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MATERIALS ISSUES IN MICROELECTROMECHANICAL SYSTEMS (MEMS)*

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Abstract—Microelectromechanical systems (MEMS) have recently become an important area of technology, building on the success of the microelectronics industry over the past 50 years. MEMS combine mechanical and electrical function in devices at very small scales. Examples include pressure sensors, accelerometers, gyroscopes and optical devices, as well as chemical, biomedical and fluidic applications. The status of MEMS technology is reviewed with particular emphasis on materials issues therein. The materials issues in MEMS are divided into three categories, the MEMS material set, microfabrication processes, and material characterization and design. Each of these areas is addressed, with particular emphasis on the potential impact of materials solutions. A discussion of the future of MEMS and the role of materials in that future is given. *© 2000 Acta Metallurgica Inc. Published by Elsevier Science Ltd. All rights reserved.*

Keywords: Microelectromechanical systems; Scaling; Microfabrication; Material selection; Mechanical properties

1. INTRODUCTION

The past decade has seen the rapid growth of microelectromechanical systems (MEMS) as an important area of technology, growth which is expected to continue well into the next century. The basic premise behind the concept of MEMS is that the efficiencies of high volume production and low unit cost achieved by the microelectronics industry over the past 50 years 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 potential economic benefits, unique capabilities can be achieved by such integration to realize devices at very small scales such as sensors [1, 2], actuators [3], power producing devices [4], chemical reactors [5] and biomedical devices [6, 7]. Furthermore, the ability to integrate the mechanical (or biological or chemical) function with the electronics required for control and power conditioning in a single device allows for consideration of concepts such as the highly distributed networks required for health monitoring of large structures and systems [8] or for distributed power and chemical production schemes.

The success of MEMS as a key technology in the twenty-first century depends in no small part on the solution of materials issues associated with the design and fabrication of complex MEMS devices [9]. 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 scale dependent properties, particularly yield and fracture strength [10]. MEMS also offer the opportunity to materials scientists and engineers to be able to characterize materials in ways that have not hitherto been possible. In this article the current status of MEMS is reviewed with a particular emphasis on the role of materials, as well as some of the opportunities for MEMS to contribute to the wider field of materials science and engineering.

Before focusing on materials issues in MEMS it is important to make some statements regarding the scope of this article. First, small size and use of some microfabrication processes in its creation does not automatically qualify a device to be defined as a MEMS. The two key attributes in the definition used here are that the microfabrication processes used to create the device should be scaleable in order to realize a low unit cost of production and that there is some level of integration between elec-

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tronic and non-electronic function. The effect of these working definitions is to confine the discussion to devices and processes that utilize or build from the experience established with microelectronics, however it does permit discussion of devices other than sensors and actuators—which have hitherto been the focus of MEMS development. The influence of this restriction will be assessed in the discussion section toward the end of the article.

The second key point is that, as their acronym suggests, MEMS are systems. Thus a description of challenges and the development of solutions for MEMS must be presented in the context of the overall system, as opposed to solutions that only address one facet of performance. The introduction of a new material to address a particular aspect of the mechanical performance of a device is worthless unless a fabrication route exists which is compatible with the other materials and structures within the device, and that the new material provides the appropriate functionality in the context of system performance. A corollary of this observation is that many of the materials issues are not unique to MEMS, and materials solutions would be likely to find application in other areas. In this article particular attention is given to materials issues which are of principal importance to MEMS, whereas issues that are common to other applications, such as microelectronic devices or packages, are only mentioned in passing.

The realization that materials technologies are enabling or limiting for some MEMS concepts has spurred a growing interest in MEMS within the materials community. Several symposia and workshops on MEMS and materials have been held over the past 3 years and the proceedings of these meetings [11–13] have helped frame the issues discussed in this paper. Interested readers are also referred to several excellent broader references/reviews of MEMS technology [14–16] and microfabrication [17].

The structure of the remainder of the paper is as follows. Section 2 discusses the effects of length scale on MEMS design. Section 3 briefly reviews the three prevalent fabrication routes used to create MEMS. Section 4 presents the MEMS materials set that arises from these three fabrication routes. Section 5 discusses materials issues associated with key fabrication steps. Section 6 discusses issues associated with the design of MEMS, and the role of material characterization. Section 7 looks to the future of MEMS and the role of materials.

2. THE EFFECT OF LENGTH SCALE

Before focusing on the particular materials issues in MEMS it is worth discussing briefly the overall influence of length scale on the design, fabrication and performance of mechanical devices. Scale effects enter into the design of MEMS and affect materials issues within MEMS from several interacting sources. In this context it is useful to subdivide the effects of scale on MEMS design and performance into three categories: quasi-fundamental, mechanism-dependent and extrinsic (or indirect). Examples of these scaling effects are provided in the next three sections.

2.1. *Quasi-fundamental scaling*

Truly fundamental scaling laws can be obtained by dimensional analysis alone, whereas quasi-fundamental involve assumptions slightly beyond this. For instance, it is usually assumed in scaling arguments that mass scales with volume and thus length raised to the third power. However, this is only strictly true so long as it is reasonable to assume that density is a scale-independent property—which is generally a good assumption for solid matter down to the micrometer scale. Perhaps the most important quasi-fundamental scaling law that applies to MEMS is the cube–square scaling that relates volumetric scale dependencies to quantities that scale with area. The chief structural example is that inertial forces depend on the acceleration and mass, and thence volume, whereas the stress that results scales with the cross-sectional area. Thus for a given material strength the acceleration that a structure can withstand increases linearly with decreasing length scale—providing a rationale for microfabricated accelerometers. Table 1 summarizes the quasi-fundamental scaling of physical parameters down to the range of sizes of interest to MEMS designers.

2.2. *Mechanism-dependent scaling*

Quasi-fundamental scaling generally assumes that physical constants or material properties remain independent of scale. However, these assumptions break down when the length scale of the device approaches the characteristic length scale of the mechanisms that control the property of interest. For MEMS which may have features in the range from 0.1 μm to 10 mm the device scales substantially overlap with characteristic material scales leading to effects beyond those predicted by quasi-fundamental scaling laws. For mechanical elements, material properties such as the thermo-elastic constants, density, and conductivities are essentially scale independent down to 0.1 μm, however, the scaling of strength-related properties is affected by mechanisms at scales which are characteristic of MEMS devices.

For ductile metals there is an extensive literature on the effect of scale on strength, which is summarized in Ref. [10]. The introduction of constraints, such as hardening particles or grain boundaries or the surfaces and interfaces bounding a thin film, act to restrict dislocation formation and motion, result-

Table 1. Key quasi-fundamental length scale dependencies of design parameters for MEMS

	Parameter	Scaling	Comments
1	Length (L)	L^1	Fundamental
2	Area (A)	L^2	Fundamental
3	Volume (V)	L^3	Fundamental
4	Surface area/volume (A/V)	L^1	Fundamental
5	Mass (M)	L^3	Assumes scale-independent density
6	Inertial force (F)	L^3	Scales with mass
7	Max. inertial stress (σ)	L^{-1}	For fixed acceleration spring–mass system
8	Max. centrifugal stress (σ)	L^0	For fixed rim speed on rotating disk
9	Power (W)	L^2	Assumes (5)
10	Power/volume (W/V)	L^{-1}	Assumes (5), also power/mass
11	Structural natural frequency (ω)	L^{-1}	Given scale-independent modulus and density
12	Characteristic diffusion time (t)	$L^{1/2}$	For fixed diffusion coefficient
13	Electrostatic force (F_{El})	L^2	Assumes scale-independent permittivity, dielectric breakdown voltage
14	Max. acceleration due to electrostatic force (a_{El})	L^{-1}	Given (13) and (5)
15a	Magnetic force (electromagnet) (F_{emag})	L^4	Assumes scale-independent maximum current density
15b	Magnetic force (permanent magnet) (F_{pmag})	L^3	Assumes scale-independent magnetic strength
16	Piezoelectric force (F_{piezo})	L^2	Assumes scale-independent piezo-mechanical constants, breakdown voltage
17	Thermal losses (q_{Th})	L^2	For scale-independent heat transfer coefficient
18	Thermal shock resistance (ΔT_{crit})	$\sim L^{-1}$	Scales with Biot number
19	Surface tension	L^1	Assumes scale independence

ing in very high strengths at small scales. Models for the constraint of dislocations within films in the thickness range 0.2–2.0 μm suggest yield strengths which scale inversely with the film thickness [18, 19] and this predicted trend has been generally borne out by experiments [20]. For MEMS devices this increase in strength can have both positive and negative consequences. On the one hand it allows for an increased force transmission capability, but on the other it can result in much higher residual stresses than would be normal at large scales.

Not all mechanism-dependent scaling effects have positive consequences for MEMS mechanical performance. For instance, the increased surface area to volume ratio at small scales will have the effect of increasing surface diffusion as a mechanism in thermally activated deformation processes such as creep [21]. It is also worth noting that the concept of toughness as a material property for ductile materials ceases to be meaningful at small scales since the toughness is largely determined by the plastic dissipation, which is controlled by the structural dimensions rather than any intrinsic material scale.

For brittle materials the strength is governed by the maximum flaw size, typically at the surface. Simple statistical scaling arguments suggest that the probability of finding a flaw of a given size decreases with the volume (or area) of material under load. Thus mechanical elements with small characteristic dimensions would be expected to be inherently stronger at small scales, this principle underlies the development of high strength fiber reinforcement for structural composites. In addition to statistical scaling, extrinsic scaling factors also play a role in defining the strength of brittle materials, the use of microfabrication processes such as etching or deposition, and single crystal substrates with low defect densities allows the creation of structures with very fine surfaces and therefore very high strengths. This favorable scaling of strength may be enabling for MEMS with very high mechanical power densities [22].

2.3. Extrinsic (indirect) scaling

Some of the most important effects of scale on MEMS design or performance cannot be attributed to a single physical factor. For instance the processing routes that are capable of achieving the necessary dimensional tolerances are restrictive in the shapes that they can achieve. Thus MEMS devices generally consist of electro-mechanical elements which are either planar, consist of stacked layers, or are cylindrical or prismatic shapes. This restriction often drives MEMS into regions of the design space that would never be considered in macroscopic elements. Similarly the high value placed on the functionality offered by MEMS, as for microelectronic devices, allows the use of materials which would never be used in macroscale applications. The fabricated cost of a high end central processing chip is of the order of 10^5 U.S.$/kg, this is more than two orders of magnitude higher than the fabricated specific cost of advanced aerospace structures.

Extrinsic scaling factors often have several quasi-fundamental origins. For instance, the restriction on geometrical shapes can be traced back to the processing routes that are available. In turn the use of these processing routes, such as deposition, etching and diffusion-limited doping, can be traced back to the scaling argument that processes which primarily act on surfaces are more economically attractive at small scales due to the cube–square scaling of volume to surface area.

By way of demonstrating how such scaling fac-

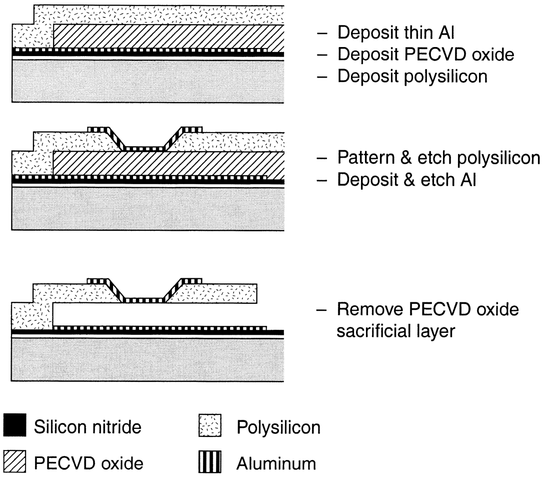

Fig. 1. Typical process flow for a surface micromachined device.

tors combine it is interesting to consider why electrostatic actuation predominates at small scales for prime movers rather than electromagnetic actuation at larger scales. Quasi-fundamental arguments suggest that the electrostatic force that can be generated between two surfaces held at a fixed potential difference scales with the second power of a characteristic length. In contrast, the force that can be generated by an electromagnet operating at a fixed current density scales with the fourth power of the length (the force due to a permanent magnet made of a particular material scales with the volume). Thus given that the mass acted on by the force scales as the third power of length, the acceleration achievable by electrostatic actuation benefits from cube–square scaling whereas electromagnetic actuation is either neutral with scale or actually deteriorates at small scales. In addition to this quasi-fundamental scaling an important mechanism dependence is introduced. The breakdown voltage of an air gap at the macroscale is of the order of 2×10^6 V/m. However, reduction of the air gap to dimensions close to the mean free path of air molecules ($\sim$1 μm) increases the breakdown voltage to 1×10^8 V/m. This increase of nearly two orders of magnitude in breakdown voltage results in a proportional increase in the scaling of the actuation force. Finally, electromagnets require three-dimensional electrical windings, which are not readily achieved via microfabrication, which further tilts the balance in favor of electrostatic actuation.

3. FABRICATION ROUTES

Three fabrication routes account for the vast majority of MEMS devices; surface micromachining, bulk micromachining and molding processes. Since the materials used in MEMS are to a great extent defined by these manufacturing processes it is worth briefly reviewing these processes. Far more comprehensive descriptions of these processes are available elsewhere [14, 17].

3.1. Surface micromachining

Surface micromachining [23] has evolved directly from the CMOS (complementary metal-oxide-semiconductor) processes used to fabricate VLSI (very large scale integration) devices. These devices consist of thin deposited layers of conductors, insulators, and semiconductors and passivation layers on doped silicon wafer substrates. In VLSI devices the layers are deposited, patterned and etched to yield highly integrated electronic devices with very small feature sizes. In surface micromachined MEMS the layers are patterned and etched to yield electromechanical elements or are used as sacrificial layers to allow motion of the mechanical layers. A surface micromachining process flow is shown in Fig. 1. The use of CMOS compatible processes and materials permits a high degree of integration of mechanical devices with the electronics required for control, signal processing and power distribution. Commercial examples of highly integrated surface-micro-machined devices include micro-accelerometer chips for controlling automobile air-bag deployment [24] and mirror arrays for portable projectors [25]. Micrographs of these devices illustrating the complexity and level of integration that can be achieved are shown in Figs 2 and 3. However, surface micromachining is typically limited to layers of thicknesses less than 5 μm which restricts the ability to create devices which can deliver significant mechanical forces or power levels (see Table 1), or to define channels or cavities for fluidic, chemical or biological applications.

3.2. Bulk micromachining

Bulk micromachining [26] involves etching features directly into silicon wafers or other substrates. Typically, if integrated electrical function is required the micro-electronic elements are created using CMOS processes on the top side of the silicon wafer, and then bulk micromachining commences from the other side of the wafer to yield mechanical elements such as thin diaphragms or beams on the top side of the wafer, or passages for fluid flow. This strategy has been used for many years to create small pressure sensors [27], in which optical, capacitative or piezo-resistive measurements are used to sense the deflection of a thin membrane over a bulk micromachined cavity. The cavity is subsequently sealed, or evacuated and sealed, to create relative and absolute pressure sensors, respectively. Figure 4 shows a schematic of a bulk micromachined cavity and membrane structure such as might be used for a pressure sensor. Figure 5

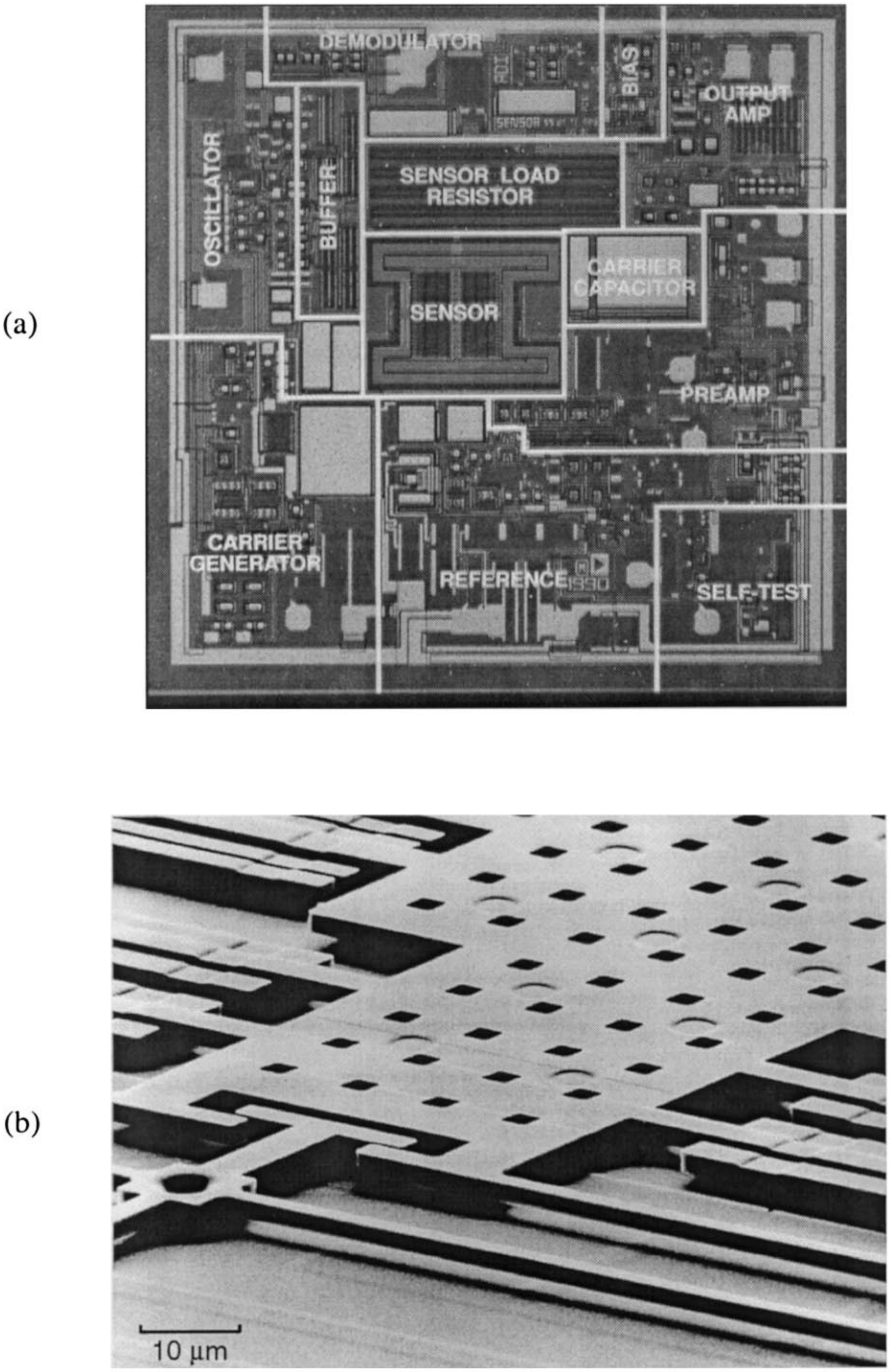

Fig. 2. (a) Overview of an integrated micromachined accelerometer and signal processing electronics. (b) Detail of proof micromachined proof-mass and motion sensing capacitance elements (pictures courtesy of R. E. Souloff, Analog Devices Inc.).

shows a micrograph of a cavity etched in silicon for a pressure sensor application. The use of the silicon substrate as the basis for mechanical elements of devices permits larger, and particularly deeper, features to be used than in surface micromachining. This is an important consideration in MEMS where higher mechanical power or force levels are desired, or in applications involving fluids, such as nozzles for inkjet printers [28], in which large losses would be associated with flow through the smaller channels that could be realized by surface micromachining.

3.3. Molding processes

The third prevalent manufacturing process used

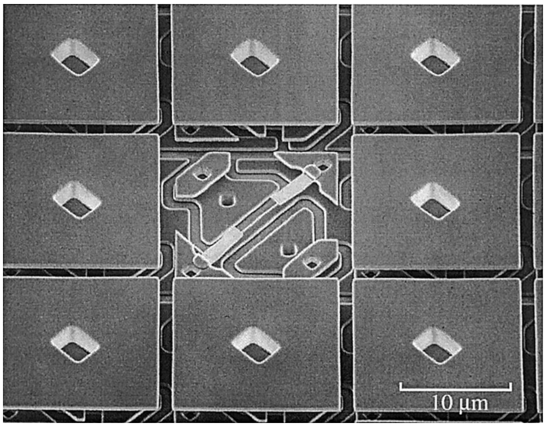

Fig. 3. Detail of micromachined mirrors from an array used in a portable digital projector (micrograph courtesy of S. J. Jacobs, Texas Instruments).

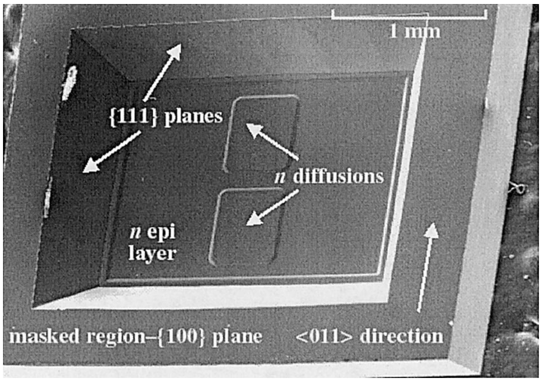

Fig. 5. A bulk micromachined cavity for a pressure sensor. Note that anisotropic etching of the cavity walls (picture courtesy of K. R. Williams, Lucas NovaSensor Inc.).

for MEMS is the creation of the mechanical elements of the device by deposition of material into a microfabricated mold. The most widespread such process is "LIGA" [the acronym stems from the German expressions for the major process steps: Lithography, Galvanoformung (electroforming) and Abformung (molding)] [29, 30]. The basic process consists of creating a polymer mold by lithography (often X-ray lithography to create high aspect ratio structures) [31, 32] and then electroplating metal into the mold cavities. A typical process flow is shown in Fig. 6 and a LIGA fabricated comb drive is shown in Fig. 7, which illustrates the small feature sizes and tolerances that can achieved by this technique. The idea of using a molding operation is not confined to electro-deposition. Other materials, such as polycrystalline silicon and silicon carbide, can be deposited using chemical vapor deposition [33, 34] and refractory ceramics structures have been created by slurry processing methods. The advantage of such molding operations is that they allow a much wider variety of materials to be considered for MEMS, beyond those traditionally used in microelectronics. They also have the same advantage of bulk micromachined parts in terms of the size of features that can be considered, however, the use of non-CMOS compatible processes and materials restricts the capability to achieve high degrees of integration of mechanical and electrical function. Although a wealth of experience has been accumulated for metal plating, there is a significant need to refine the capabilities of this technology so as to be able to achieve the very precise control of dimensions and material properties required for MEMS applications.

The conventional classification of microfabrication into three principal fabrication routes is somewhat crude, and there are examples of hybrid approaches emerging that challenge the restrictions described above. Examples include the use of sacrificial LIGA (SLIGA) [35] on silicon wafers, and the use of wafer bonding to combine microfabrication

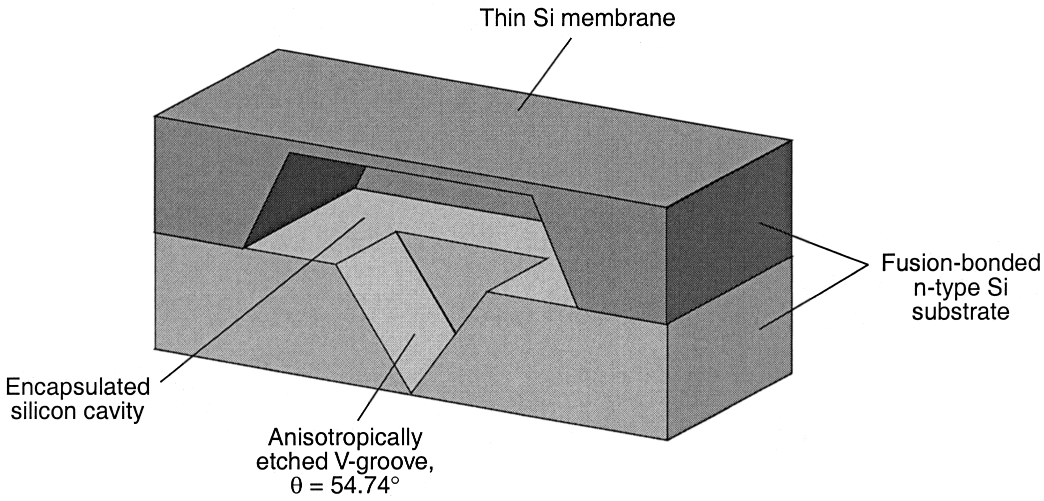

Fig. 4. Schematic showing a typical bulk micromachined structure.

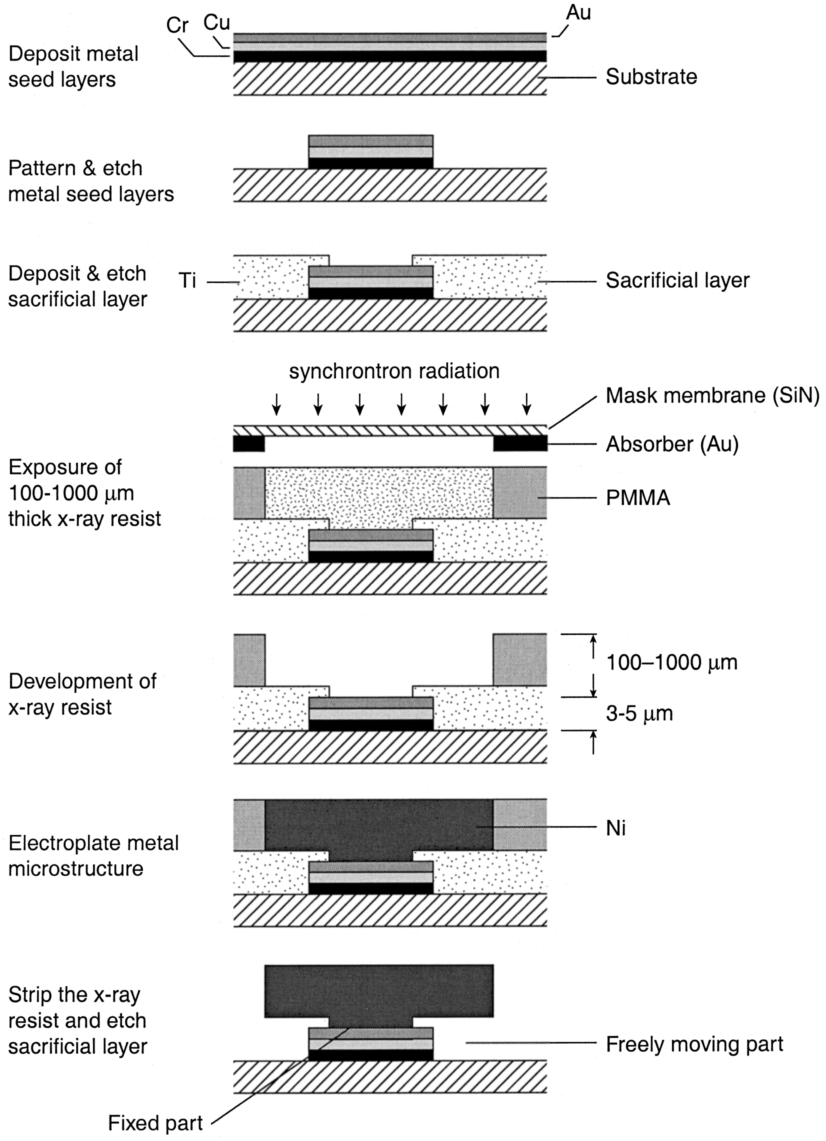

Fig. 6. Typical process flow for a LIGA device.

routes on a single device. It can also be argued that wafer bonding itself represents a distinct microfabrication route in its own right inasmuch as it offers the ability to transfer functionality that would traditionally be achieved through first level packaging to the microfabricated device itself.

4. THE MEMS MATERIAL SET

The three fabrication routes described above have hitherto largely defined the materials set available to MEMS designers. One of the keys to achieving the high level of reliability and low unit cost of microelectronic devices is that a limited set of materials are used and their composition is very carefully controlled to ensure reproducible performance. The principal materials used in VLSI devices include: doped single crystal silicon wafers as the semiconductor substrate and deposited layers of polycrystalline silicon ("polysilicon") for resistive elements, aluminum (and now copper) as the principal conductor and silicon oxide, silicon nitride and titanium nitride for electrical insulation and passivation/protection, respectively. This limited selection of materials has also formed the basis for the vast majority of surface micromachined and bulk micromachined MEMS. Silicon, polysilicon and silicon nitride are generally used for mechanical elements, aluminum as the electrical conductor for power and signal transmission, and silicon oxide as a sacrificial layer to allow the release of moving or deforming mechanical elements. The restriction to this set of materials ensures compatibility with the processes used to create the microelectronic

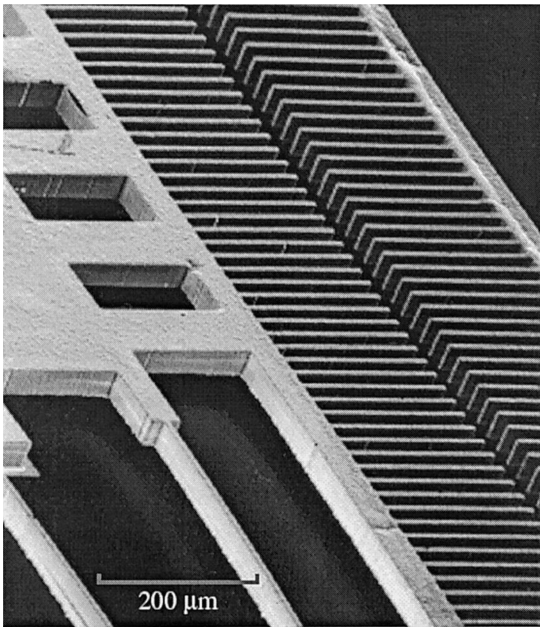

Fig. 7. Detail of electroplated nickel finger-style electrodes (220 μm long, 10 μm wide and 40 μm thick) separated from their equilibrium position (micrograph courtesy of R. Ghodssi, MIT).

elements and therefore permits a high degree of integration on a single chip. From a mechanical perspective these materials are also reasonably attractive. Silicon, silicon oxide and silicon nitride are elastic materials which exhibit no yield or other hysteretic behavior at room temperature, a key requirement for high precision sensors and actuators using micromechanical elements. Although these materials are of low toughness, the high strength of brittle materials at small scales increases the available strain levels and reduces the susceptibility to damage and fracture that prevents the use of these materials for macroscale devices [22, 36].

Notwithstanding the utility of CMOS materials for mechanical elements, the silicon microelectronics material set is somewhat restrictive if the full potential for MEMS is to be realized and a wide range of other materials are being explored. Broadly, the opportunities for expansion of the MEMS material set can be divided into materials which enable higher performance mechanical elements and those required for transducer elements which permit power or signal conversion from one physical domain to another.

4.1. Materials for mechanical elements

The performance metrics for materials for mechanical elements are well understood [37]. These materials selection principles apply equally to MEMS devices. Three basic mechanical elements that are commonly used in MEMS devices are diaphragms for pressure sensors, high frequency vibrating elements for gyroscopes and rotating disks for pumps and power producing turbines. The performance indices for these applications can be shown to be [37]: $\sigma_f^{3/2}/E$, E/ρ, σ_f/ρ, where σ_f is the fracture strength, E is the Young's modulus and ρ is the density. Table 2 summarizes the performance of several microfabricatable materials with respect to these performance indices. It is clear that silicon is a very attractive material for high strength applications such as pressure sensors and turbomachinery, however for devices in which specific stiffness is critical, diamond, silicon carbide and aluminum oxide may offer significant performance enhancements.

The most well-established attempt to broaden the materials available to MEMS designers is the use of LIGA. This permits consideration of virtually any material that can be electroplated from solution. Nickel and nickel alloys are the most commonly used materials, but a much wider set is available, including copper, chromium, iron and cobalt. In addition it is possible to electroplate some alloys [38] and materials strengthened by embedding hard particles in the plated matrix [39]. The ability to microfabricate metals with high precision is attractive for devices in which large mechanical forces and power levels are required. The relative ductility of the metal reduces the risk of failure by fracture inherent to the use of the brittle materials in the CMOS core material set, in principle this also permits significantly larger devices to be fabricated.

Silicon carbide has attracted considerable interest as a material for MEMS devices [40]. SiC, in a single crystal, form is a high bandwidth semiconductor capable of operation at high temperatures

Table 2. Material performance indices for mechanical elements applied to microfabricatable materials, where possible data from microfabricated structures are used. Note the fracture strength data are the most subject to variation

Material	Density, ρ (kg/m^3)	Modulus, E (GPa)	Fracture strength, σ_f (MPa)	E/ρ (GN/kg m)	σ_f/ρ (MN/kg m)	$\sigma_f^{3/2}/E\ \sqrt{}$(MPa)
Silicon	2330	129–187	4000	72	1.7	1.5
Silicon oxide	2200	73	1000	36	0.45	0.43
Silicon nitride	3300	304	1000	92	0.30	0.10
Nickel	8900	207	500	23	0.06	0.54
Aluminum	2710	69	300	25	0.11	0.75
Aluminum oxide	3970	393	2000	99	0.50	0.228
Silicon carbide	3300	430	2000	130	0.303	0.208
Diamond	3510	1035	1000	295	0.28	0.31

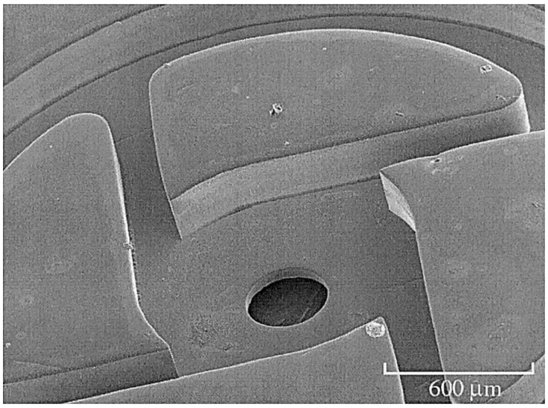

Fig. 8. A SiC fuel atomizer produced by chemical vapor deposition (micrograph courtesy of M. Mehregany, Case Western Reserve University).

and high power levels compared to silicon [41, 42]. In addition it offers much higher stiffness, hardness, toughness, and wear resistance than the core CMOS material set. These are particularly attractive features for MEMS applications. The desire to produce devices utilizing these properties to achieve superior performance for microelectronic and sensor applications has focused attention on developing techniques for creating large single crystals of SiC [43] and developing microfabrication processes analogous to those available for Si. These efforts are complicated by the relatively low chemical reactivity of SiC, its extremely high melting temperature and the tendency to form polytypes and defects during crystallization. Nevertheless, considerable progress has been achieved toward making defect-free single crystals and semiconductor devices are starting to become available commercially and at least one SiC MEMS pressure sensor has been developed [44].

SiC MEMS have also been demonstrated using molding techniques in which silicon carbide is chemically vapor deposited into or over microfabricated silicon molds or mandrels. An example of such a device is the fuel atomizer nozzle shown in Fig. 8. Typically the approach used has been to create silicon molds or mandrels by bulk etching which are then overcoated with SiC [45, 46]. This approach leverages the fabrication capabilities available in Si, and can achieve devices with useful performance.

As yet the use of SiC in MEMS is relatively immature compared to surface and bulk micromachined silicon and LIGA materials. As a result materials issues abound ranging from the processing of SiC substrates, etching and masking technologies and issues associated with residual stresses of deposited layers.

Single crystal aluminum oxide (sapphire), amorphous aluminum oxide, fused silica and diamond [47] are available in wafer form and the last of these materials can be deposited by chemical vapor deposition to create MEMS devices [48]. As shown in Table 2, these materials offer higher specific stiffnesses, and therefore higher resonant frequencies, than silicon (diamond having the highest known specific stiffness of any material) as well as being optically transparent. It should also be noted that glasses have been used in MEMS for applications for some time, although mainly as insulating or packaging layers in bulk micromachined devices, rather than for reasons of mechanical performance.

For MEMS in which structural performance is not an issue other materials are available, notably polymers. The direct use of lithography to pattern polymers to create flow channels [49, 50] or other mechanical elements is economically very attractive since it eliminates many of the fabrication steps associated with harder materials. The use of such materials in MEMS also provides the opportunity to create flexible MEMS structures and packaging that might be particularly useful for embedded systems.

Also in the category of non-structural mechanical performance is the issue of creating thermal barriers. Various schemes have been proposed for microheat engines [51] and the thermodynamic efficiency of such devices requires that the maximum possible temperature difference be maintained across the operating cycle. This demands materials or structures with a high thermal resistance. However, strategies for thermal isolation which work at the macroscale, such as barrier coatings or physical separation, are harder to implement in MEMS because of the small scale, which largely eliminates the benefits that can be achieved by using low thermal conductivity materials.

4.2. *Materials for transducer elements*

MEMS sensors and actuators require means of converting mechanical inputs to electrical outputs and vice versa. As noted in Section 2, the most common transduction principle is that of electrostatics, in which case capacitance changes are used to measure displacements in pressure sensors and accelerometers or electrostatic forces are used to cause displacements in actuators such as comb drives [52, 53] or micromotors [54, 55].

For macroscale devices electromagnetic forces are the dominant means of converting electrical power to mechanical, however there has been much less use of this principle at the microscale. As noted in Section 2 this stems from the favorable scaling and ease of implementation of electrostatic operation, and the relative difficulties of microfabricating coils for inductors and motors. Recent success has been demonstrated in using electrodeposition to create micromachined permanent magnets which offer some promise for electromagnetic devices [56, 57]. Given the capability for microfabricating electromagnetic devices it can be shown that their performance would be broadly comparable to those of electrostatic devices, and probably superior at the larger end of the MEMS size range [58].

Piezoelectric materials are capable of very high energy and power densities at small scales. The high frequency of operation inherent to MEMS devices matches well with the high frequency capability of piezoelectric materials and the favorable scaling of strength at small scales overcomes some of the limitations encountered in using piezoceramics for macroscale devices. The most commonly used piezo-materials in MEMS devices are lead zirconate titanate (PZT) [59], zinc oxide (ZnO) [60] and aluminum nitride (AlN). These are typically deposited as thin films by sputtering or, in some cases, sol–gel deposition onto silicon micromachined elements [61]. In addition molding techniques can be used in conjunction with conventional slurry processing of ceramics to create somewhat larger piezoelements suitable for integration with LIGA fabrication processes [62]. Some progress has also been made with piezoelectric polymers, notably polyvinylidene fluoride (PVDF) [63]. In addition it is worth noting that silicon itself is a piezoresistor and this property has been used in many pressure sensors. Other phenomena have also been employed to create MEMS transducers including shape memory alloys [64, 65] and magnetostrictive materials [66].

Although the earliest MEMS generally addressed electrical–mechanical energy transduction, more recent advances in biological and chemical sensors require specialty materials to permit detection of specific biological or chemical agents [67]. In addition, devices for chemical and biological synthesis or combustors for power production may require catalysts. Transition metals such as platinum or palladium are often used for this purpose in macroscale chemical plants and these metals can be deposited in thin film form, suitable for integration with other microfabrication processes.

The breadth of materials available to MEMS designers is rapidly expanding. It is to be expected that the range of materials should ultimately exceed that available to the designer of devices at the macroscale. The use of materials in very small quantities largely eliminates constraints of cost and availability that dominate material selection for macroscale devices. However, the ability to introduce new materials is still somewhat restricted by the need to maintain compatibility with existing processes and microfabrication tools. This is particularly true in cases where MEMS fabrication shares tools which are used for VLSI/CMOS processes which require very low levels of material contamination.

5. FABRICATION ISSUES

Microfabrication of MEMS devices draws heavily on the processes originally developed for creating microelectronic devices. The materials available to a MEMS designer are largely defined by the processes used to create them. This section focuses on those microfabrication processes that have particular application to MEMS.

5.1. Substrate creation

The success of the microelectronics industry has been based on the development of sophisticated processes to create wafers of single crystal semiconductors, primarily silicon. Much of MEMS development to date has made extensive use of the availability of this material. However, due to its extremely low toughness silicon is not the primary material of choice for mechanical devices. There is significant potential for broadening the range of materials available for MEMS by developing the technology to create large, low defect density, substrates of more mechanically attractive materials, such as diamond [68], aluminum oxide and silicon carbide [69] and also the techniques required to etch them [70]. Electrical functionality could then be achieved entirely by thin film deposition processes upon the substrate or by wafer bonding.

5.2. Masking and etching

The creation of patterns via lithography, their transfer to solid material and the subsequent etching of this material is at the heart of microfabrication, both for MEMS and conventional microelectronic devices. Many of the basic steps are common to both microelectronics and MEMS, particularly for surface micromachined devices, and are both well described in texts and articles on the subject [71]. Photolithography using photo-sensitive polymers has evolved to become a highly sophisticated technology capable of creating features on devices by deposition or etching with widths of less than 100 nm. For the most part MEMS applications do not stretch lithography and etching to these limits of precision. However, various novel lithographic and etching techniques have found particular applications in MEMS, these are largely driven by the desire to create high aspect ratio features with relatively large absolute scales of the order of 100 μm. These requirements demand relatively thick applications of photoresists combined with a high degree of selectivity of the etchant for the material to be etched vs the mask material. Various approaches to this have been taken, including the generation of so-called “hard” masks of metal or silicon nitride or silicon oxide materials [72]. The creation of high aspect ratio structures has driven the development of highly anisotropic etches.

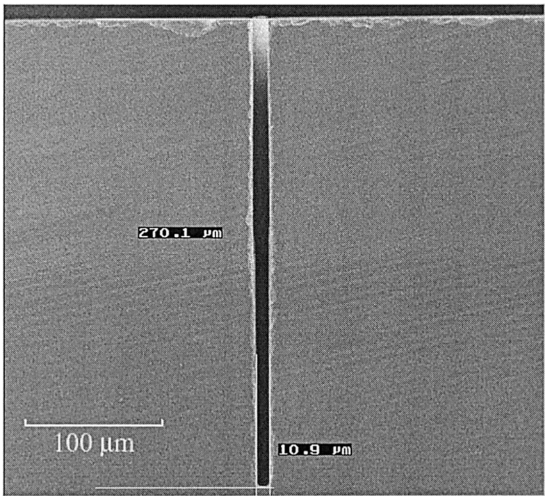

Fig. 9. A high aspect ratio trench produced by deep reactive ion etching (micrograph courtesy of A. Ayon, MIT).

Recent advances in reactive ion etching, in which alternating etching and mask deposition is utilized has allowed trenches up to 400 μm to be created with very parallel side walls [73], as shown in Fig. 9.

Developments in etching technology also hold the key to creating truly three-dimensional structures, as opposed to the current capabilities which generally limits the designer to considering features which can be created by lamination or vertical etching (i.e. cylinders). Examples of non-orthogonal etching include alkali etches, such as aqueous potassium hydroxide, which etch preferentially on the ⟨111⟩ planes of silicon, as used to create the cavity shown in Fig. 5, or simply isotropic wet or plasma etches which tend to create rounded features. Recent advances include the use of grayscale masks [74] which may allow the creation of features with controlled angle and curvature as a function of etch depth. However, these advances are still far from being able to create arbitrarily shaped features via etching or deposition. The expansion of the range of masking and etching technologies is a key area for advancement and depends in part on addressing materials issues.

5.3. Additive processes

The predominant additive processes in microfabrication are the deposition of layers by chemical vapor deposition (CVD), physical vapor deposition (PVD), sputtering or electrodeposition (particularly for LIGA). As for masking and etching, highly evolved processes exist for the CMOS material set in which polysilicon, silicon oxide and silicon nitride layers are created by low pressure CVD (LPCVD) or plasma-enhanced CVD (PECVD), and metallizations are deposited by PVD or sputtering. For the most part surface micromachining and bulk micromachining have taken these processes and directly applied them. LIGA has taken electrodeposition processes commonly used for creating metallizations in electronic packaging and combined them with mask creation to generate high aspect ratio structures.

The key directions for additive processes in MEMS tend to be towards creating structures with larger absolute sizes, higher aspect ratios and greater degrees of three-dimensionality. In addition, additive processes offer a means to broaden the materials set that is available for MEMS devices.

5.4. Wafer bonding

Wafer bonding is widely used in MEMS to create cavities and quasi-three-dimensional structures by lamination and to encapsulate and package devices [75–78]. Conducting these operations at the wafer level (as opposed to performing the operation separately for each die) is economically attractive. Several methods are used to bond wafers, including gold eutectic bonding, thermal compression bonding, glass frit bonding, anodic bonding and fusion bonding. The first three methods are derivatives of conventional electronic packaging techniques and use intermediate layers of material as adhesives. Gold eutectic bonding [79] requires the deposition of a thin layer of gold on the silicon surface to be bonded. The surfaces are then brought together and heated above the Au–Si eutectic temperature of 363°C, allowing interdiffusion of the Au and Si, and local melting to occur. The bonding temperature is sufficiently low to allow most on-chip metallizations to survive the bonding step. Thermal compression bonding relies on the creep-plasticity of thicker layers of gold and similar metallizations in contact with each other to form a strong bond, also at relatively low temperatures. Glass frit bonding [80] replaces the metal or eutectic with a glass layer and requires slightly higher temperatures (in the range 450–700°C).

Anodic bonding [81, 82] relies on charge migration to produce bonds between silicon and alkali glass wafers. In this approach the presence of mobile metal ions in the glass is exploited to create a space charge at the silicon–glass interface resulting in a sufficiently strong attraction to create a moderately strong bond. Subsequently holding the bonded pair at temperatures up to 500°C allows SiO_2 to form at the interface, creating a permanent bond. Fusion bonding or direct wafer bonding [83] is the preferred method for creating very high strength bonds between silicon wafers. The bond formation is conducted in two phases, initially the silicon surfaces are treated so as to make them hydrophobic or hydrophillic. They are then brought into contact with each other and pressure applied such that a moderately strong electrostatic bond is

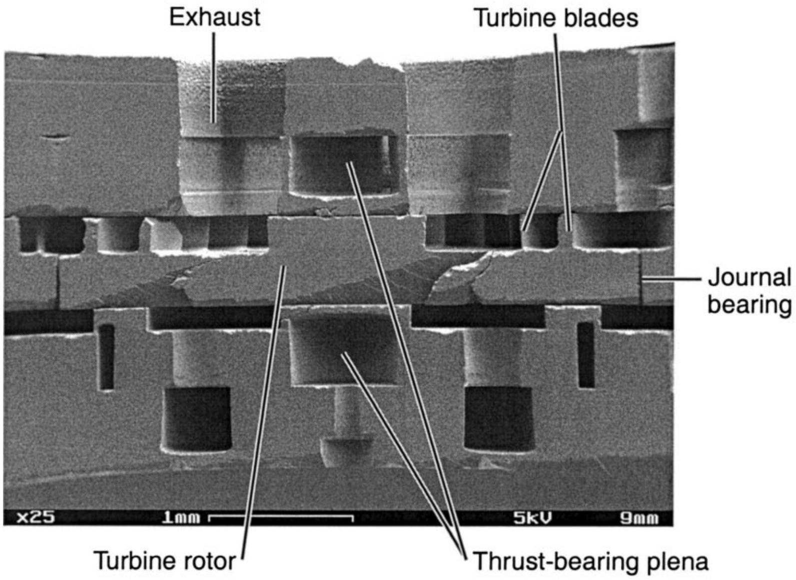

Fig. 10. A five-layer wafer-bonded stack (picture courtesy of C. C. Lin and R. Ghodssi, MIT).

formed. Subsequent heating (annealing) allows a permanent diffusion bond to form, which if the annealing temperature is high enough can have a strength equal to that of the native silicon. In addition, the silicon fusion bond results in a stress free structure. Figure 10 shows a cross-section of a bonded five wafer stack.

All of these wafer bonding techniques are strongly dependent on achieving very flat, planar surfaces and carefully controlling the surface chemistry. Significant challenges exist in turning wafer bonding into a robust process. Since it often represents one of the final fabrication steps in creating a device, low yields are particularly unacceptable. Key materials science issues include developing an understanding of what determines "bondability" and corresponding inspection procedures to verify that a good bond can be formed. In addition, further work is required on developing techniques for bonding dissimilar materials and controlling the residual stresses that can arise in these structures [84].

5.5. Planarization

The planarization of surfaces plays a key role in microfabrication. The most common means to achieve planarization is the use of chemical–mechanical polishing (CMP) [85] in which the wafer is polished in an abrasive slurry on a polishing pad. In contrast to etching as a micromachining tool CMP has the advantage that it is relatively non-selective between materials, i.e. different materials are removed at almost identical rates. In surface microfabrication CMP provides a means to create discrete elements from deposited layers. Deposition of a uniform, conformal, layer into a mold of a sacrificial material, then CMP to remove the excess deposited material and then etching to remove the mold material allows the creation of free standing elements in the deposited material. In bulk micromachining and other applications where wafer bonding is used, CMP is usually necessary in order to create sufficiently flat surfaces required for high reliability bonds. Planarization can also be achieved by purely additive processes if the only objective is to obtain a flat surface, rather than to remove material. This can be achieved by vapor deposition, the use of "spin on glass" (SOG) [86], or using polymer films.

6. DESIGN ISSUES AND MATERIALS CHARACTERIZATION

A key reason for the sustained technical progress and economic growth of the microelectronics industry is the speed and confidence with which complex products can be designed without the need for extensive prototyping. Design in microelectronic devices is largely enabled 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 low unit cost and large volume production it is important that similar design procedures be developed. Several simulation tools have been developed to address this need [87, 88] and various packages are available commercially and are particularly used in the design of highly integrated MEMS devices.

The development of standardized test methods and material property data bases has lagged behind that of the design and simulation tools, limiting their utility. As early as 1986 the need to develop such a capability was recognized [89], but it is only recently that wide scale activity has been directed in this area. The issue here is that microfabricated materials have properties that are highly dependent on the fabrication route used to create them and the scale of the structures that they constitute. The mechanical properties at the microscale can vary considerably from those measured on bulk samples of material at the macroscale. Even properties such as density and elastic modulus which are not inherently scale-dependent can be altered from bulk values in deposited layers by the creation of non-equilibrium microstructures, dissolved gases from vapor deposition and the influence of the substrate. In order to fully realize the potential for accurate and rapid simulation tools for the design of MEMS, models are required which link the material property achieved, to the fabrication route and material used. The first step towards this is to develop standard test methods with which to characterize the mechanical properties of microfabricated material produced by the same processes and at the same scales as the intended application. This will enable the creation of validated material property and process data bases and correlations between processing route and properties, to permit simulation-based design. The following sections illustrate where progress in this direction has been made.

6.1. Elastic properties

Perhaps the most mature area of material testing is the measurement of elastic properties of microfabricated materials using simple test structures. Cantilever beams and diaphragms which are loaded electrostically [90], mechanically by nanoprobes [91], or by fluid pressure [92], with deflections measured by means of capacitance or optical sensors have also been extensively used. Resonant structures have also been utilized for this purpose [93] and offer the potential for extremely accurate measurements. These methods have allowed reproducible evaluation of the Young's moduli of deposited thin film materials. However, less work has focused on obtaining other elastic constants such as Poisson's ratios [94] and shear moduli or the thermal expansion coefficients [95]. In addition, very little account has been taken of the potential for anisotropic material behavior, particularly in the through-thickness direction of deposited materials. It is also noteworthy that even for a widely used material, such as polysilicon, values of moduli ranging from 132 to 174 GPa have been reported in the literature [96] on material deposited by nominally identical processes. This discrepancy is presumably solely due to differences in experimental technique and illustrates the potential for error associated with obtaining measurements of material properties at the MEMS scale.

6.2. Strength characterization

The characterization of the strength of microfabricated materials is a key issue for MEMS devices which are designed to operate at high mechanical power densities or large deflection levels. The ability to achieve such devices is limited by the strength of the materials of construction. Since the strength of both ductile [10] and brittle materials [22] 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. Strength tests on single crystal silicon specimens with surfaces created by different etching "recipes" in the same deep reactive ion etch chamber have been shown to have strengths which can vary by nearly an order of magnitude [97].

Various approaches have been taken to obtain room temperature strength-related properties. For plastic materials nano-indendation has proven to be a viable means to extract information regarding plastic constitutive behavior [98]. Electrostatic actuation has been used to generate forces sufficient to cause fracture in surface micromachined structures [99]. This approach has also been used to derive measurements of the fracture toughness of such materials [100]. However, it has generally been found that in order to generate sufficiently high stresses to cause fracture by such means the cross section of the part has had to be limited to a small fraction of the area used to generate the electrostatic force. In order to test large specimens at higher force levels various studies have used mechanical loading applied via modified microhardness indentors [101] or nano-indentors to generate bending stresses to cause failure [91]. In addition, tensile tests have been performed using mechanical or electrostatic gripping and *in situ* strain measurement [102]. These approaches are particularly necessary for the thicker structures realized by bulk micromachining and LIGA processes.

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 [103] have been used as one means of obtaining such data, as well as more conventional macroscale bend tests and indentation creep tests.

6.3. Adhesion and bond strength

At the heart of virtually all MEMS devices is a basic architecture consisting 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 [104], peel testing and residual stress driven cohesion measurements [105] 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.

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 [66]. This is particularly valuable during the initial (electrostatic) phase of anodic and fusion bonding operations since poor bonds can be identified 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 [69, 106] and other mechanically loaded structures which expose the bond to combinations of tension and shear stresses. 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 [107–109]. 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 that 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.

Residual stresses in thin films and other deposited layers arise from several sources: thermal expansion mismatch, incorporation of residual gases into deposited materials, lattice mismatch, grain growth and grain size, point defects and sintering. The relative importance of these stress producing mechanisms depends crucially on the materials, processing conditions and microstructure. The ability to control and characterize residual stresses is very important for the development of higher performance MEMS, and microfabrication techniques offer the possibility of creating novel test structures to permit residual stress characterization [110, 111].

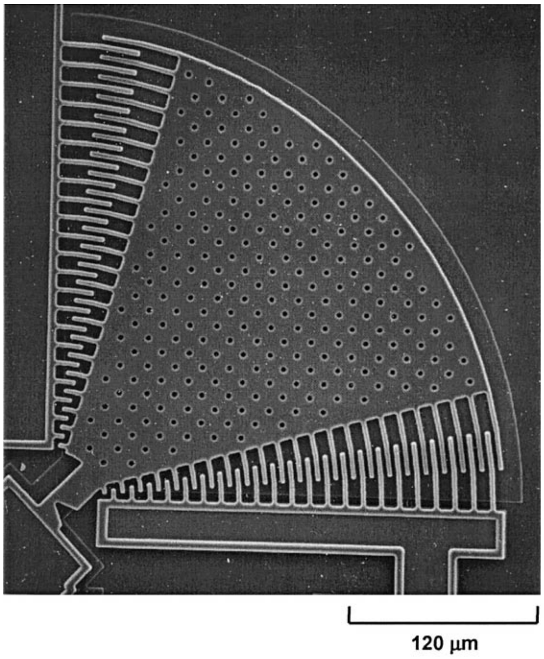

Fig. 11. A resonant test structure used to obtain fatigue data for polysilicon (micrograph courtesy of S. Brown, Exponent Failure Analysis Associates).

6.5. Fatigue

Some 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 Fig. 11. Actuation of the interdigitated electrostatic comb drives allows a moment to be applied to the notched gauge section at the lower left of the figure. Although such test methods are still in development, initial results have shown that fatigue processes can operate in both ductile [112, 113] and brittle microfabricated materials [114]. There is some doubt as to whether the mechanism observed in brittle materials, particularly polycrystalline silicon, is a cyclic fatigue process, or rather an environmentally assisted slow crack growth process. It is also worth noting that many commercial accelerometers and pressure sensors have experienced extremely high numbers ($>10^8$) of cycles apparently without sustaining any fatigue failures. 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 [115] and micromotors [116] suggest that surface adhesion due to charge build up or moisture adsorption 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 for surface micromachined devices 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 [11] and 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 [117] or apply low friction coatings [118] 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 [119] or magnetic levitation, offer promise for overcoming some of the tribological issues associated with high speed MEMS.

7. CONCLUDING REMARKS

As noted in Section 1 MEMS represent a rapidly developing area of technology with great economic potential. Advances in materials science and technology have played key roles in the evolution that has occurred thus far, and will continue to do so in the coming decades. Near term developments are relatively straightforward to forecast in relation to MEMS which are derived from microelectronic devices and share the microelectronic tool set for fabrication. These areas for advancement include: new material development, fabrication process advancement and the development of standard mechanical characterization techniques. With regard to new material development the integration of silicon carbide and possibly diamond for mechanical elements and the expansion of the set of possible transducer materials offer great potential for increased performance. With regard to fabrication processes the continued development of masks and etches that can yield high aspect ratio structures and the development of deposition techniques, particularly with regard to creating thicker coatings with reduced residual stress levels, are key activities. The development of standard characterization techniques, particularly with regard to the mechanical properties, is very important if the full potential for paralleling the simulation-based design methodology achieved for VLSI devices is to be realized.

In the longer term, great potential exists for expanding the fabrication tool set for MEMS, and relaxing the restrictions imposed by closely following processes used for microelectronic fabrication. Particular advances include the development of techniques for creating truly three-dimensional structures, while still allowing for wafer-level "multi-up" fabrication.

Advances are being demonstrated in materials chemistry in the creation of self-assembling organic materials [120]. These materials offer the promise of radically altering the fabrication tool set and the structures and materials that can be considered as well as permitting consideration of devices at very small scales. It remains to be seen what, if any, role these materials play in MEMS devices as we currently understand the term. There is also considerable interest in so-called "Nanotechnology" [121] which presupposes that self-assembling devices could be developed at scales several orders of magnitude below those currently occupied by MEMS. This may be possible, but careful scrutiny needs to be applied since existing MEMS are already at scales where performance is limited by dissipative phenomena such as viscous flow and stiction.

Paradoxically the most significant advances in MEMS may occur by developing technologies to produce *larger* devices with similar unit costs to those for existing microelectronics. These devices would have more useful power and force capabilities than current MEMS and are perhaps more properly termed mesoscale machines.

MEMS also offer considerable opportunities to advance the field of materials science at larger scales. Microfabricated probe elements enable atomic force microscopes and scanning tunneling microscopes that have revolutionized surface science and tribology. Microfabricated test structures enable the measurement of properties at small scales for applications other than MEMS. MEMS sensors can also be used as monitors for large scale processes [122]. The development of MEMS devices to monitor microstructural evolution during processing or degradation and damage during operation is also feasible. In addition, microscale chemical and biological reactors may permit the synthesis of novel materials due to the ability to very closely control the conditions under which the synthesis occurs.

Key areas for materials science to focus on include the extension of the available set of materials that can be microfabricated, the refinement of the set of processes available to microfabricate structures, and improvement in the methods used to characterize and select materials for MEMS applications. In addressing these issues it is important to do so in the context of MEMS as systems, since materials solutions are only viable if they are compatible with the overall fabrication route and the requirements for the application.

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REFERENCES

1. Gabriel, K. J., *Proc. I.E.E.E.*, 1998, **86**, 1534.
2. Paula, G., *Mech. Engng*, 1996, **118**, 64.
3. Horsley, D. A., Horowitz, R. and Pisano, A. P., *IEEE–ASME Trans. Mechatronics*, 1998, **3**, 175.
4. Epstein, A. H. and Senturia, S. D., *Science*, 1997, **276**, 1211.
5. Srinivasan, R., Firebaugh, S. L., Hsing, I.-M., Ryley, J., Harold, M. P., Jensen, K. F. and Schmidt, M. A., *Proceedings, Transducers '97, 1997 International Conference on Solid-State Sensors and Actuators*, Chicago, June 1997, pp. 163–166.
6. Bisson, C., Campbell, J., Cheadle, R., Chomiak, M., Lee, J., Miller, C., Milley, C., Pialis, P., Shaw, S., Weiss, W. and Widrig, C., *Proceedings, Solid State Sensor and Actuator Workshop*, Hilton Head Island, South Carolina, 8–11 June 1998, pp. 1–6.
7. Henry, S., McAllister, D. V., Allen, M. G. and Prausnitz, M. R., *J. Pharmaceut. Sci.*, 1998, **87**, 922.
8. Berlin, A. A. and Gabriel, K. J., *I.E.E.E. Comput. Sci. Engng*, 1997, **4**, 12.
9. Olivas, J. D. and Bolin, S., *JOM*, 1998, **50**, 38.
10. Arzt, E., *Acta mater.*, 1998, **46**, 5611.
11. Bhusan, B. (ed.), *Tribology Issues and Opportunities in MEMS, Proceedings of the NSF/AFOSR/ASME Workshop on Tribology Issues and Opportunities in MEMS*, Columbus, OH, 9–11 November 1997. Kluwer, Dordrecht, 1998.
12. Brown, S., Gilbert, J., Guckel, H., Howe, R., Johnson, G., Krulevitch, P. and Muhlstein, C. (ed.), *Microelectromechanical Structures for Materials Research*, in *Mater. Res. Soc. Symp. Proc.*, Vol. 518, 1998.
13. Heuer, A. H. and Jacobs, S. J. (ed.), *Materials Science of Microelectromechanical Systems (MEMS) Devices*, in *Mater. Res. Soc. Symp. Proc.*, Vol. 546, 1999.
14. Wise, K. D. (ed.), *Integrated Sensors, Microactuators, and Microsystems (MEMS)*, in *Proc. I.E.E.E.*, Vol. 86, 1998.
15. Fukuda, T. and Menz, W. (ed.), *Handbook of Sensors and Actuators*, in *Micro Mechanical Systems: Principles and Technology*, Vol. 6. Elsevier, Amsterdam, 1998.
16. Trimmer, W. (ed.), *Micromechanics and MEMS: Classic and Seminal Papers to 1990*. IEEE Press, New York, 1997.
17. Madou, M. J., *Fundamentals of Microfabrication*. CRC Press, Boca Raton, FL, 1997.
18. Freund, L. B., *J. appl. Mech.*, 1987, **54**, 553.
19. Nix, W. D., *Metall. Trans.*, 1989, **20A**, 2217.
20. Keller, R.-M., Baker, S. P. and Arzt, E., *J. Mater. Res.*, 1998, **13**, 1307.
21. Rösler, J. and Arzt, E., *Acta metall.*, 1990, **38**, 671.
22. Spearing, S. M. and Chen, K.-S., *Ceram. Engng Sci. Proc.*, 1997, **18**(4), 11.
23. Bustillo, J. M., Howe, R. T. and Muller, R. S., *Proc. I.E.E.E.*, 1998, **86**, 1552.
24. Souloff, R. E., *Tribology Issues and Opportunities in MEMS, Proceedings of the NSF/AFOSR/ASME Workshop on Tribology Issues and Opportunities in MEMS*, Columbus, OH, 9–11 November 1997, ed. B. Bhusan. Kluwer, Dordrecht, 1998.
25. Van Kessel, P. F., Hornbeck, L. J., Meier, R. E. and Douglass, M. R., *Proc. I.E.E.E.*, 1998, **86**, 1687.
26. Kovacs, G. T. A., Maluf, N. I. and Petersen, K. E., *Proc. I.E.E.E.*, 1998, **86**, 1536.
27. Esashi, M., Sugiyama, S., Ikeda, K., Wang, Y. L. and Miyashita, H., *Proc. I.E.E.E.*, 1998, **86**, 1627.
28. Bassous, E., Taub, H. H. and Kuhn, L., *Appl. Phys. Lett.*, 1977, **31**, 135.
29. Ehrfeld, W., Bley, P., Götz, F., Hagmann, P., Maner, A., Mohr, J., Moser, H. O., Munchmeyer, D. and Schelb, W., in *Micromechanics and MEMS: Classic and Seminal Papers to 1990*, ed. W. Trimmer, *A selected reprint volume*. IEEE Press, New York, 1997, pp. 623–633.
30. Mohr, J., *Sensors Mater.*, 1998, **10**, 363.
31. Ruprecht, R., Hanemann, T., Piotter, V. and Hausselt, J., *Microsyst. Technol.*, 1998, **5**, 44.
32. Chaudhuri, B., Guckel, H., Klein, J. and Fischer, K., *Microsyst. Technol.*, 1998, **4**, 159.
33. Keller, C. G. and Howe, R. T., *Transducers '95*, Stockholm, Sweden, 1995, pp. 99–102.
34. Hui, E. E., Keller, C. G. and Howe, R. T., *Solid-State Sensor and Actuator Workshop*, South Carolina, 8–11 June 1998, pp. 256– 260.
35. Dewa, A. S., Deng, K., Ritter, D. C., Bonham, C. and Guckel, H., *Proc. Transducers '97*. IEEE, 1997, pp. 757–760.
36. Madou, M. J., in *Fundamentals of Microfabrication*. CRC Press, Boca Raton, FL, 1997, pp. 405–447.
37. Ashby, M. F., *Materials Selection in Mechanical Design*. Pergamon Press, Oxford, 1992.
38. Saito, T., Sato, E., Matsuoka, M. and Iwakura, C., *J. appl. Electrochem.*, 1998, **28**, 559–563.
39. Balaraju, J. N. and Seshadri, S. K., *J. Mater. Sci. Lett.*, 1998, **17**, 1297.
40. Mehregany, M., Zorman, C. A., Rajan, N. and Wu, C. H., *Proc. I.E.E.E.*, 1998, **86**, 1594.
41. Choyke, W. J., Hiroyuki, M. and Pensl, G. (ed.), *Silicon Carbide, a Review of Fundamental Questions and Applications to Current Device Technology I*. Akademie Verlag, Berlin, 1997.
42. Choyke, W. J., Hiroyuki, M. and Pensl, G. (ed.), *Silicon Carbide, a Review of Fundamental Questions and Applications to Current Device Technology II*. Akademie Verlag, Berlin, 1997.
43. Barrett, D. L., McHugh, J. P., Hobgood, H. M., Hopkins, R. H., McMullin, P. G., Clarke, R. C. and Choyke, W. J., *J. Cryst. Growth*, 1993, **128**, 358.

44. Okojie, R. S., Ned, A. A. and Kurtz, A. D., *Proc. Transducers '97*. IEEE, 1997, pp. 1407–1418.
45. Rajan, N., Mehregany, M., Zorman, C. A. and Kicher, T. P., *Proc. Solid-State Sensor and Actuator Workshop*, Hilton Head Island, South Carolina, 1998, pp. 31–34.
46. Flannery, A. F., Mourlas, N. J., Storment, C. W., Tsai, S., Tan, S. H., Heck, J., Monk, D., Kim, T., Gogoi, B. and Kovacs, G. T. A., *Sensors Actuators A*, 1998, **70**, 48.
47. Butler, J. E. and Windischmann, H., *MRS Bull.*, 1998, **23**, 22.
48. Kitabatake, M. and Deguchi, M., *Sensors Mater.*, 1999, **11**, 1.
49. Boone, T. D., Hooper, H. H. and Soane, D. S., *Proceedings Solid-State Sensor and Actuator Workshop*, Hilton Head Island, South Carolina, 1988, pp. 87–92.
50. Brittain, S., Paul, K., Zhao, X. M. and Whitesides, G., *Physics World*, 1998, **11**, 31.
51. Epstein, A. H., Senturia, S. D., Al-Midani, O., Anathasuresh, G., Ayon, A., Breuer, K., Chen, K.-S., Ehrich, F.E., Esteve, E., Frechette, L., Gauba, G., Ghodssi, R., Groshenry, C., Jacobson, S., Kerrebrock, J. L., Lang, J. H., Lin, C.-C., London, A., Lopata, J., Mehra, A., MurMiranda, J. O., Nagle, S., Orr, D.J., Piekos, E., Schmidt, M.A., Shirley, G., Spearing, S.M., Tan, C. S., Tzeng, Y.-S. and Waitz, I., AIAA Paper AIAA-97-1773, Presented at 28th AIAA Fluid Dynamics Conference/4th AIAA Shear Flow Control Conference, Snowmass Village, CO, 29 June–2 July 1997.
52. Tang, W. C., Nguyen, T. C. H., Judy, M. W. and Howe, R. T., *Sensors Actuators A*, 1990, **21**, 328.
53. Ye, W., Mukherjee, S. and MacDonald, N. C., *J. Microelectromech. Syst.*, 1998, **7**, 16.
54. Mehregany, M., Senturia, S. D., Lang, J. H. and Nagarkar, P., *I.E.E.E. Trans. Electronic Devices*, 1992, **39**, 2060.
55. Sniegowski, J. J. and Garcia, E. J., *I.E.E.E. Electronic Device Lett.*, 1996, **17**, 366.
56. Ahn, C. H. and Allen, M. G., *I.E.E.E. Trans. Ind. Electronics*, 1998, **45**, 866.
57. Park, J. Y. and Allen, M. G., *J. Micromech. Microengng*, 1998, **8**, 307.
58. Busch-Vishniac, I., *J. Sensors Actuators A*, 1992, **A33**, 207.
59. Flynn, A. M., Tavrow, L. S., Bart, S. F., Brooks, R. A., Ehrlich, D. J., Udayakumar, K. R. and Cross, L. E., *J. Microelectromech. Syst.*, 1992, **1**, 44.
60. Yoshino, Y., *Mater. Res. Soc. Symp. Proc.*, 1998, **518**, 9.
61. Wang, S. N., Li, J. F., Li, X. H. and Esashi, M., *Sensors Mater.*, 1998, **10**, 375.
62. Hirata, Y. H., Okuyama, S., Numazawa, T. and Takada, H., *Proc. IEEE Micro Electromechanical Systems (MEMS '95)*, Amsterdam, The Netherlands, 1995, pp. 191–195.
63. Lee, I. and Sung, H. I., *Exp. Fluids*, 1999, **26**, 27.
64. Krulevitch, P., Lee, A. P., Ramsey, P. B., Trevino, J. and Northrup, M. A., DSC 59 Microelectromechanical Systems (MEMS), ASME, 1996, pp. 301–306.
65. Kahn, H., Huff, M. A. and Heuer, A. H., *J. Micromech. Microengng*, 1998, **8**, 213.
66. Rombach, R. and Langheinrich, W., *Sensors Actuators A*, 1994, **A41–42**, 410.
67. Tian, C. Y., Jia, N. Q., Wang, R., Zhang, Z. R., Zhu, J. Z. and Zhang, G. X., *Sensors Actuators B*, 1998, **52**, 119.
68. Butler, J. E. and Windischmann, H., *MRS Bull.*, 1998, **23**, 22.
69. Palmour, J. W., Tsvetkov, V. F., Lipkin, L. A. and Carter, C. H., *Compound Semiconductors*, 1995, **141**, 377.
70. Taniguchi, J., Miyamoto, I., Ohno, N., Kantani, K., Komuro, M. and Hiroshima, H., *Japan J. appl. Phys., Pt 1*, 1997, **36**, 7691.
71. Ghandhi, S. K. (ed.), *VLSI Fabrication Principles: Silicon and Gallium Arsenide*, 2nd edn. John Wiley, New York, 1994.
72. Rembetski, J. F., Rust, W. and Shepherd, R., *Solid St. Technol.*, 1995, **38**, 67.
73. Ayon, A. A., Braff, R., Lin, C. C., Sawin, H. H. and Schmidt, M. A., *J. Electrochem. Soc.*, 1999, **146**, 339.
74. Daschner, W., Long, P., Larsson, M. and Lee, S. H., *J. Vacuum Sci. Technol. B*, 1995, **13**, 2729.
75. Schmidt, M. A., *Proc. I.E.E.E.*, 1998, **86**, 1575.
76. Tong, Q. Y., *Semiconductor Wafer Bonding: Science and Technology*. John Wiley, New York, 1998.
77. Maszara, W. P., *Microelectron. Engng*, 1993, **22**, 299.
78. Bengtsson, S. J., *Electron. Mater.*, 1992, **21**, 841.
79. Wolffenbuttel, R. F. and Wise, K. D., *Sensors Actuators A*, 1994, **A43**, 223.
80. Ristic, L. J. (ed.), *Sensor Technology and Devices*. Artech House, Boston, MA, 1994, Chap. 5/6.
81. Ko, W. H., Suminto, J. T. and Yeh, G. J., in *Micromachining and Micropackaging of Transducers*, ed. C. D. Fung, P. W. Cheung, W. H. Ko and D. G. Fleming. Elsevier, Amsterdam, 1985, pp. 41–61.
82. Anthony, T. R., *J. appl. Phys.*, 1983, **54**, 2419.
83. Maszara, W. P., *J. Electrochem. Soc.*, 1991, **138**, 341.
84. Imthurn, G. P., Garcia, G. A., Walker, H. W. and Forbes, L., *J. appl. Phys.*, 1992, **72**, 2526.
85. Gui, C., Elwenspoek, M., Gardeniers, J. G. E. and Lambeck, P. V., *J. Electrochem. Soc.*, 1998, **145**, 2198.
86. Wiesner, J. R., *Solid St. Technol.*, 1993, **36**, 63.
87. Senturia, S. D., *Proc. I.E.E.E.*, 1998, **86**, 1611.
88. Senturia, S. D., *Sensor Actuators A*, 1998, 1.
89. Senturia, S. D., in *Micromechanics and MEMS: Classic and Seminal Papers to 1990*, ed. W. Trimmer, *A selected reprint volume*. IEEE Press, New York, 1997, pp. 659–663.
90. Osterberg, P. M. and Senturia, S. D., *J. Microelectromech. Syst.*, 1997, **6**, 107.
91. Wilson, C. J. and Beck, P. A., *J. Microelectromech. Syst.*, 1996, **5**, 142.
92. Vlassak, J. J. and Nix, W. D., *J. Mater. Res.*, 1992, **7**, 3242.
93. Lu, M. S.-C., Zhu, X. and Fedder, G. K., *Mater. Res. Soc. Symp. Proc.*, 1998, **518**, 27.
94. Vlassak, J. J. and Nix, W. D., *J. Mater. Res.*, 1992, **7**, 3242.
95. Ziebart, V., Baltes, H. and Paul, O., *Mater. Res. Soc. Symp. Proc.*, 1999, **546**, 103.
96. Sharpe, W. N., Brown, S., Johnson, G. C. and Knauss, W., *Mater. Res. Soc. Symp. Proc.*, 1998, **518**, 57.
97. Chen, K.-S., Ayon, A. A., Lohner, K. A., Kepets, M. A., Melconian, T. K. and Spearing, S. M., *Mater. Res. Soc. Symp. Proc.*, 1999, **546**, 51.
98. Nix, W. D., *Mater. Sci. Engng A*, 1997, **234**, 37.
99. Turner, K. and Edwards, R. L., *Mater. Res. Soc. Symp. Proc.*, 1998, **518**, 191.
100. Ballarini, R., Mullen, R. L., Kahn, H. and Heuer, A. H., *Mater. Res. Soc. Symp. Proc.*, 1998, **518**, 137.
101. Chen, K.-S., Ayon, A. and Spearing, S. M., *J. Am. Ceram. Soc.*, in press.
102. Sharpe, W. N., Turner, K. T. and Edwards, R. L., *Exp. Mech.*, 1999, **39**, 162.
103. Huff, M. A., Nikolich, A. D. and Schmidt, M. A., *J. Microelectromech. Syst.*, 1993, **2**, 74.
104. Allen, M. G. and Senturia, S. D., *J. Adhesion*, 1988, **25**, 303.

105. Bagchi, A., Lucas, G. E., Suo, Z. and Evans, A. G., *J. Mater. Res.*, 1994, **9**, 1734.
106. Fitzgerald, A. M., Dauskardt, R. H. and Kenny, T. W., *Proc. Transducers 99*, Sendai, Japan, 1999, in press.
107. Ohring, M., in *The Materials Science of Thin Films*. Academic Press, London, 1992, pp. 413–438.
108. Smith, D. L., in *Thin Film Deposition: Principles and Practice*. McGraw-Hill, New York, 1995, pp. 196–197.
109. Evans, A. G. and Hutchinson, J. W., *Acta mater.*, 1995, **43**, 2507.
110. Allen, M. G., Mehregany, M., Howe, R. T. and Senturia, S. D., *Appl. Phys. Lett.*, 1987, **51**, 241.
111. Zhang, X., Zhang, T. Y. and Zohar, Y., *Thin Solid Films*, 1998, **335**, 97.
112. Hommel, M., Kraft, O., Arzt, E. and Baker, S. P., *Mater. Res. Soc. Symp. Proc.*, 1999, **546**, 133.
113. Cornella, G., Vinci, R. P., Suryanarayanan Iyer, R. and Dauskardt, R. H., *Mater. Res. Soc. Symp. Proc.*, 1998, **518**, 81.
114. Muhlstein, C. L. and Brown, S. B., in *Tribology Issues and Opportunities in MEMS*, ed. B. Bhusan. Kluwer, Dordrecht, 1998, pp. 529–537.
115. Souloff, R. E., in *Tribology Issues and Opportunities in MEMS, Proceedings of the NSF/AFOSR/ASME Workshop on Tribology Issues and Opportunities in MEMS*, Columbus, OH, 9–11 November 1997, ed. B. Bhusan. Kluwer, Dordrecht, 1998.
116. Sniegowski, J. J. and Garcia, E. J., *I.E.E.E. Electron. Device Lett.*, 1996, **17**, 366.
117. Rymuza, Z., *Microsystems Technologies*, 1999, **5**, 173.
118. Lee, S.-H., Kwon, M.-J., Park, J.-G., Kim, Y.-K. and Shin, H.-J., *Mater. Res. Soc. Symp. Proc.*, 1998, **518**, 143.
119. Lin, C. C., Ghodssi, R., Ayon, A. A., Chen, D.-Y. and Schmidt, M. A., Solid-State Sensor and Actuator Workshop, Late News Poster Session Supplemental Digest, 1998, pp. 25–26.
120. Whitesides, G., *Technol. Rev.*, 1998, **101**, 84.
121. Drexel, K. E., *Nanosystems, Molecular Machines, Manufacturing and Computation*. Wiley, New York, 1992.
122. Tada, H., Abramson, A. R., Nieva, P., Zavracky, P., Miaoulis, I. N. and Wong, P. Y., *Mater. Res. Soc. Symp. Proc.*, 1998, **518**, 161.