPS also has an extended projected pressure range of up to 400 bar opposed to 3.5 bar for the RPT. To maximise this they have done some finite element (FE) modelling of the diaphragm and the resonator but they would like to use NPL's vibrometer to measure the natural resonances of both structures to verify their FE model. Resonance occurred over a range of 10 kHz across the pressure range. They see the TERPS sensor as key to the future success of the company.

GE Sensing also have ongoing issues with varying diaphragm thickness. They are currently not sure if this is caused by non-uniformity of the silicon wafer or non-uniformity of the etch rate. They believe that adjacent to the bosses they leave deposited on diaphragms etches are typically 2 μm more, the same as the typical diaphragm deflection. They are keen to have greater control over the thickness as their diaphragms vary in thickness from 20 μm for high sensitivity devices to 750 μm for high-pressure applications, and they would like to increase the pool of wafers they use to reduce production time.

They currently carry out die inspection by electrical probe tests and by visual inspection looking for pyramids, undercutting, *etc*. GE Sensing aim to speed up this process by automation.

They are also concerned with wafer bow across a diaphragm as this could be a contributor to non-linearity in sensor performance. GE |Sensing suspects the bow may be introduced during anodic bonding to the glass device housing.

7.5.2 Metrology wish list

In addition to the above:

- GE Sensing would like to use NPL as a knowledge source on the benefits and limitations of various measuring techniques. For example, they would like to be able to get readily advice on wafer thickness measuring.

- They questioned the traceability of vibrometers and think that an intercomparison may be worthwhile.

- They thought a standard for fracture points of stress in silicon would be a good idea. This could allow prediction of fracture when the diaphragms become so thick they are almost compressive cubes.

- They are also keen for NPL to collaborate towards on the fly measurements to help decrease calibration times.

7.6 MEMSSTAR

MEMS Surface Treatment And Release (MEMSSTAR) are a start up company based at the University of Edinburgh specialising in wafer processing equipment for the MEMS and nanotechnology industries. The process modules they offer include:

- SVR – silicon vapour release that uses XeF2 chemistry to etch silicon isotropically and selectively over other materials. The module is adjustable between continuous flow or pulsed etch modes.

- SPD – surface preparation and deposition, designed to allow for tuneable film properties and layers.

- OVR – oxide vapour release using HF chemistries with undoped and doped films.

Their metrology tools include a white light interferometer, a SEM, a profilometer and focused ion beam instrument to measure dimensions such as top-down linewidth. They are currently considering acquiring an AFM.

7.6.1 Metrology requirements

They have a problem in being able to measure the quality of the very thin anti-stiction films they deposit. They would like to be able to measure the hardness and wear characteristics of the film and its anti-stiction properties. They currently use the water contact method that gives them the hydrophobic properties of the film but not all the information they would like. They have looked into the problem with Herriot Watt University using an AFM but there is no standard measurement that is generally accepted. They would endorse the development of any such standard.

Other problems they consider obstacles include residual stress within a wafer and sidewall roughness measurement. They would also like to improve the quality of their dimensional metrology.

7.6.2 Metrology wish list

- Measurement of anti-stiction of thin films particularly wear/hardness stiction properties.
- Sidewall roughness measurement.
- They would like to improve the quality of their dimensional metrology.
- They would like to improve the uniformity of the deposition of thin films across a batch.

7.7 QINETIQ

QinetiQ (formally DERA) began work on MEMS technology in the early 1990’s from a microelectronics research background plus a well-equipped silicon MEMS microfabrication facility. They are now the largest MEMS group in the UK with a team of around thirty five science and engineering staff. QinetiQ offers a ‘one stop shop’ in the development of microsystems, from materials development, device design, simulation and layout, to low volume production in a 450 m^2 class 100/1000 MEMS clean room with 100 mm standard wafer size. They also undertake a range of analogue electronics design from full-custom CMOS-ASIC against commercial foundry CMOS processes, to hybrid (COTS) electronic subsystems in order to control and read data from the MEMS device. The group has an extensive materials characterisation capability as this is critical to realising the overall MEMS device performance. They have experience in working with a diverse range of MEMS technologies including inertial sensors, acoustic and ultrasonic sensors, pressure sensors, magnetic sensors, bioMEMS, microfluidic devices, optical devices, RF devices and MEMS actuators.

Their production tool kit includes:

- HARM processes (High Aspect Ratio Micromachining) utilising deep reactive ion etch in conjunction with bulk silicon and silicon on insulator (SOI);

- Sacrificial Surface Micromachining processes including polysilicon and metal-nitride, involving CVD (Chemical Vapour Deposition, both Plasma-Enhanced, PE and Low Pressure, LP) tools for the deposition of stress controlled polycrystalline and dielectric layers plus stress controlled metal deposition;
- SUSS double-sided mask alignment and double sided lithography for functionality on both sides of a substrate.

7.7.1 Metrology requirements

Broadly speaking QinetiQ can define two separate categories of metrology requirements:

- metrology required in support of the development of new micromachining processes;
- metrology required in maintaining stabilised micromachining processes.

Both these categories rely extensively on off-line metrology techniques, which are either destructive to the sample (or wafer) or prevent further processing of the specific sample (or wafer). Although the practice for maintaining its stabilised processes utilises more in-line metrology techniques QinetiQ would ideally like to extend the in-line capability with periodic sampling for off-line tests. Reliable and representative in-line metrology is a significant challenge to the MEMS field.

QinetiQ currently uses a range of its own and outsourced (off-line) metrology techniques including: static and dynamic white light interferometry; AFM; profilometry; scanning and transmission electron microscopy; Raman spectroscopy; secondary ion mass spectrometry (SIMS); x-ray photoelectron spectroscopy (XPS); plus in-line techniques including: wafer bow; non-contact film thickness, on-chip stress test structures, critical dimension and alignment structures.

QinetiQ measures nanometre-level surface structure over several hundreds of micrometres or even millimetres. For example, some of their microfluidic devices feature HARM channels which are typically 100 µm to 200 µm in depth and 25 µm wide or less but are in excess of a metre in continuous length (ideally the total length of the channel needs to be examined). They currently inspect channels manually looking for point defects which affect device functionality. This is a time consuming exercise. The aspect ratios used to fabricate inertial sensors are 2 µm wide by 100 µm deep and at present can only be evaluated using cross-sectional SEM techniques.

QinetiQ require a large range of materials data in order to accurately fabricate a device to the required specification. This includes parameters such as stress, stress gradient, density of material, porosity, microstructure, electrical properties, chemical and biological properties, reflectivity, refractive index, thermal conductivity and heat capacity.

For the majority of QinetiQ's physical (mechanical) sensors and actuators fabricated utilising SSM of composite films, the primary parameter which has a significant effect on device performance and reliability is (composite) film stress. For membrane, plate and cantilever MEMS devices the measurement and control of this parameter is critical for varying film thickness, varying composites of mechanical layer plus metalisation, variation across a wafer and wafer-to-wafer. Wafer bow and on-chip stress test structures are extensively used although there are limitations due to, for example, accuracy and in the case of on-chip measurement time, automated test methods. On-chip stress structures include carefully designed combinations of (Guckel) rings and (fixed and free) beams in conjunction with interferometric measurements.

Dimensional metrology requirements of interest to QinetiQ include: critical dimension control, alignment, layer thickness, interfaces and surface roughness, sidewalls and sidewall roughness. Surface roughness has a critical influence on the performance of, for example, microfluidic devices and optical devices. Surface roughness can also be critical for some HARM devices operating under extreme mechanical environmental conditions as it may result in the formation of potential fracture points in the MEMS structure.

Critical aspects of the high aspect ratio micromachining (HARM) technique employed by QinetiQ include: the dimensions of the mask pattern; mask undercut; etching depth (up to several hundred micrometres) and aspect ratio; sidewall angle to determine verticality (which can effect device linearity); side notching when the etch reaches the end-stop dielectric (which can also have a dramatic effect on subsequent device performance); and sidewall scalloping which occurs inherently in the micromachining process, QinetiQ currently uses destructive analysis which involves cleaving the wafer for subsequent microscopy (SEM, TEM) analysis.

7.7.3 Metrology wish list

- QinetiQ are keen to identify non-optimised (to the design) or failed MEMS devices early in the production cycle ideally before packaging as this could amount to 70% of the overall fabrication cost.

- Data fusion techniques are perceived to be vital for achieving the required nanometre resolution over millimetre scales.

- QinetiQ would ideally like to complement the (inevitable) timely and expensive on-chip test structures and off-line destructive testing with in-line techniques.

- In addition to point measurements QinetiQ require wafer-level and wafer-to-wafer ‘mapping’ of key mechanical parameters such as (composite) film stress and stress gradient associated with SSM processes (for example, PECVD nitride and sputtered metal).

7.8 RUTHERFORD APPLETON LABORATORY

The Central Microstructure Facility (CMF) of the Rutherford Appleton Laboratory was established in 1976. Its strategic role includes the development of underpinning processes for micro and nanotechnology and hybrid assembly. This requires integration of destructive and non destructive metrology to the process flow. With a strong focus on wafer scale processing and assembly of ceramic, semiconductor and plastic materials the CMF is well placed to assist with proof of concept subsystems. Current programmes include:

- Silicon, germanium, and gas microstrip detectors.
- High-resolution scintillators and x-ray optics.
- Stem cell micro-environments including tissue scaffolds.
- Proteomics.
- Nanofibre synthesis.
- Hybrid assembly and bump bonding.

CMF is a neutral site where academic-industry collaborations offer good technology transfer opportunities, especially in the areas of x-ray detectors, sensors, microfluidics, interconnect, MEMS and bioMEMS.

7.8.1 Metrology requirements

The CMF takes a strong interest in the metrology techniques of the IC industry, where dimension control is critical to device performance and yield. However, the breadth of metrology techniques required for successful implementation of micro and nanotechnology processes is vast, ranging from the need to measure chemical, physical and biological properties of nanolitres and nanoparticles, to obtaining statistical data of wall angle for deep etched silicon surfaces.

For micro and nanotechnology the critical issues vary. For example, nanoparticles may be homogeneous or heterogeneous structures with multiple shells. Knowing the statistical variation of the diameter and the shape of the particles is essential. The same applies for fibres, which require measurement of surface area, tensile strength, and alignment. For more conventional surface micromachining, the planar dimensions utilise many of the techniques from the IC industry. However, there is a need to measure the residual stress in layers prior to release and any sub-surface damage that may impair the performance of the fabricated component. For components that utilise layers produced by bulk micromachining, such as deep trenching and cavity formation and through wafer etching sidewall profile control, step height and surface roughness is essential. Coatings on the other hand may be required for fluidic control, anti-stiction, electron emission and bonding layers require metrology during growth and post processing. In essence there is a vast range of metrology requirements for micro and nanotechnology research and production.

The current tool-set used to characterise production processes include: optical microscopes, SEM, an automatic high resolution stylus profilometer (2D and 3D), a vertical scanning white light interferometer including optional increased depth measurements (5 mm range) and optional thin film metrology characterisation (up to 50 μm). The CMF has an automatic film thickness measurement system including a spectrophotometer head to measure thin film thickness. In addition they have access to AFM technology *via* internal partnership (mobile high resolution AFM) and Raman/AFM combined microscopy.

Film stress is measured by a bow measurement technique on a profilometer; measurements are taken before and after film deposition or process step. The Stoney formula is applied to the data to derive the film stress. However, each process results in different stresses and the technique cannot measure stress variation across a wafer.

7.8.2 Metrology wish list

- Measurement of sidewall roughness.
- Non contact measurement of micro-features including slope more than 40° and scan length up to 15 mm. Also high resolution camera to improve performance on samples with high slopes.
- Measurement of film characteristics by ellipsometry from 1 nm to 500 µm (anisotropy coefficient, multilayer, roughness, film thickness).
- Measurement of residual stress in processed structures.
- Measurement of sub-surface damage.
- Measurement of overlay errors for alignment
- High resolution SEM on large samples (up to 8” wafer)
- High resolution SEM on bioMEMS samples
- Accurate measurement of high aspect ratio structures.
- Optical interferometer for flatness on 4” wafers.
- Measurement of nanofibre mats. Mean diameter, alignment, chemical, physical and biological properties.

7.9 SURFACE TECHNOLOGY SYSTEMS

STS designs and manufactures a range of machines incorporating innovative technology used in the production of semiconductors and semiconductor related devices. STS is a market leader in silicon etching within the MEMS market. STS was originally established in 1984 to develop and manufacture plasma processing machines and they now manufacture a number of etch process systems which are described below.

Advanced Silicon Etch (ASE®) is a process for deep anisotropic etching of silicon through a series of alternating passivation and etch steps.

Advanced Oxide Etch (AOE) is a process for deep anisotropic etch of dielectric materials.

Inductively Coupled Plasma (ICP) Etch is an anisotropic etch process for a wide range of materials including compound semiconductors, metals, dielectrics, ferroelectrics, polymers and magnetic materials.

Reactive Ion Etch (RIE) is a general etch process for a wide range of materials.

Chemical Vapour Etch (XeF_2) is a dry, plasma-less, isotropic etch for silicon.

Plasma Enhanced Chemical Vapour Deposition (PECVD) involves the deposition of a wide range of organic and inorganic, doped and undoped films.

7.10.1 Metrology wish list

- STS see MEMS manufacturing facing a number of metrology challenges in the foreseeable future including monitoring faster etch rates.
- Roughness measurement and verticality of trench sidewalls.
- Non-destructive measurement of tilt angle in high aspect ratio trenches
- Stress measurement of membranes.
- STS are very interested in a possible project to investigate metal contamination of silicon etched wafers. In multi-layered or photo/electrically active etched components even very low levels of metal contamination can adversely the device.
- STS have interest in technology to count contamination particles and in development of AFM/CMM machines for nano/micro metrology.
- STS is interested in developing novel metrology and etching techniques for novel silicon and non-silicon devices such as print heads, MEMS-based displays, acoustic MEMS devices, bioMEMS and novel IC packaging concepts.

7.10 TECAN

Tecan was founded in 1970. They largely employ photochemical machining, photo electro forming, precision photolithography and precision electroplating. Tecan consider measurement as one of the major issues in the industry. One of the main problems they have is measuring an electro formed print head with holes of diameter 14.5 μm to ± 1 μm and want to measure their position to within 2 μm. There are 390 holes per component and 146 components per sheet. They are making the print film for a customer and if successful want to bring the metrology in house as they would potentially make fourteen sheets per day. They currently use white light interferometry and have a Mitutoyo QV CMM. Tecan mostly work with metal and are seldom concerned with variations of material properties.

7.10.1 Metrology wish list

- They are interested in improving the speed of measurements while retaining accuracy of small features to ± 1 μm.

8. SUMMARY OF COMPANY NEEDS

Table 6 summarises the metrology needs of all companies included in the report

Metrology Problem	Companies interested
Wafer thickness/flatness	BAES, GE Sensing, AML, Memsstar
High aspect ratio measurement	BAES, RAL, QinetiQ, STS
Sidewall roughness	Epigem, Memsstar, RAL, QinetiQ, STS
Vibrometry	ETB, BAES, GE Sensing
Residual Stress	RAL, BAES, GE Sensing
Measurement of small features over large distances	Epigem, BAES, QinetiQ , Tecan
Micro scale materials characterisation	ETB, QinetiQ
High spatial resolution temperature measurement	Epigem, Herriot-Watt University
Silicon fracture analysis	GE Sensing
Measurement of anti stiction thin films wear/hardness	Memsstar
Non invasive pressure measurement	Epigem

9 SUMMARY

This report has introduced many of the critical issues and commercial requirements for metrology during the fabrication of MEMS sensors. The report was undertaken to establish what National Measurement System (NMS) funded research would be of most assistance to underpin the UK MEMS sector. Some of the issues raised included the following:

- Several companies and academics have raised the issue of non-destructive characterisation of high aspect ratio structures. However, this measurement problem is being addressed by a project in the NMS Engineering Measurement Programme 2005 – 2008 entitled 'High Accuracy Multi-probe Micro-measurement Facility'. This project will develop a probe for use with a commercial micro-CMM platform and will consist of an optical system to locate features and high aspect ratio micro-probes to measure such features.

- The issue of sidewall roughness and measurement of small features across large distances was raised by a number of companies relating the measurement to performance and reliability of microfluidics and inertial sensors. This problem is also being addressed by the current NMS funded project 'High Accuracy Multi-probe Micro-measurement Facility'.

- Vibrometry has become increasingly important, particularly with the increased use of resonant devices, and a number of companies have requested that NPL develop verification methods and a traceability route for vibrometers.

- Wafer thickness, flatness and thickness variation has also become apparent as a major issue for UK fabrication plants. There is currently a lack of viable techniques to measure the thickness across a silicon wafer, especially now that thicknesses as small as 100 µm are now being used. Controlling thickness can be essential to the performance of mechanical MEMS sensors.

- Variation of materials properties across wafer and batch, particularly for silicon nitride and silicon dioxide was raised on several occasions. This can result in variance of performance in identical sensors across a batch. There is a desire to measure these properties non-destructively.

- A number of other problems have also been identified including the wear of anti-stiction films, fracture analysis and high spatial resolution temperature measurement. The Process Materials Team and the Thermal Measurement Team at NPL are keeping a watching brief on these areas.

Following discussions at NPL and with the companies involved in this report, it was decided that the next deliverables of the Metrology for Advanced Sensors project should be:

1. Methods of measurement of wafer thickness and thickness variation across a wafer in the thickness range from 100 µm to around 1 mm should be investigated. The methods to be investigated should be non-destructive and

traceable. Any system being developed should also be capable of measuring the thickness of diaphragms and other such structures. Note that NPL is also involved in similar work to develop in-process solutions to wafer thickness measurement.

2. Development of a traceability route and verification schemes for vibrometry. NPL has an existing high-accuracy vibrometer that will be calibrated by laser interferometry. Transfer artefacts with known modal structures will be developed for both in- and out-of-plane measurements over a number of frequencies.

These projects, together with other work on MEMS measurement and characterisation being carried out at NPL, will help to ensure that the MEMS sensors industry in the UK can overcome some of the current metrology problems at the manufacturing stage. This will in turn help the UK to maintain a healthy share of the worldwide MEMS sensors market.

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