A Reassessment of Materials Issues in Microelectromechanical Systems (MEMS)

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Abstract | Over the past 7 years there has been an explosion of research activity into materials for MicroElectroMechanical Systems (MEMS). This paper reviews the current issues associated with materials for MEMS. Five topical areas are addressed: the effect of lengthscale, the selection of materials and processes, the MEMS material set, microfabrication processes and material characterization. Each of these areas is examined, with particular emphasis on the potential impact of materials solutions. The paper concludes with an assessment of the progress in MEMS materials made since 2000.

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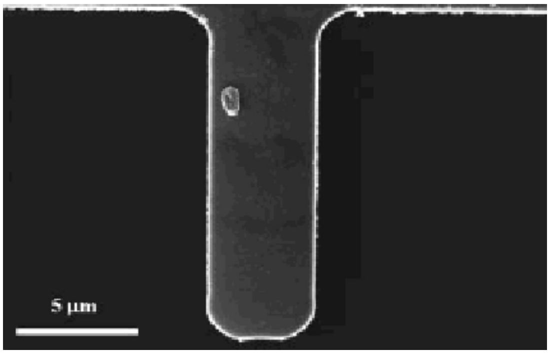
1. Introduction

MicroElectroMechanical Systems (MEMS) represent a significant industry sector, with a net value of chip level devices (i.e. unpackaged) estimated to be in the range of US$7–$10bn for 2006 with a sustained growth rate of 15–20% per annum over the past decade. The basis of this commercial impact is that the efficiencies of high volume production and low unit cost routinely achieved by the microelectronics industry can be translated to devices in which mechanical and electrical components are integrated within a single silicon chip (or equivalent structure). In addition to the economic benefits, unique capabilities can be achieved by such integration to realize a wide range of systems including: sensors[1,2], actuators[3], power producing devices[4], chemical reactors[5], biomedical devices[6] and for tissue engineering[7]. Furthermore the ability to combine the sensing/actuating (or other) function together with the electronics required for control and power conditioning in a single device allows for consideration of concepts such as the highly distributed networks[8] required for health monitoring of large structures and systems[9] or for distributed flow control[10].

The continued success of MEMS depends crucially on the solution of materials issues associated with the design and fabrication of complex MEMS devices. The small scales of MEMS offers the opportunity to exploit materials which would not normally be available for large scale devices as well as taking advantage of the favourable scaling of some properties, notably fracture strength. MEMS also offer the opportunity to materials scientists and engineers to be able to characterize materials in ways that have not hitherto been possible. One of us (SMS) first examined the interactions between developments in Materials and MEMS in a review article published in 2000[11]. In the present article we reassess the topic and the very significant developments that have occurred over the intervening seven years. Given the rate of the growth of the field of MEMS and the role of materials within it, the present article makes no pretence at being comprehensive. Interested readers are referred to several excellent broader references/reviews of MEMS technology[12–14] and microfabrication[15].

The structure of the remainder of the paper is as follows: Section 2 discusses the effects of length scale

Figure 1: Scanning electron micrograph of a single *E. coli* bacterium on an antibody-coated silicon nitride cantilever oscillator[18].



on MEMS design. Section 3 discusses approaches to material and process selection for MEMS. Section 4 presents the MEMS materials set. Section 4 discusses materials issues associated with key fabrication steps. Section 5 presents the key microfabrication processes used for MEMS. Section 6 presents a review of mechanical characterization approaches for MEMS and section 7 offers concluding remarks.

2. Scale issues in MEMS

The small scales associated with MEMS have proven to be beneficial to enable new functions and/or permit significant cost-reductions. For example mechanical resonators are useful for wireless communications[16] and offer the potential for ultrasensitive sensing such as single-molecule detection applications[17,18]. Fig. 1 shows a single bacterium attached to a cantilever resonator. To achieve resonant frequencies in the high MHz or even GHz ranges with high quality factors (Q), micro/nano-scale resonators fabricated from low-loss materials such as Si[19] , SiN[20], SiC[21] and even carbon nanotubes[22], are required. Other applications requiring specific micron or even nanometre scales to ensure their functionality include; ink-jet print heads, cantilever tips for AFM and thin film magnetic disk heads for mass-memory storage. By contrast in many cases, the realisation of significant cost-reduction has been a primary motivation for MEMS. Key examples include micromachined accelerometers and pressure sensors for automotive applications. Fabrication of micro-accelerometers through micromachining techniques has enabled their mass production at very low cost. These fully packaged microdevices retail for only a few US dollars each[23]. Regardless of whichever is the stronger driver for creating small dimensioned devices, the effect of scale is important in all MEMS as it affects system design, material properties and manufacturing processes. This section highlights the main scale effects in MEMS and resulting issues attributable to them.

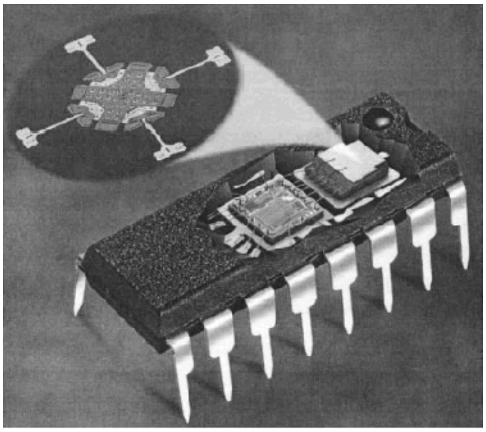
Table 1: Quasi-fundamental scaling of physical parameters for MEMS.

Physical parameters	Scaling	Units
Length	L	m
Area	L^2	m^2
Volume	L^3	m^3
Surface area/volume ratio	L^{-1}	m^{-1}
Mass	L^3	kg
Strength	L^2	$N.\ m^{-2}$
Inertial force	L^3	N
Electrostatic force	L^2	N
Piezoelectric force	L^2	N
Magnetic force (electromagnet)	L^4	N
Natural frequency	L^{-1}	Hz
Ohmic current	L^2	A
Resistance	L^{-1}	Ω
Voltage	L	V
Thermal conductance	L	$W.K^{-1}$

2.1. *Scaling Laws*

At the macro scale, fundamental scaling laws are encountered in which physical constants and material properties are independent of scale. These may cease to be appropriate as the scale diminishes. More properly such scaling laws might be termed "quasi-fundamental"[11]. Inevitably they break down at some scale, and are not truly fundamental or universal in their applicability. Cube-square scaling is one of the most important such scaling laws for devices in which performance is governed by the ratio between parameters with volumetric and areal dependencies respectively, for instance the shock resistance of MEMS sensors or the power/volume of power generators. Table 1 lists various physical parameters and their quasi-fundamental scale dependencies that are relevant to MEMS designs. Material properties become scale dependent when the length scale of the structure being characterized approaches the length scale of the mechanism governing the property of interest at smaller scales. For example, the plastic response of metals is due to the mechanism of dislocation motion. Thin metallic films deposited on substrates are stronger than the bulk material[24]. Dislocation formation and motion in thin films with thickness below a characteristic thickness are restricted and consequently high mechanical strengths can occur. The increase in mechanical strength also allows higher residual strengths to be exhibited than in macro-scale structures, which is a key challenge for MEMS. Obviously, these scaling effects in

Figure 2: Two-chip accelerometer in an industry standard 16-pin dual-in line package (DIP)[28].



material properties play roles in defining device performance and therefore should be taken into consideration during MEMS design. Meanwhile, it is also important to recognise the limitation of current fabrication techniques which often restrict the geometries of the key elements in MEMS. In particular, the dimensional tolerances in various lithography techniques very much determine the minimum feature size of MEMS, while element shapes are mainly attributed to the deposition and etching techniques used. These dependencies result in indirect scaling, which is not attributable to a single mechanism or property.

2.2. *Implications of small scale*

The shrinkage of devices into small scales not only generates many advantageous material properties but also complications in many aspects of MEMS. One of the primary consequences is the increased surface area to volume ratio at small scales which has a negative effect in many MEMS applications especially microfluidic channels[25]. The increased influence of surface tension and viscous losses in microfluidic channels limits the potential for down sizing in these systems. In the same vein, the performance of MEMS inertial sensors and other force sensors is ultimately limited by thermal noise[26] . Small structures also have limited thermal stability which has become a critical bottleneck in applications such as MEMS actuators in magnetic hard disk drives where a stable actuator head must follow the narrow data track with high accuracy[27]. Finally, with the rapid emergence of functional MEMS prototypes, in order to develop these prototypes into commercialized products, packaging has become a prominent factor influencing the overall product dimensions as well as the unit cost of MEMS. Many MEMS especially those containing moving components require hermetic or near-hermetic packaging due to their susceptibility to environmental damage such as damping and moisture. MEMS' relatively high surface-area-to-volume ratio makes the hermetic environment critical. Fig. 2 shows a typical accelerometer package[28]. This induces significant challenges on the dimensional reduction of final MEMS products. Similarly RF MEMS packaging consumes a large area of the devices[29,30] and often reaches more than 70% of the total cost of the devices[31]. Packaging is a major factor contributing to the failure of many MEMS. Therefore, in order to realize the performance and dimension advantages of MEMS products, it is necessary to develop cost-effective and reliable packaging with small dimensions.

2.3. *The potential for NEMS?*

In recent years, a multitude of research has been carried out to scale MEMS to submicron dimensions thereby creating Nanoelectromechanical Systems (NEMS) with a view to achieving advanced device performance as well as exploiting attractive material properties occurring at nanometer scales. The anomalous properties of carbon nanotubes (CNT) are perhaps one of the best examples of substantially enhanced material properties at the nano-meter scale. Since the phonon mean free path is comparable to the length of CNTs, ballistic thermal and electrical conduction occur in CNTs replacing the mechanisms described by Fourier's law in bulk materials[32,33]. By virtue of their graphene structure CNTs also show extremely high Young's moduli (on the order of 1TPa)[34]. These electrical and mechanical properties suggest CNTs might be excellent building blocks for NEMS. As a result, CNT elements have been explored for resonators[35], sensors[36,37] and relays[38]. Solely realising a dimensional advantage is the primary drive for many NEMS developments. For instance, due to the nanoscale track widths in magnetic recording, magnetic recording heads with nanometer precision are required. Prototypes of heads with trackwidths smaller than 100 nm have been achieved enabling an areal density of the order of Tbit/in^2 [38]. The continued reduction in scales imposes increasing challenges on device design, including the lack of information of material properties at the nanometre scale. There are also significant challenges to the fabrication and testing of electromechanical devices at the nanometer scale. For example, a resonant frequency of over 1GHz has only been achieved at low temperatures (4.2 K) in ultrahigh vacuum[39]. This inevitably limits many NEMS to specific applications, which could offer satisfactory working environments.

3. Materials and Process Selection

Hitherto commercial MEMS products have largely utilized the materials and process set bequeathed by the semiconductor microelectronics industry. This has had the consequence that the devices which have been realized have tended to be those which can be made using the available materials and processes. As the MEMS sector expands and diversifies it is increasingly important to select materials and processes that are optimized with respect to the functional requirements of the devices themselves. To this end it is worthwhile examining the selection of materials and processes that are available to the MEMS designer using quantitative performance metrics by which to compare the candidates.

3.1. *Material Selection*

The fundamental approach to such selection activities has been developed by Ashby[40] and has subsequently been adapted to MEMS[11, 41,42]. At the heart of this approach to materials selection is the idea that the "performance" of a mechanical design can be expressed in terms of the functional requirements, geometric parameters, and material indices. A materials index is a combination of material properties that govern the scaling of the design performance. For instance the resonant frequency of a device scales with $\sqrt{(E/\rho)}$, the maximum acceleration to fracture a sensor scales with (σ_f/ρ) and the deflection capability of a flexure scales with (σ_f/E), where E is the Young's modulus, ρ the density and σ_f the failure strength of the material. Such metrics are easy to derive and a convenient way of presenting the data is to construct "charts" in which the properties of engineering materials are plotted on axes of the relevant material properties for a particular application. The performance indices can then be plotted as functions on the same axes. For more complicated designs, where multi-objective is required other techniques can be employed[43]. For the purposes of illustration it is instructive to consider the cases in which the information can be presented on a materials selection chart.

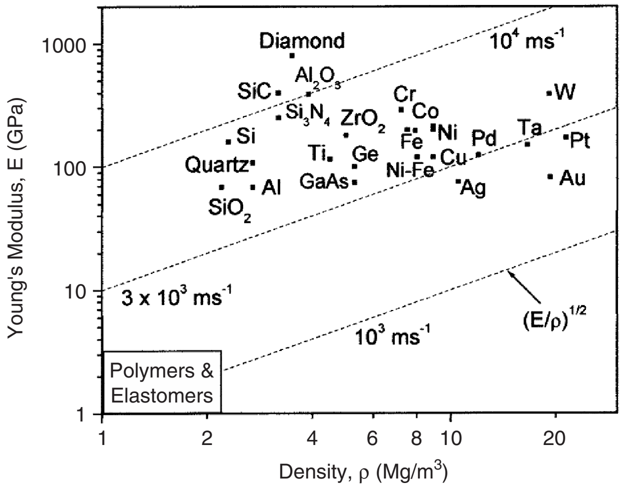


Figure 3: MEMS Materials plotted on an Ashby-style Material Selection Chart for Young's Modulus and Density.

Figure 3 shows an example of the case for Young's modulus and density. A range of materials are included, consisting of those commonly used for MEMS devices and a few others that might be considered candidates. Contours of equal $\sqrt{(E/\rho)}$ are also plotted on the same chart. Materials that offer higher resonant frequency for a given device geometry lie to the upper left of the chart. It is clear that commonly used MEMS materials such as Si and SiN_x are amongst the better materials for such an application. High stiffness ceramics such as SiC and Al_2O_3 offer the prospect of some improvement, with only diamond, or diamond like carbon offering more than a factor of two in higher frequency capability. A more detailed discussion of this selection methodology together with material property charts for a range of materials and properties is provided in reference [42].

The overall exercise described in [42] leads to the conclusion that for most existing mechanical sensor applications (pressure sensors, accelerometers and gyroscopes) Si and the other legacy CMOS materials are quite well suited to the functional requirements of the devices. Si is a reasonably stiff material, with low density, high fracture strength and low loss coefficient. Materials such as diamond-like-carbon, with its much higher stiffness have the potential to exceed the capabilities of Si, however the cost of developing and optimizing processes and tool sets for any new material for a large volume application provides a significant barrier to entry for any new candidate material. Furthermore the ability to integrate the mechanical elements of MEMS with the electronic functionality may be compromised if non-CMOS compatible materials are introduced.

The opportunity for integrating novel materials may be broader in the realm of functional materials for actuators, where piezoelectric, shape memory and thermo-electric actuation principles can be utilized. Similar selection principles can be applied. Recent work[44–46] on bimaterial electro thermal and piezoelectric bimaterial actuators has examined the suitability of different pairs of material for creating actuators optimized against the metrics of force, displacement, work, frequency and efficiency. The actuators consist of a cantilever beam with one material deposited on a substrate of another material. For an electrothermal actuator one or other of the two materials is heated resistively causing a thermal expansion, resulting in force or deformation. In this case the approach is to identify the capability of a candidate material on a given substrate. It is important to recognize that the optimum thickness ratio between the pair of materials will also depend on the material properties, particularly the Young's moduli. This approach allows the comparison of candidate material pairs via similar material selection charts to those described above. Figure 4 shows such a chart for a wide range of materials. The axes of the chart are the moduli and thermal expansion coefficient of the material. Contours of performance for displacement, force and work are overlayed. It is significant that the optimal materials choices vary depending on the performance metric chosen. Al/Si is found to be a very good material combination for such actuators, which is convenient given that this combination is compatible with the CMOS material set.

3.2. *Process Selection*

It is also instructive to compare the capabilities of the available processes. This has been achieved by surveying the literature and identifying generic "process chains" by which canonical structures, such as trenches and suspended cantilever beams or membranes can be achieved[47]. Metrics such as the absolute dimensions, tolerances, surface roughness etc. have been identified for each process chain. These metrics can then be used to compare the capabilities of candidate process chains to yield a particular geometric feature. These results can be displayed graphically in the form of process selection charts in which pairs of process metrics are cross-plotted and the envelopes associated with particular process chains are superimposed. An example is given in figure 5 for the in plane and out of plane dimensions of a trench. This exercise reveals that for the most part in plane features are limited by lithography, and that relatively few processes are capable of yielding features with sub 1 micron resolution. The maximum feature depth achievable is of the order 100 μm–1 mm, which is limited by reaction product removal for etching processes and mask uniformity microstructure control issues for deposition-based processes such as LIGA. Similar consideration of reaction kinetics and the diffusion of reaction products result in pronounced aspect-ratio limits for most of the process chains examined, i.e. a linear dependence of etch depth achievable on in-plane dimensions. Minimum etch depths are due to a combination of factors including the accuracy of chemical mechanical polishing to define the surface of the initial wafer and the ability to use etch stops or timed etches or deposition to achieve a target feature depth. Although these charts are constructed based on purely empirical data culled from the literature, they do provide valuable insight as to where there might be scope for process improvement by developing new processes. Furthermore the charts covering process chain tolerances can provide valuable assessments of whether a particular device's dimensions can be controlled by the process alone or whether subsequent electrical or mechanical calibration and tuning would be required.

3.3. *Sensor and Actuator Mechanism Selection*

Having investigated the selection of materials and processing route it is natural to use similar approaches to investigate the selection of operating principles of MEMS sensors and actuators themselves. Clear performance metrics can be identified for sensors and actuators. These include force, displacement, frequency and the resolution achievable for each of the preceding parameters. The capabilities of fabricated MEMS transducers in the literature have been evaluated and plotted on process capability charts[48]. These allow the comparison of MEMS devices and transduction principles with each other, but perhaps of more interest is the comparison of MEMS with macro-scale transducers for the same purpose. This exercise sheds light on to the wide breadth of sensing and particularly actuating principles that have been attempted in microfabricated devices. Figure 6 provides an example of a chart for MEMS actuators, comparing achievable force and displacement. The MEMS are generally distinct from macroscale actuators in terms of their lower force capability, however there is less distinction in terms of the maximum displacements achievable. This particular chart clearly indicates that there is much relatively unexplored space for MEMS actuators, where hitherto electrostatic actuation with some use of piezoelectric actuation has dominated. Effective SMA actuators apparently have great potential for high force and high work (force–displacement product) actuators. Hybrid actuators such as scratch drives and external field actuators offer promise for increasing the displacement capability above that achievable by existing actuator physics. More broadly this mapping exercise provides a clear basis for selecting actuation principle, and also for identifying gaps and opportunities to create more effective MEMS transducers or to insert MEMS in place of macroscale devices.

In conclusion the quantification of performance and the selection of materials and processes is an

Table 2: Properties of commonly utilised MEMS materials.

Properties	Si	SiO_2	Si_3N_4	SiC	Diamond
Density (kg/m^3)	2330	2200	3300	3300	3510
Modulus (GPa)	129–187	73	304	448	1050
E/ρ (GN/kg.m)	72	36	92	130	295
Hardness (kg.mm^{-2})	1000	710–790	1580	3500	10000
Fracture strength (MPa)	4000	1000	1000	2000	1000
Thermal conductivity at 300 K (W/cm.K)	1.5	0.014	0.3	4.9	20
Thermal expansion coefficient (10E$-$6.K^{-1})	2.6	0.4–12.3	3.3	3.8	1.1
Max. operation temperature	300	1100	1000	1240	1100
Dielectric constant	11.9	3.9	7.5	9.7	5.5

important step in moving MEMS technology away from a path in which capabilities are entirely dictated by what is easily achieved using the materials, processes and transduction principles which have been inherited from Microelectronics. These exercises allow the identification of promising new materials, processes and transduction principles, as well as allowing a clear quantification of where the benefits lie with employing the existing options.

4. The MEMS Material Set

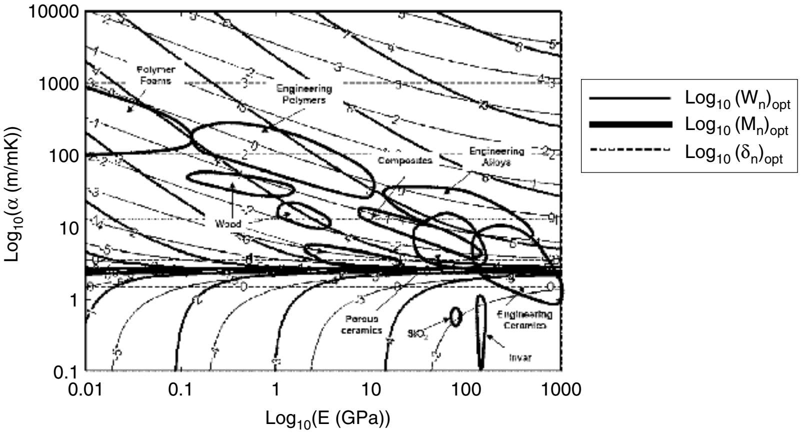
The available materials have played a key role in determining the classes of MEMS developed thus far. Table 2 lists the properties of the principal MEMS materials available. Extensively used in microelectronics industry, this Si-compatible material set has advantages for MEMS in terms of some material properties, its microfabrication feasibility and the availability of reasonably low-cost substrates. Within this material set Si is mainly utilized for structural elements, thin metal such as Al and Cu for electrical interconnects and passive layers such as SiN and SiO_2 for electrical insulation, and SiO_2 as sacrificial layers. Si is not only elastic and strong but is also a good piezoresistor and thermal conductor. Therefore, it is suitable for both mechanical and some transducer elements in MEMS. With similar mechanical properties to those of single crystalline Si, polycrystalline and amorphous Si are usually deposited as thin films and used as mechanical elements. The Si material set has been developed in parallel with microfabrication processes for microelectronics, ensuring that it allows integration with electronics as well as providing a high degree of process stability. Thus, Si-based MEMS still represent the overwhelming majority of commercial MEMS. However, the properties of the Si material set also restrict the applications that can be considered and there is great potential for advancing the field of MEMS by widening the materials available for their fabrication.

4.1. *Materials for Micromechanical Components*

Micromechanical elements are key components in many MEMS devices such as suspended proof masses and springs in inertial sensors, diaphragms in pressure sensors, beam structures in resonators and stators/rotors in micromotors. In these systems, device performance is dictated by the mechanical properties of the structural materials, particularly; Young's modulus, fracture strength, residual stress and tribological properties. As shown in Table 2, microfabricated Si has a high strength-to-density ratio and a high strain to failure, making it a good candidate material. However, for devices required to operate at high temperatures, or for very high resonant frequency resonators materials with superior properties to Si are sought[49], with silicon carbide (SiC) and diamond as leading examples.

With the highest known specific stiffness of any material, diamond has attracted interest as an mechanical material for MEMS. Diamond resonators for radio frequency (RF) MEMS have demonstrated GHz resonant frequencies with ultrahigh quality factors[50,51]. This opens up potential markets in the communications industries. However, in exploration of diamond as a MEMS material, one of the key challenges lies in the difficulty of integrating diamond films with other materials mainly due to its high deposition temperature. Also, the quality of most of the diamond films deposited still present rough surfaces and high internal stress due to the mismatch between the substrates and the diamond films, which are detrimental to MEMS devices. Recent findings suggest[52] that ultrananocrystalline (UNCD) films have promising micromechanical, morphological and tribological properties, which could be better suited for MEMS devices than polycrystalline and amorphous diamond. A UNCD microturbine is shown in Fig. 7. Also, low temperature (550°C) deposition of UNCD has been developed[53] and efforts have been made to realise UNCD oscillators and resonators integrated

Figure 4: Materials Selection Chart (thermal expansion coefficient, α vs Young's modulus E) for bimaterial thermal actuators using a silicon substrate. Contours are for normalized moments (M), deflections (δ) and work (W).



with CMOS chips as a part of a joint collaboration between Advanced Diamond Technologies Inc. and Argonne National Laboratory[54]. The main challenge towards future commercialisation of diamond MEMS is the development of cost-effective deposition techniques capable of large area and high volume production without compromising its material properties.

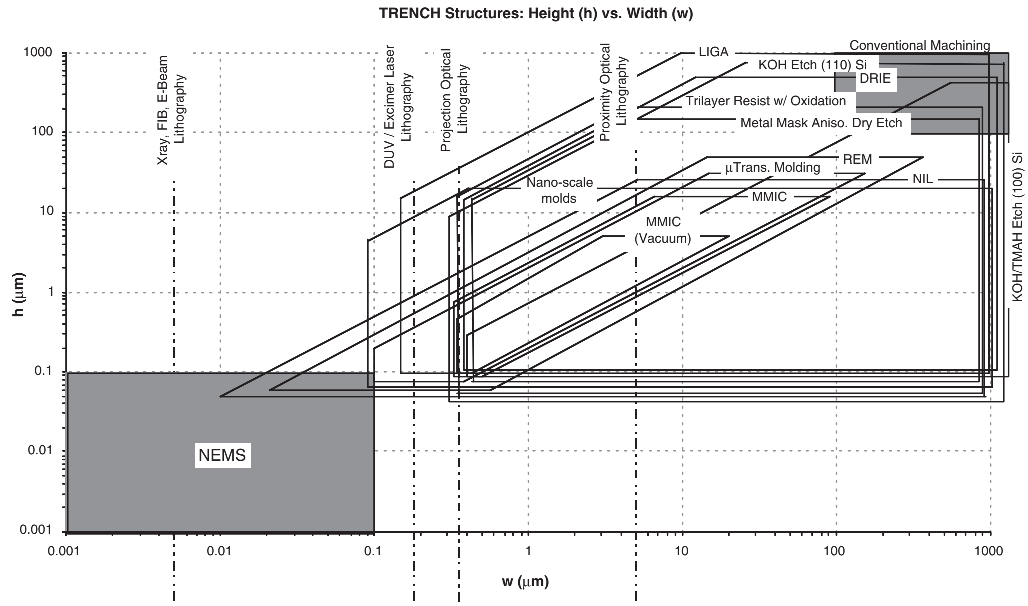
SiC is more advanced than diamond in terms of device development. It has also been recognised as an excellent candidate for microsensor and microactuator applications in harsh environments such as high temperature, high power level and strong corrosion, where Si is not suitable. Since Cree Research Inc. became the first supplier of SiC substrates in 1987, single crystal SiC wafers (4H and 6H) have been commercially available. In recent years, epitaxial grown single[55] and poly-crystalline[56] SiC layers on Si or SOI wafers have enabled large area SiC deposition which further stimulates the development of SiC MEMS prototypes with a view towards their commercialisation. In particular, SiC resonator structures have been realised using mechanical[57], electrostatic[58] and electrothermal[59] actuation, respectively. SiC can also be employed as the diaphragm[60] as well as piezoresistors[61] in pressure sensor applications. Another important area of technology is SiC accelerometers, which are particularly attractive for detecting high-*g* acceleration at elevated temperatures such as in aeroplane engines, military and space applications[62,63]. From a commercialisation point of view, the field of SiC is currently in its infancy and occupies a niche MEMS market. However, companies such as FLX Micro offer a limited commercial SiC foundry service. Also, for applications in harsh environments, it is particularly important to realise the integration between SiC MEMS and electronics. Thus, the development of SiC electronics has a direct impact on its MEMS counterpart.

One of the major reliability issues relating to Si MEMS is wear and unwanted adhesion. Due to the relatively low toughness of Si, fracture can occur when the structures are subject to high contact pressures. This can introduce debris and friction potentially leading to wear failure. Adhesion results from the dominance of surface forces due to the affinity of water or static from the structural components at the micrometer scale. Si micromechanical devices such as pinwheels[64], micromotors[65] and microturbines[66]are often subject to stiction problems preventing start-up[67] and wear-related failure[49]. Both diamond[68] and SiC[69] have been proposed as effective coating materials for Si micromechanical components in order to reduce friction and stiction and thereby achieve better reliability and enhancement of device lifetime.

4.2. *Materials for Transducer Elements*

Signal transduction from one physical domain to another is essential for the operation of MEMS sensors and actuators. Among them, electrical–mechanical and electrical–thermal–mechanical transductions are the most common transduction pathways and have been well demonstrated by the operation of electrostatic and electrothermal actuators and sensors. In electrical-mechanical transduction, external force can induce variation

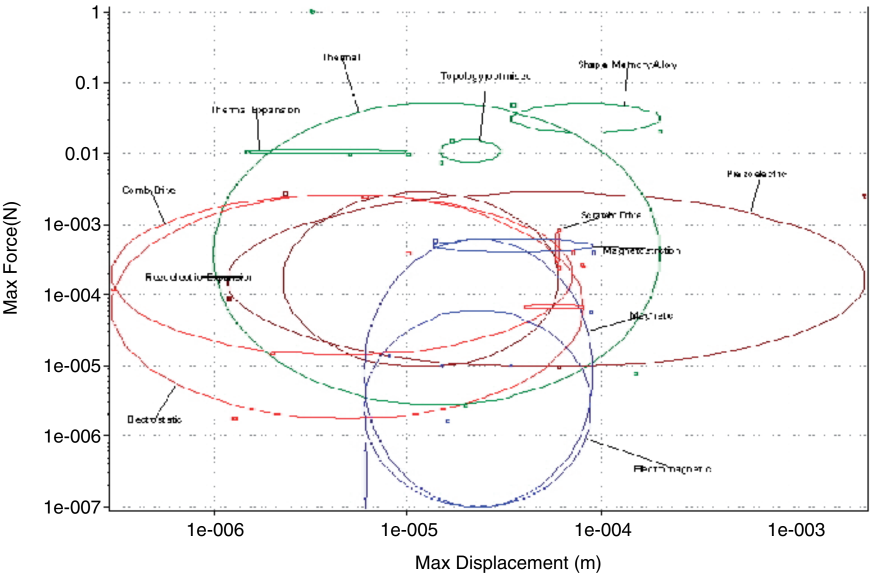
Figure 5: Process Selection Chart for determining capabilities of various microfabrication processes to achieve a trench of depth, h, and width w.



in electrical signals due to displacement as in pressure sensors while input electrical energy can also generate mechanical function as in micro switches and motors. For a typical "U" shaped electrothermal actuator, input current passes through the structure and generates different ohmic heating between the two arms which leads to lateral force and then motion. Most materials such as Si and metals with a certain level of conductivity or with conductive components can be utilized as the structural elements in electrostatic or electrothermal applications. However, in many other cases, materials with specific properties are required to enable a particular transduction function. Many of these materials such as piezoelectric materials, thermal electric materials, magnetic materials and shape memory alloys (SMA) have enabled new avenues of applications in MEMS.

Crystalline materials that lack a centre of symmetry can exhibit piezoelectric properties. Thin film piezoelectric materials such as lead zirconate titanate (PZT)[70], zinc oxide (ZnO)[71] and polyvinylidene fluoride (PVDF)[72] are particularly attractive for MEMS applications because Si can be used as a substrate. Piezoelectric materials offer a large power density with low impedance and power requirements as well as an inherently high operating frequency, which are advantageous for MEMS actuators and sensors. A detailed review of the applications of piezoelectric materials in MEMS is provided in reference[73]. Shape-memory alloys undergo a temperature-induced phase change, resulting in a large volumetric strain, when heated above a critical transition temperature. Heating in MEMS can be readily achieved electrically. Shape memory alloys can exert larger forces than their piezoelectric and electrostatic counterparts which is particularly attractive for actuation functions. Among the broad range of SMA such as Ti/Ni, Cu/Al/Ni, Fe/Ni and Fe/Pt, thin film Ti_xNi_{1-x} alloys are the most widely used for MEMS actuators[74,75] due to their simple composition and robustness. A TiNi micromirror structure is shown in Fig. 8. Thermal energy can also be directly converted into electrical energy and vice versa by thermoelectric materials. This material set can be particularly attractive for micro-cryogenic coolers based on the Peltier effect as well as power generators based on the Seebeck effect. Thin film thermoelectric materials are mainly considered for MEMS applications as they can be readily grown or deposited using common cleanroom facilities. In particular, the $(Bi_{1-x}Sb_x)_2Te_3$ compounds[76], $Si_{1-x}Ge_x$ compounds[77] and polycrystalline Si[78,79] have been explored. Inadequate energy conversion efficiency is still the main drawback related to the performance of these thermoelectric MEMS. Finally, in the presence of magnetic fields, magnetostrictive materials allow the interchange of mechanical and magnetic energies. The most advanced magnetostrictive materials such as $Tb_xDy_{1-x}Fe_y$ (Terfenol-D) have been explored[80,81] for MEMS

Figure 6: Actuator selection chart showing the force and displacement capabilities of MEMS actuators.



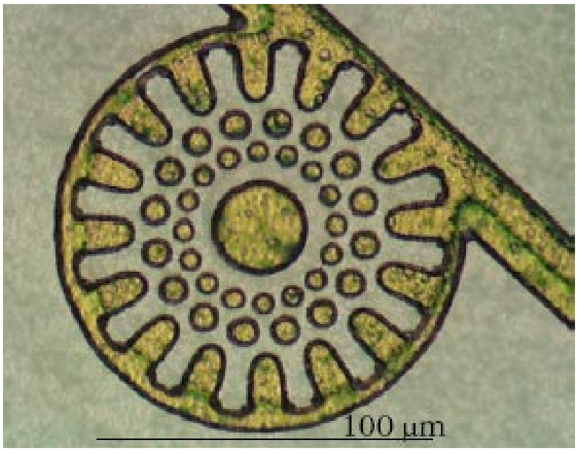
because they exhibit large magnetostriction at room temperature and require relatively small fields. However, the exploitation of magnetostrictive materials in MEMS is still very much restricted due to the relative low force and displacement output.

4.3. *Polymer MEMS*

Polymers especially synthetic polymers offer many advantages because they can be tailored to give a wide range of properties while requiring low temperature processing. A wide variety of polymer materials have been used for MEMS including; PMMA (polymethylmethacrylate), polyimide, photoresists, SU-8 resist, PDMS (polydimethylsiloxane), biodegradable polymers, parylenes, liquid crystal polymers and Teflon. One of the most important advantages of using polymer materials in MEMS applications is their low cost. It is relatively expensive to use Si wafers which have limited area as well as to create high aspect ratio (depth to width ratio) microstructures with conventional dry etching techniques. The requirement for low processing temperatures allows MEMS devices to be fabricated on large area or flexible substrates such as glass and plastics at high volumes. Thermoplastics and thermosets also allow low cost processing methods to be effectively used including; molding, embossing, melt processing, and imprinting. The inert properties of polymers such as polyimide and their relatively easy coating and bonding processes can also be advantageous for packaging purposes. The cost of polymer MEMS can be reduced by a factor of ten over Si-based devices.

Meeting the biocompatibility requirements of biological and chemical applications, polymer materials such as polyimide, PMMA, SU-8 have been explored extensively for MEMS in the life sciences and medicine especially for microfluidic applications. Deep features can be economically fabricated in polymers. For instance, structures with heights of more than 1000 μm can be formed in SU-8. The pre-patterned polymer layers can then be thermally bonded together to create sealed channels for microfuidic systems[82], as shown in Fig. 9. Biocompatible parylenes have also been used in the form of coatings on implantable microelectrodes[83]. Polymers with specific functionalities have also been utilized in MEMS sensors and actuators such as PVDF[72] and piezoelectric polyimide[84]. Electroactive polymers (EAP)[85], so called "artificial muscles", exhibit shape changes in response to electrical stimulation and thereby can be used as effective transducer components in MEMS. However, in order to raise the performance of these devices, a generic challenge is to develop polymers with a higher actuation stress capability, higher mechanical energy density and higher operating temperatures. For example, the current temperature range over which the piezoelectric properties of PVDF can be maintained is limited to be less than 80°C. Also, polymers are generally less stiff than conventional inorganic substrates such as Si and therefore they have limited applications for MEMS

Figure 7: An optical micrograph of an UNCD microturbine[52].



in which micromechanical performance is critical. However, this also suggests that polymer MEMS require lower operating voltages in applications such as electrostatic actuators compared to their Si counterparts.

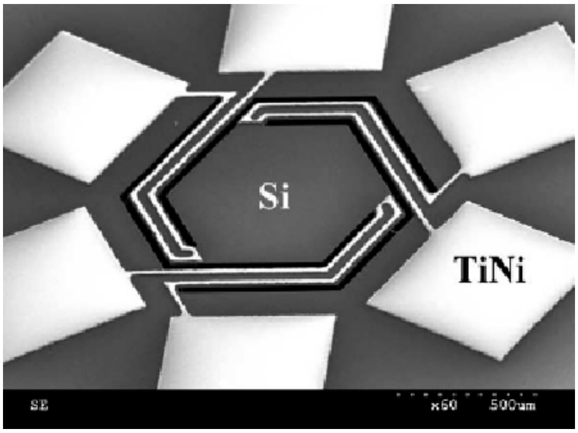
4.4. *Nanostructured Materials in MEMS/NEMS*

As described in Section 2, exceptional material properties often occur at extremely small scales, particularly in the nanometre range, because the feature size is of the same scale as the critical size for several physical phenomena. This has initiated the exploitation of nanostructured materials in NEMS devices. The defining characteristic of nanomaterials is that they have a feature size of 1–100 nm. Discrete nanomaterials such as CNTs and nanowires as well as continuous materials with nanomaterial compositions such as nanocomposites or ultrathin films can exhibit distinctive properties and thereby can be employed as building blocks in NEMS.

When discrete nanomaterials are used as structural materials, their extremely small size, large surface to volume ratio, specific functionalities or combinations of them can be utilized for NEMS to achieve advanced performance. Ultra high frequency micromechanical resonators have been reported using metal nanowires[86] and CNTs[87] to achieve resonant frequencies from hundreds of MHz to the GHz range. The tiny geometries and high mechanical strength herein play key roles. These resonators not only offer the potential for extreme mass and force sensitivity but also provide a possible approach to observe quantum phenomena directly. One-dimensional nanostructures such as Si[88,89] or conducting polymer nanowires[90,91] have also been used as biosensors. In this case, the electrical properties of nanowires are strongly influenced by minor perturbations because of their high surface-to-volume ratio and tunable electron transport properties due to the quantum confinement effect. Recent studies[92] of piezoelectric nanowires such as ZnO have also demonstrated the potential to harvest vibration energy via an electrical generator, which could be utilized in future self-powering nanodevices. However, when discrete nanomaterials are used in NEMS, it is important to anticipate significant and generic challenges in sample handling and device testing.

Continuous nanostructured materials can be formed by the incorporation of nanomaterials into conventional material matrices or combinations of different nanomaterials. The overall material properties can then be improved and tailored over a wide range by tuning the relative densities of the compositions and thereby generating desirable materials suitable for certain applications. For instance, theoretical studies suggest[93] nanofibre (nanotubes, nanorods and nanowires) reinforced composites could exhibit relatively low modulus and high wave speed. The combination of these conflicting properties is required by some MEMS applications where low actuation force or actuation voltage and high actuation frequency are required[94]. Ceramic nanocomposites have also been proven[95] to be more effective than their conventional ceramic counterparts in MEMS applications due to the increased fracture toughness. As another important continuous nanomaterial set, ultrathin films with submicrometer thickness have been utilized as structural materials for NEMS sensors in order to achieve ultrahigh sensitivity and fast response[96]. However, these systems usually are susceptible

Figure 8: TiNi micromirror structure with a Si cap acts as top mirror and the arms fabricated with TiNi/Si beam structure[75].



to mechanical energy loss due to the increase in surface to volume ratio and thereby appropriate surface treatment and a passivation process needs to be applied[97]. Nanocomposite ultrathin films have also been investigated for NEMS applications. A recent result[98] demonstrated the possibility to engineer metal nanocomposites to achieve nearly atomically smooth surfaces, high stiffness and high electrical conductivity. These metal nanocomposite ultrathin films shows advantageous for applications such as NEMS switches. Generically, continuous nanostructured materials usually require optimisation processes to obtain materials with the desired properties as well as developing effective micromachining techniques before they can be exploited in MEMS.

5. MEMS Fabrication Processes

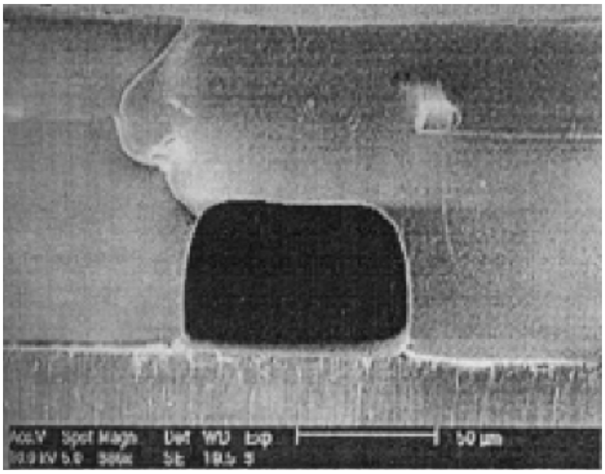
Originally developed in the microelectronics industry, microfabrication processes are essential to the creation of functional MEMS devices and are often the major constraint to realising commercial MEMS products. Furthermore, the development of the MEMS material set largely depends on the availability of processing techniques. Thus, developments of effective fabrication processes are not only important for conventional Si MEMS but are also critical for the realisation of MEMS with new materials.

Based on micromachining dimensions, fabrication processes are often coarsely categorised into bulk and surface machining and detailed in most of MEMS textbooks[15]. Bulk micromachining refers to process sequences in which three-dimensional features are created in a substrate for the purpose of diaphragm or cavity formation. On the contrary, surface micromachining mainly involves deposition and etching of relatively thin layer materials on bulk substrates. Throughout their evolution MEMS material and fabrication processes have evolved from well-established microelectronic processes. A recent example is the increasing usage of silicon on insulator (SOI) substrates in MEMS devices stimulated by the fact that SOI has entered into the mainstream of the microelectronic industry[99,100]. However, the continuous increase of Si substrate dimensions in the microelectronic industry has started to bring negative consequences for the MEMS industry. Tool sets to accommodate large Si wafers will inevitably be developed and dominate the mainstream microfabrication processes. But most MEMS currently are fabricated using relatively small substrates (100 mm or 150 mm in diameters) and many of these are still in prototype stages. To address this issue, it is important to establish mature MEMS fabrication processes particularly IC-compatible processes. Furthermore, the continuous emergence of novel MEMS material sets for advanced device applications has also posed new challenges towards microfabrication techniques. This section focuses on the key fabrication processes and their associated issues in MEMS.

5.1. *Lithography for MEMS*

Lithography is the first step for patterning. As described in most microfabrication text books[15], optical lithography using e.g. deep-ultraviolet, x-ray, excimer laser as energy sources has been the enabling technologies for virtually all integrated circuits (ICs) and MEMS productions to-date. For decades, the continuous shrinkage of electronic

Figure 9: Cross section of a microchannel made of SU-8 [82].



circuits has pushed optical lithography to achieve increasingly small line widths. In the semiconductor industry, currently 90 nm features are already in mass production of electronic devices and 29.9 nm high quality line patterns have been recently reported[101]. These developments also provide effective high resolution lithography techniques for MEMS. However, unlike IC devices which only require two dimensional or planar structures to be fabricated, MEMS usually contain 3D features. This has posed new challenges to develop novel lithography techniques to suit special MEMS patterning requirements. As a result, "soft lithography" which encompasses imprinting techniques for polymer MEMS has been developed and proven to be cost-effective and advantageous to create features with high aspect ratios. Also, technologies such as holographic lithography[102,103], stereo lithography[104] and gray-scale lithography[105] are particularly attractive for the formation of 3D MEMS structures. Techniques using numerically controlled e-beam writing[106], flexible stamp[107], flexible mask[108], shadow-masking[109] and laminated film resist[110] have been employed to produce microstructures on nonplanar surfaces and even deep trenches. With optical lithography reaching its practical limit, the lithography techniques originally derived from MEMS devices such as nanoimprint could transfer to future generation microelectronic products.

5.2. *Pattern transfer techniques*

Following pattern definition by lithography, these patterns are transferred into structural materials to create microfeatures. The pattern transfer processes usually involves removal or addition of materials or both, which are described in the following subsections, respectively.

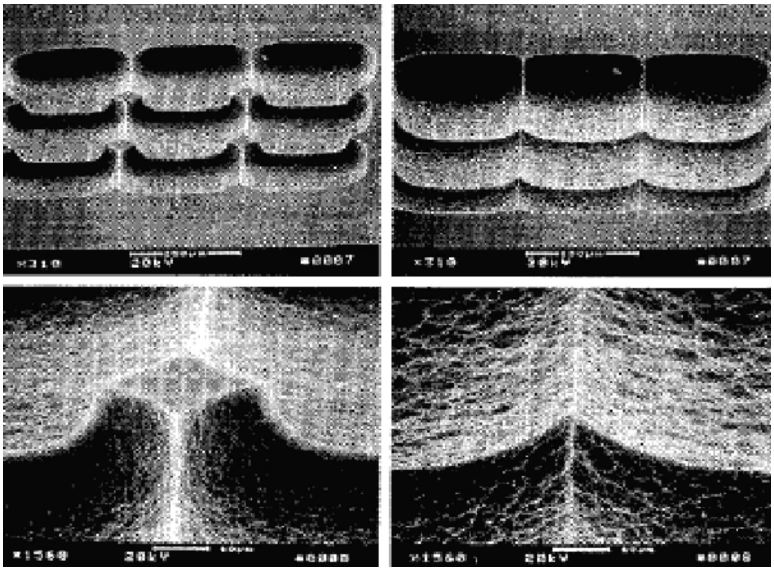
5.2.1. *Etching processes*

The most prevalent material subtractive method for pattern transfer in MEMS is based on etching processes which are usually categorized as wet and dry etching. Wet etching utilizes suitable liquid chemicals to attack and remove the exposed substrate regions while dry etching usually takes place in chemically reactive vapour or reactive species in glow-discharge plasma. Both wet and dry etching are extensively used in Si bulk and surface micromachining and their standard processes are well-described elsewhere[15]. An important recent dry etching innovation is the emergence of XeF_2 which etches Si spontaneously with an isotropic etch profile as shown in Fig. 10[111]. Using XeF_2 in its gaseous form (non-plasma), high Si etch rates (up to 15um/min) have been achieved with extreme etching selectivity over Al, SiO_2, SiN and even photoresist[111]. This implies that existing CMOS electronics can be protected during the etch process and therefore suggests it is potentially suitable for post-CMOS etching. For plasma related dry etching, the Bosch process[112] is still extensively used to achieve Si high aspect ratio features in which repetitive etch and passivation steps are utilized during the cyclic process. Due to the involvement of both physical and chemical reactions in the plasma, plasma etch processes can often be tuned into either the physical- or chemical-dominated regimes which can be particularly attractive in the developments of effective etching processes for new MEMS material sets such as SiC[113,114].

5.2.2. *Additive processes*

Common additive processes in MEMS mainly involve material growth and/or thin film deposition. MEMS structural layers such as polysilicon, metal electrodes/interconnects and sacrificial/insulation layers such as SiO_2 and SiN can be deposited by chemical vapour deposition (CVD), physical vapour deposition (PVD), or electrodeposition (or electroplating). These additive processes have also been extensively explored towards the development of new material sets that can be utilized in MEMS applications. It is worth noting that additive processes associated with high temperatures hinder the development of cost-effective MEMS in terms of integration with ICs. For example, polycrystalline Si is still commonly used as a MEMS structural material. However, the high temperature (over 600°C) required for its CVD deposition is incompatible with CMOS electronics. Therefore, for future MEMS and IC integration, it is important to further develop low temperature additive processes or CMOS compatible materials. Micromolding is another important additive process

Figure 10: SEM images of XeF_2 etched pit openings to illustrate its isotropic etch profile[111].



in which materials are deposited into pre-patterned micromolds followed by removal of the mold along with unwanted structural materials. LIGA was the first MEMS micromolding process. In LIGA metal is electroplated into a polymer mold preformed by high energy x-ray lithography. It is an effective technique by which high aspect ratio structures with good side-wall controls can be fabricated[115–117]. Micromolding allows the formation of MEMS components from a range of materials with flexible geometry especially those that are difficult to etch. Thus, it is particularly attractive for MEMS prototyping. For instance, using prepatterned polysilicon mold, SiC micromotors[118] have been fabricated, as shown in Fig. 11. Despite these advantages, micromolding is still not at the level of high volume production and commercialisation. This is partially due to insufficient knowledge in process control, difficulty in reproducibility[119] and also requirement to use highly collimated synchrotron sources in the case of LIGA[120] .

5.3. *Wafer bonding processes*

Wafer bonding is an important technique for material and microsystem integration. It enables the formation of SOI substrates[121], sealed microstructures/cavities[122] and the integration of devices at different levels[123,124] and dissimilar materials[125,126]. Therefore, it has been identified as a promising process for the realisation of future three-dimensional integrated circuits (3D IC) in microelectronics as well as for the creation of multilayered systems, 3D microcavities/microchannels and effective packaging in MEMS. Wafer bonding techniques utilized in MEMS can be classified into direct bonding (fusion bonding), anodic bonding and intermediate-layer bonding. As depicted in many articles[127] and books[128,129], the direct bonding process is used to mechanically join two Si wafers together by creating hydrophobic or hydrophilic surfaces that are brought into contact and annealed at high temperatures. Anodic bonding joins a Si wafer to an alkali glass (e.g. pyrex borosilicate glass) wafer by the aid of charge migration driven by an applied electrostatic field. Intermediate-layer bonding includes eutectic, glass-frit and thermal compression bonding which utilized intermediate layers such as metal, glass or polymers to adhere the substrates together.

In general, wafer-bonding utilises a three step sequence: surface preparation, aligned bonding and annealing. Wafer bonding quality is strongly dictated by wafer surface conditions in terms of contamination, roughness and flatness. For instance, generally Si wafers with very few particles, $\leqslant 5$ Å roughness and $\leqslant 5\ \mu$m flatness on 100 mm wafers are necessary to ensure a good direct bond[130]. Combined with extensive post-cleaning processes, chemical-mechanical polishing (CMP)[131] has been a common technique to create sufficiently flat and smooth surfaces to achieve high reliability bonds. Furthermore, wafer bonding alignment is commonly achieved by a variety of optical means, however alignment accuracy of a micron at best is currently obtained due to the large optical structural loop[132]. These optical means are fundamentally limited by the wavelength of light and practically limited by the mechanical positioning systems required to match the two wafers. However, nanoprecision bonding alignments is necessary to ensure desired functions of multilayered MEMS[124] and electronic devices[133]. Based on kinematic and elastic averaging effects, an innovative micromechanical method[134] has been recently proposed and the proof-of-concept results at the Si chip level demonstrated better than 200 nm bonding alignment accuracy without using any optical alignment facilities. Fig. 12 shows schematic drawings of the utilized micromechanical alignment features at the chip level. Finally, direct Si or SiO_2 bonding requires high temperature annealing ($\sim$800°C) to attain a strong and permanent bonding. The use of high temperature is not always acceptable, especially when there are low temperature materials (e.g. Al, polymers) or pre-fabrication electronic devices involved in the systems. Consequently, low temperature bonding techniques (lower than 400°C) have been widely developed. In most cases, plasma treatments[135] particularly oxygen plasmas[136], are applied to activate the surfaces before bonding which lead to a high bonding energy after annealing at low temperatures.

5.4. *Packaging Issues*

MEMS devices usually have to be packaged to provide electrical contact, mechanical protection as well as interfaces with the environment for sensing, interconnection and actuation. Hermetic seals are often required in MEMS packaging for environmentally sensitive components or fragile moving elements to ensure appropriate protection, assembly and long term reliable operations. In general, materials such as ceramics, metals and polymers are used in MEMS packaging as detailed elsewhere[137]. However, unlike well-established IC packaging, MEMS packaging still faces significant technology barriers and cost issues. This has been a major obstacle to the commercialization of many MEMS products. The difficulty in MEMS die handling, the high level of protection required and custom packaging for each application have led to high package cost which may be as high as 80% of the product cost[138] . In recent years, wafer level packaging (WLP) has become a promising alternative for high volume and low cost MEMS production[137, 139] and is widely accepted by MEMS manufactures. WLP utilizes wafer bonding techniques to encapsulate devices. It allows MEMS devices and packaging to be manufactured and tested on wafers prior to singulation. The economic advantage of WLP will be more prominent with the increase of wafer size and shrinkage of MEMS die dimensions. Furthermore, since MEMS packages can also consume (absorb) and emit materials (outgas), to help control/maintain the atmosphere/vacuum within hermetic packages, the integration of effective getter materials into MEMS packages has also emerged as a promising technology [90, 140].

6. Materials Characterization

The success of the microelectronics industry has been underpinned by the reliability of the simulation tools available and the extremely well characterized electronic properties of the materials being utilized and the processes with which the products are created. For MEMS to achieve their promise of

Figure 11: SiC wobble micromotor formed using a sacrificial polysilicon mould[118].

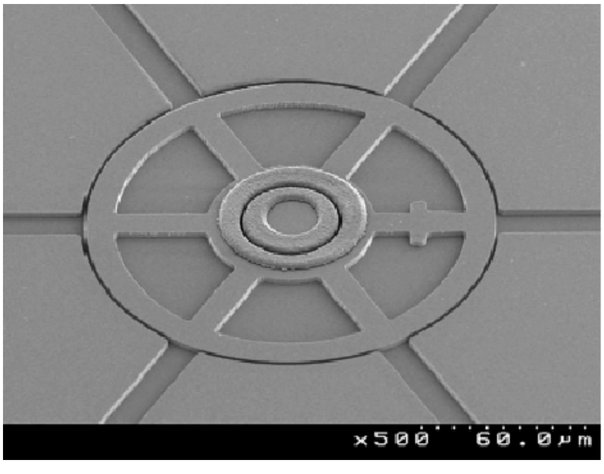
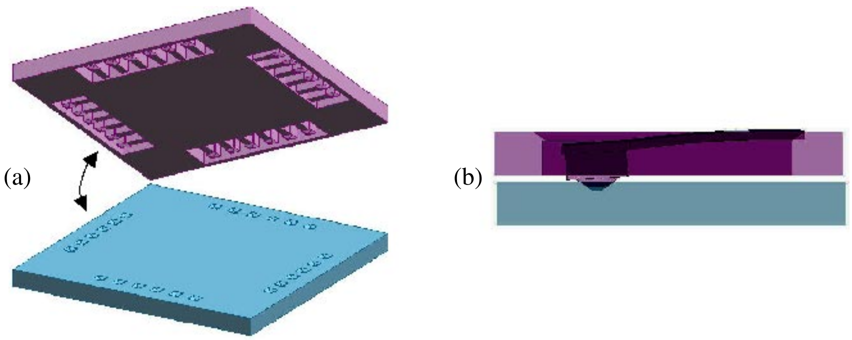


Figure 12: (a) Chip designs containing alignment features (not to scale), (b) profile view of a pair of engaged alignment features.



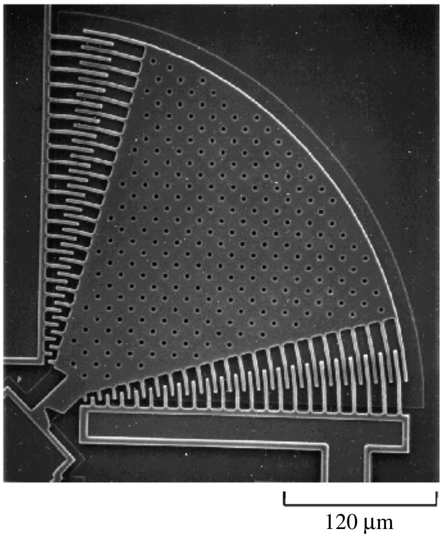
low unit cost and large volume production it is important that similar confidence exists in the output of design codes, which in turn implies that the capabilities to characterize the material properties are well proven. Given that electronic and other functional (e.g. optical and magnetic) properties receive considerable focus for mainstream applications (microelectronics, optoelectronics and memory devices), the most important MEMS-specific requirements for characterization are of the mechanical properties.

The key issue is that microfabricated materials have mechanical properties that are highly dependent on the fabrication route used to create them and the scale of the structures in which they are employed. As noted in section 2 properties at the microscale can vary considerably from those measured on bulk samples of material at the macroscale. In order to fully realize the potential for accurate and rapid simulation tools for design of MEMS models are required which link the fabrication route used to the value of the material property achieved via the microstructure and composition of the material. The first step towards this is to develop standard test methods with which to characterize the mechanical properties of microfabricated structures produced by the same processes and at the same scales as the intended application. This enables the creation of validated material property and process data-bases and correlations to permit simulation-based design. The following sections illustrate where progress in this direction has been made. There have also been several recent reviews of this area[141,142].

6.1. *Elastic Properties*

Measurement of elastic properties at small scales is relatively mature and can generally be achieved accurately. Cantilever beams, double clamped-beams[143] and diaphragms which are loaded electrostatically[144], mechanically by external means (such as nanoindentor tips)[145] or by fluid pressure[146], with deflections measured by means of capacitance or optical sensors have been notably popular for this purpose. Raman spectroscopy can also be used to obtain strain distributions in silicon specimens[147]. Tensile tests have been developed with interferometric strain measurement methods[148]. Resonant structures have also been utilized[149] and offer the potential for particularly accurate measurements. These methods have allowed reproducible evaluation of the Young's moduli of deposited thin film materials. In addition the development of focused ion beam machining techniques have permitted test specimens to be fabricated without recourse to wafer-level patterning. The use of the unloading compliance during the nanoindentation of unpatterned thin films has received considerable interest as a method for extracting elastic properties, however this is not as accurate for this purpose as the methods described above. It does however have advantages in the extreme simplicity of the measurement. Hitherto relatively little work has focused on obtaining other elastic constants such as Poisson's ratios[150] and shear moduli or the thermal expansion coefficients[151] and on understanding the possible effects of anisotropy due to the crystallographic texture of deposited thin films. It is noteworthy that a decade ago, even for a widely used material, such as polysilicon, values of moduli ranging from 132 GPa to 174 GPa were reported in the literature[152] on material deposited by nominally identical processes. Test techniques, metrology and understanding of likely sources of error have improved significantly in the interim to the point where such measurements can be considered to be routine[153]. Another significant recent development

Figure 13: A MEMS Fatigue test structure (Courtesy S. Brown).



is the introduction of test techniques that permit accurate property measurement without recourse to highly sophisticated instrumentation[154]. This is a key step to migrate mechanical characterization of materials for microsystems into routine industrial practice.

6.2. *Strength Characterization*

The characterization of the strength of microfabricated materials and structures is required for microsystems that are designed to operate at high mechanical power densities and/or large deflection levels. The performance of such devices is limited by the strength of the materials of construction. Since the strength of materials, can be very dependent on the scale and the fabrication route, it is critical that measurements to be used for design purposes are obtained from test structures fabricated by the same processing route and at a similar scale to that to be used for the application for which they are intended.

Various approaches have been taken to obtain room temperature strength related properties. Nanoindendation has proven to be a viable means to extract information regarding plastic constitutive behavior[155] although it struggles in cases where there is anisotropy or heterogeneity. Electrostatic actuation has been used to generate forces sufficient to cause fracture in surface micromachined structures[156]. However, in order to generate sufficiently high stresses to cause fracture by such means the cross section of the part typically has to be limited to a small fraction of the area used to generate the electrostatic force, and even then significant stress concentrations need to be introduced. In order to test larger specimens at higher force levels various workers have used mechanical loading applied via modified microhardness indentors[157] or nano-indentors to generate bending stresses to cause failure[158]. In addition tensile tests have been performed using mechanical or electrostatic gripping and *in situ* strain measurement[148]. These approaches are particularly necessary for the thicker structures realized by bulk micromachining and/or SOI layers. In the case of brittle materials, the statistical variation of strength is a key variable. Although Weibull statistics has been applied[159], it does not seem to adequately represent the scaling of strength into structural designs. This is most likely due to the strong interactions between the specimen geometry, the processing route and the resulting flaw population. Further work is required on this topic.

Obtaining elevated temperature properties for microfabricated materials is important as the MEMS devices are designed for high temperature applications, as well as to help develop models for microfabrication processes which utilize elevated temperatures for bonding or annealing. Bulge tests of pressurized cavities[160] have been used as one means of obtaining such data, as well as more conventional macroscale bend tests[161] and compression tests[162].

6.3. *Adhesion and Bond Strength*

Virtually all MEMS consist of multiple layers of materials created by deposition or bonding operations. The structural integrity of the bonds between layers is a key parameter in determining reliability. Several techniques are well established for measuring thin film adhesion including bulge testing[163], peel testing and residual stress driven cohesion measurements[164] and these are not unique to MEMS devices, although it is worth noting that microfabrication techniques play a key role in creating the test structures which allow these measurements. Of direct relevance to MEMS are test techniques used to measure inadvertent adhesion due to "stiction". The most well developed techniques use arrays of cantilever beams of defined stiffness, and then observe the critical length at which they adhere to the surface[165]. Such methods are important in order to allow the development of surface modification and process sequences that eliminate the danger of stiction, which is a key problem for compliant surface micromachined structures.

As previously noted wafer bonding is of more specialized application to MEMS. A number of techniques have been developed to allow determination of bond quality and strength. Non-destructive methods, including infra red, ultrasonic and X-ray imaging have been employed to detect macroscopic voids[166]. This is particularly valuable during the initial contacting phase of fusion bonding operations since poor bonds can be indentified and the wafers separated and rebonded before the elevated temperature annealing step is carried out. Bond strength has been characterized by a number of techniques, including pressure burst testing, double cantilever beam specimens[167] and other mechanically loaded structures, which expose the bond to combinations of tension and shear stresses. More recently attention has focused on developing the ability to map bond toughness across a bonded pair of wafers using smaller micromachined chevron-notch specimens, which can be tested individually[168]. Other work has also used patterning to measure the bonding energy (as opposed to the fracture energy)[169]. Given the importance of bonding operations to MEMS fabrication this is a fertile area for materials science and mechanical engineering advancement.

6.4. *Residual Stresses*

Since MEMS devices typically contain several deposited and bonded layers of dissimilar materials residual stresses can play an important role in determining the reliability of the processes and the fabricated devices. The issues of thin film residual stresses have received considerable attention due to their importance in the microelectronics industry, and to a large degree these issues are the same as those found in MEMS. However, as MEMS devices are created which have larger mechanical power and force capabilities, thicker deposited layers are being investigated than are typically utilized in microelectronic applications. This is particularly true in devices which use molding operations, such as LIGA and CVD deposition of SiC. These thicker layers have a greater tendency to fracture and the thickness (and therefore size of the device that can be realized) may be limited by the residual stress state. The ability to control and characterize residual stresses is very important for the development of higher performance MEMS and various novel test structures have been created to permit residual stress characterization[170,171].

6.5. *Fatigue*

MEMS devices may be subject to very high numbers of fatigue cycles during their service lifetimes due to their inherently high operating frequencies. This raises the possibility of fatigue being a limiting factor on the allowable stress levels or useful life. These concerns have resulted in the recent development of test structures to probe the fatigue behavior of microfabricated materials. Typically these structures utilize electrostatic loading and excitation at resonance to obtain stress levels sufficient to cause fatigue failure. Such a structure is shown in figure 13. Such test methods have shown the possibility of fatigue processes in both ductile[172,173] and brittle microfabricated materials[174]. It is a matter of considerable discussion as to whether the mechanism observed in brittle materials, particularly polycrystalline silicon is a cyclic fatigue process[175], or rather an environmentally assisted slow crack growth process, albeit with some synergy between load cycling and crack growth[176]. It is also worth noting that many commercial accelerometers and pressure sensors have experienced extremely high numbers ($> 10^{10}$) of cycles apparently without sustaining any fatigue failures, and at least one major company has concluded that fatigue is not of sufficient concern for their polysilicon sensors to merit direct consideration in their design process. However, as MEMS devices start to push towards higher mechanical power levels fatigue may increasingly become a concern.

6.6. *Surface Forces and Tribology*

The high surface area to volume ratio of MEMS devices implies that tribological effects are likely to be important factors in determining performance. Experiences with surface micromachined accelerometers[177] and micromotors[178] suggest that surface adhesion due to charge build up or moisture adsorbtion is a critical issue that results in stiction and hysteresis. The same scaling of electrostatic forces that makes it attractive for prime movers at the microscale also can prove a liability. In addition the use of a wet etch as the release step can be complicated by the introduction of capillary forces between elements that prevent their separation. Experience with micromotors and micro-gear trains running at high rotational speeds on unlubricated sliding contacts has indicated that wear processes are very important in both allowing the bearing surfaces to be worn in to allow low friction operation, and subsequently in contributing to failure. This is despite the very low inertial and gravitational forces associated with the devices.

The importance of tribology for MEMS has resulted in a growing literature on the subject[179], quantitative measurements of surface adhesion forces, friction and wear, and erosion behavior have been obtained from a variety of devices. Attempts are being made to modify micromachined surfaces[180] or apply low friction coatings[181] in order to promote better tribological characteristics and there is a great need for increased understanding in this area if reliable and durable devices are to be created. In addition non-materials solutions, involving the use of air bearings[182] or magnetic levitation offer promise for overcoming some of the tribological issues associated with high speed MEMS.

The mechanical characterization of materials is a key activity if reliable and durable MEMS devices are to be realized. Addressing the topic of durability is particularly important if MEMS are to be used in embedded systems for system health monitoring and other safety critical applications. It will also become extremely important to be able to perform failure analyses in cases where structural integrity is lost. This is not a trivial activity at the microscale.

7. Concluding Remarks

Since 2000 the research activity in materials issues associated with MEMS has expanded dramatically. The number of research articles associated with the topic has increased by more than an order of magnitude and the annual rate of publication of research articles has increased by a commensurate factor over the past decade. The manifestation of this activity can be seen in all the areas considered in the present article. The MEMS material set has significantly expanded, and is no longer limited by the constraints of CMOS-compatible materials and fabrication facilities. Similarly the range of processes available has increased beyond those that are solely the province of conventional CMOS. The characterization techniques for mechanical properties have matured and several are being used, or considered for use, in industry. Furthermore microfabrication and microfabricated structures are routinely used to characterize materials, particularly thin films for microelectronic applications and biological materials. Notwithstanding the significant progress in the development of new materials and techniques associated with MEMS it is noteworthy that the vast majority of commercial MEMS still are produced with the CMOS-compatible material and process set. This reflects the massive investment of financial capital in fabrication facilities and intellectual capital in the scaling up of mass-production processes. It is also significant that no-truly nanomechanical systems have emerged, which partially reflects unfavourable scaling for many mechanical performance metrics below the 1 μm scale, although these constraints do not apply for non-mechanical integrated systems. It is clear however that the foundations have now well and truly been laid for the irreversible broadening of the MEMS materials and process set. It is also significant that some processes which were primarily developed for MEMS devices, such as multi-wafer bonding and deep anisotropic etching are being increasingly considered for mainstream microelectronic devices, particularly with regard to 3-D interconnect schemes. There is no sign of the rate of decline in the rate of progress in materials and processes for MEMS, which suggests that the coming seven years will witness at least as much technical progress as the previous seven.

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