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Materials issues in microelectromechanical devices: science, engineering, manufacturability and reliability[☆]

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Abstract

MicroElectroMechanical Systems (MEMS) technology offers considerable potential throughout the manufacturing sector, because of certain intrinsic advantages in terms of low cost, reliability, and small size. Relatively simple MEMS are used in applications ranging from automobile air bag sensors to electronic games. Considerably more complex devices have been designed for defense applications, for which government funding is available; however, the fledgling industry suffers from insufficient knowledge of materials physics at micrometer size and from the fact that currently commercialized MEMS devices are designed for specialized and rather disparate purposes, do not have a broad user base, and therefore have not generated industry standards or the design and process software that would be built upon those industry standards. In addition to industry standards, further advances in MEMS technology require a more complete understanding of the physics underlying performance and reliability. The first half of this paper reviews general issues related to fabrication and commercialization; the second half addresses the technical materials issues that relate to MEMS performance and reliability.

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1. Introduction and overview

MicroElectroMechanical Systems (MEMS), commonly known as micromachines, captured the imagination of the world in the 1980s with the first demonstration of a functioning silicon motor that

had been manufactured entirely with standard integrated circuit (IC) manufacturing techniques [1–3]. This new technology was widely viewed as ushering in a new age of engineering, and speculation about its potential use was widespread.

A number of different micromachining technologies have emerged in the past decade. Bulk micromachining, which creates mechanical elements by etching into a Si wafer, has been used to create a variety of products, including pressure sensors and ink-jet print heads. Surface micromachining is a technique that creates microscopic mechanical elements on the surface of substrate Si

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wafers by sequentially depositing thin films on the wafers, photopatterning those films, and then etching the films. Surface micromachining has been used to create high-performance projectors and accelerometers for airbag deployment. LIGA (acronym for Lithography, electroforming [German: *Galvanoformung*], and molding [German: *Abformung*]), is a technology that creates mechanical elements by electroplating into tiny molds formed photolithographically in a polymer. A comprehensive review of the manufacturing processes employed in these technologies has been published by Madou [4]. While each of these technologies has its own specialized applications, and presents interesting concomitant material and engineering challenges, this paper focuses on Si surface micromachining. This enables us to explore the business opportunities associated with high value MEMS-based products, and their related scientific challenges, in greater depth than otherwise would be possible.

Surface micromachining will enable the creation of a new generation of microsystems that will be able to ‘sense, think, act, and communicate’. Monolithic integration of electronic circuitry on the same chip as surface micromachined devices could have revolutionary implications. Batch fabrication of ‘systems on a chip’ enables very low cost production. By reducing the number of components in the system, significantly improved system reliability may be achieved. Reducing the chip count, eliminating the bond wires connecting electrical to mechanical circuits, and reducing the complexity of the packaging/assembly process all benefit reliability. Finally, monolithic integration enables overall system performance, particularly for micro-sensing systems, to be increased by reducing electrical interconnect parasitics such as capacitance.

1.1. Fundamental MEMS characteristics

In order to understand the opportunities and promise of the technology, it is important to understand certain fundamental characteristics:

1.1.1. Batch fabrication

Surface micromachining enables fabrication of complex microscopic machines using standard IC manufacturing techniques. IC-based technologies are based on mass-production where thousands of devices are produced simultaneously. Within the IC framework, the production of 1000 devices costs essentially the same as the production of a single device, allowing economies of scale. This approach provides the key fundamental properties of MEMS devices, and gives them enormous potential to impact a variety of commercial fields.

1.1.2. Small device size

It is now possible to build complex mechanical elements with micrometer feature sizes. While size is the characteristic of MEMS that has most captured popular interest, it is arguably the least important aspect of the technology. This characteristic does have important materials-physics ramifications, as will be discussed below.

1.1.3. Low cost

MEMS is revolutionary because it produces complex electromechanical functions at low cost. The cost savings are achieved by employing essentially the same manufacturing techniques that are used to produce today’s high-performance information processing and storage devices.

1.1.4. Reliability

Systems fail almost always as a result of problems occurring within the interconnections between components, not because of failures in the components themselves. MEMS offers a way to greatly increase the reliability of systems by reducing the number of solder joints and wires. An accelerometer system created with traditional technology is compared to an IMEMS-based (Intelligent MEMS) device in Fig. 1. Here, thousands of solder joints have been eliminated by integrating the mechanical and electrical devices present on a single silicon chip. The chip pictured contains more than 10,000 transistors, integrated with mechanical elements that serve as accelerometers. It is based on designs from the University of California’s Berkeley Sensor and Actuator Center (BSAC), and built at Sandia National

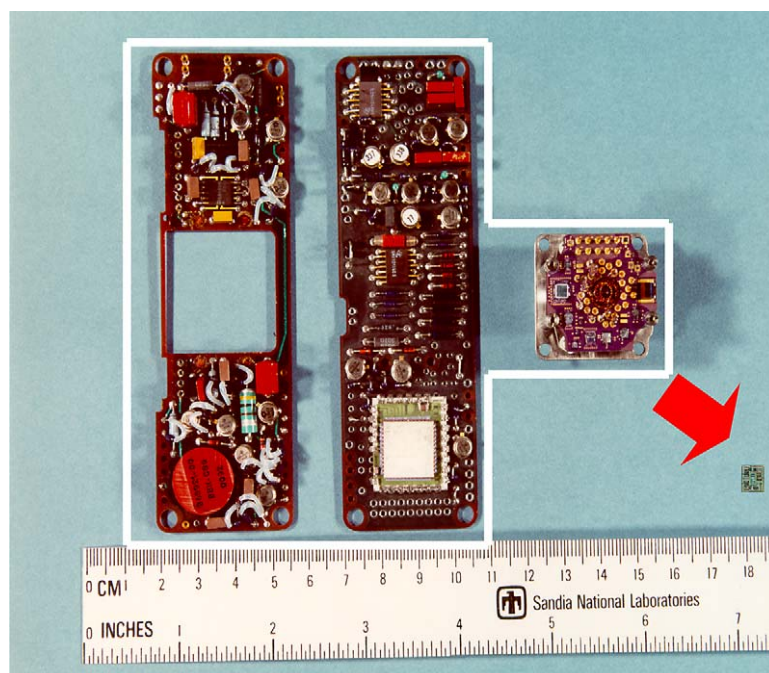


Fig. 1. Comparison of an accelerometer built using traditional technologies and MEMS. The single chip is capable of performing the same function as the complex hand assembly pictured.

Laboratories' Microelectronics Development Laboratory.

1.1.5. Enabling capability

Some things can be done with MEMS that simply cannot be done in any other way. For example, in today's telecommunications infrastructure, there is no direct way to switch optical signals. In redirecting a data stream from a given input fiber to the correct output fiber, conventional systems first convert the optical signals to electrical signals, then switch the signals electrically. The electrical impulses are sent to lasers connected to the output fibers. It is extremely unlikely that this relatively slow optical–electrical–optical (O–E–O) technique can keep up with the world's seemingly insatiable demand for telecommunications bandwidth. There is a critical need for an all-optical switching technique: in other words, an optical–optical–optical (O–O–O) switch. MEMS technology makes it possible to build thousands of mirrors on a single device, with each mirror capable of switching one data stream. Hence, a single MEMS chip can serve

as the heart of an all-optical switch system capable of connecting any one of a thousand input fibers to any one of a thousand output fibers. MEMS will almost certainly serve as an enabler for all-optical channels in the telecommunications infrastructures of the future (see Section 1.5 below.)

1.2. Commercialization

MEMS has enabled a number of solid commercial successes, particularly in automotive and consumer products. It likely will expand next into telecommunications and radio-frequency (RF) systems, then into biomedical and medical care applications.

1.2.1. Automotive and consumer products

Analog Devices has developed an entire product line of MEMS-based accelerometers. Most new cars contain these devices, which detect a car crash and deploy the airbag. Since being developed for the automotive market, the Analog Devices MEMS chip has found its way into products ranging from

Nike tennis shoes to Sony's Playstation®. Another commercial success has been the ink-jet print head, a component that has enabled continued improvement in print quality, cost, and speed of ink-jet printers. A third commercial success is Texas Instruments' MEMS Digital Micromirror Device (DMD). The DMD chip serves as the heart of many of today's lightweight portable projection systems. It contains more than one million microscopic mirrors that tilt in response to a digital signal and project bright, clear video onto a screen. Sony Corporation anticipates that within 5 years virtually all its products will contain MEMS devices. MEMS-based accelerometers will be part of game controllers, MEMS-based microphones will be integrated into products such as video cameras, and tunable MEMS-based RF devices will allow more and more devices to communicate with each other.

1.2.2. Telecommunications

MEMS-based optical switches for telecommunications applications show considerable promise. Today's global telecommunications infrastructure is a web of glass fibers transferring optical signals containing the world's voice communications, e-mail, web pages, and data transfers. However, the optical–electrical–optical conversion that occurs at each entrance and exit of an optical fiber act as speed bumps on the information superhighway. Early MEMS advocates proposed solving this problem with all-optical networks that would be completely free of O–E–O conversions. However, it has become clear in the last two years that electronic switching will remain an important part of the network, and many now believe that future cross-connects will be hybrid optical and electrical devices. Express traffic will be routed through optical channels, taking advantage of low cost, simple MEMS-based mirror switches, while data that need to be groomed or manipulated with more fidelity will be routed through more expensive electronic channels.

1.2.3. RF applications

MEMS also holds promise for enabling small, affordable, reliable tuning and switching elements for next-generation RF applications. Cellular tele-

phone traffic has grown continuously over the last decade, and the world appears poised for an explosion of wireless networks in homes, businesses, and retail locations. MEMS may play an important role in this arena. Today's RF circuits, primarily designed with components with fixed values, must operate in a world where almost everything is changing. In the case of a cell phone, variations in distance to cellular towers, changes in the charge state of the battery, continuously varying signal strength, volatile weather conditions, and even different signal protocols combine to challenge RF circuit design. Designers seek tunable devices that would enable the circuit to adjust, or to optimize itself for varying conditions. Almost all RF devices could benefit from affordable, high-performance tuning and switching elements, such as variable capacitors, variable inductors, and RF switches. MEMS has the potential of offering a new generation of high performance, affordable tunable RF circuits with improved range, battery life, and connection reliability.

1.2.4. Biomedical and medical care applications

Farther in the future, MEMS is expected to play an increasingly important role in biomedical engineering and medical diagnostics. MEMS will likely prove valuable in miniaturizing diagnostic equipment, enabling medical diagnostics to be moved from the hospital laboratory to the patient, and, at the point of care, allowing increased real-time monitoring and diagnosis of the patient's condition. Further, drug microdelivery systems could be integrated with chemical sensors, and allow automated chemically-driven response. For example, blood sugar fluctuations in a diabetic person could be automatically detected and corrected with a release of insulin.

1.3. Materials and manufacturing issues

While opportunities in MEMS derive primarily from their similarities with microelectronic devices, risks and challenges arise from the differences between the two. The further a MEMS device strays from standard microelectronics design, fabrication, and test techniques, the greater the risk because the store of science and engineer-

ing knowledge about this relatively new field is small by comparison.

1.3.1. Fabrication

Further development of MEMS fabrication technology is a key issue. Certain ‘standard’ manufacturing techniques were developed very early in the development of microelectronics. CMOS (Complementary Metal Oxide Semiconductor) technology became the standard adopted by virtually the entire industrial manufacturing base. In the world of MEMS, because of the diversity of applications, many different fabrication technologies have been developed and no clear standard has emerged. Each particular fabrication approach carries its own critical risk factor. Currently the lowest-risk strategy is based on standard microelectronics processes and standard microelectronics fabrication tools. An example is surface micromachining, which draws almost exclusively on well-established microelectronics tools and processes. Another example is Analog Devices’ IMEMS technology, which integrates simple MEMS devices with microelectronics on the same piece of Si. While embodying more risk, products that make use of non-standard microelectronics fabrication processes can enable increased design flexibility. Texas Instruments’ DMD is an example of this approach. Integration of an aluminum surface micromachining process with underlying silicon CMOS circuitry took several decades and a huge dollar investment, but has resulted in a successful product line. In this case, tools developed for IC fabrication have been combined in a new process flow to realize a multiple level aluminum structure on top of a CMOS wafer.

The breadth of materials currently available for micromachines is quite limited compared to the breadth of conventional materials. It follows that as new fabrication technologies broaden the available MEMS materials palette, a broader set of applications will become feasible.

1.3.2. Performance and reliability

A key issue in the early stages of any MEMS development effort is design for performance and reliability, which differs markedly from the case of ICs, where fundamental failure mechanisms have

been addressed for several decades (electromigration, oxide rupture, hot carriers, stress voiding). Since these problems are well-established, and some fundamental understanding has been developed, it is straightforward to test and screen ICs with a high degree of confidence that parts will meet customer requirements. But new failure mechanism possibilities arise in the case of MEMS. Issues such as adhesion, friction, wear, strength, toughness, impact tolerance, fatigue, and creep become important, especially for MEMS devices of greater complexity. Since we have yet to gain a fundamental understanding of these mechanisms, developing absolute methods to predict and control them remain elusive.

1.3.3. Packaging

Packaging can be much more complex for MEMS than for ICs, with the packaging requirements and difficulty strongly dependent on the application. Since it is closely connected with reliability and qualification, packaging can represent a significant risk in the process of achieving a commercially viable product. Typically, ICs are placed in a hermetically sealed package that protects the delicate chip from the environment. However, some MEMS devices must be exposed to, and interact with, the environment. Accelerometers and gyros require only electrical inputs and outputs, and can be hermetically sealed in a ceramic package, exploiting standard microelectronics packaging techniques because they require only electrical inputs and outputs. Packaging becomes more complex in optical MEMS devices because of optical input/output considerations, but it is possible to hermetically seal the chips in a package with a glass lid that allows the transit of optical signals. More complicated are microfluidic devices that might require gas or liquids as inputs and outputs. Examples include fuel cells, pumps, biomedical devices, chemical sensors, and micro total-analytical-systems (TAS). Here the packaging requirements are the most unlike traditional microelectronics, and therefore represent the most significant risk.

When exposed to external environments, unique challenges can arise. For example resonant device performance can change with changes in gas press-

ure and humidity, and in non-dry environments, corrosion degradation mechanisms can become problematic, especially for metallic microdevices.

1.4. Building a technical base

Developing industry standard manufacturing technologies, with a large user base, is a major challenge faced by the MEMS community. Currently the field is fragmented, with companies tending to develop proprietary technologies. Thus, while impressive research and prototype demonstrations continue in the MEMS arena, the lack of a MEMS-specific manufacturing base, including design tools, test hardware, packaging techniques, and reliability infrastructure, makes transition from research demonstrations to fieldable products particularly challenging. Companies that make microelectronics design tools, test systems, packaging tools, and reliability tools therefore have been slow to enter the MEMS market because no one technology has emerged as a standard and the user base is not sufficiently broad to encourage investment.

In other words, industry standard MEMS technologies have yet to become broadly accessible, to be run on a true manufacturing line, and to be supported by a full suite of design tools and libraries of proven ‘standard cell’ designs. A promising move in this direction is Fairchild Semiconductor’s recent offering of a MEMS foundry service using SUMMiT™ V technology developed at Sandia. The advent of a commercial state-of-the-art surface micromachine technology, encourages optimism that SUMMiT™ V will become an industry standard technology, and that, as it becomes a standard, other companies will begin to develop design tools, packaging tools, test systems, and the other elements needed to have a MEMS product realization infrastructure in place and available to a broad user base.

While fragmentation of the community has slowed the development of standard technologies, no such barrier exists in the development and better understanding of materials used in silicon MEMS devices, and (as a prerequisite for qualification and testing) and understanding the performance characteristics of actual devices. These issues are summa-

rized here and discussed in greater detail in Section 3.

1.4.1. Intrinsic material properties

In order to understand and optimize the performance of any device, it is necessary to understand the device at the appropriately small length scales. For example, all materials engineers recognize the need for understanding at the micro-domain to optimize the performance of the meso- or macro-scale device. Similarly, to understand and optimize the performance of devices at the micro-scale, an understanding at the nano-domain is necessary.

Specific issues include the relationship between the chemistry of MEMS surfaces and the forces that develop when structures make contact or rub. Even in devices that do not rely on contacting surfaces, a better understanding of this relationship is required to ensure that inadvertent contact will not cause failure. The total force at real points of contact is the sum of the applied force and intrinsic forces such as van der Waals, electrostatic, or capillary attraction. In macroscopic engineering systems, intrinsic forces frequently do not manifest themselves in the physics of failure; however, in MEMS, these forces can be significant when compared with the applied force. Theories exist to treat the contact of simple geometries in the presence of intrinsic forces, but contact in MEMS involves complex geometries and surfaces with one to tens of nanometers root mean square (rms) roughness.

In addition to relating surface interactions between individual points of contact to the integrated response of the interface, the evolution in surface chemistry with time is also important if we are to predict the reliability of a system after aging. Here, a critical issue is the degradation kinetics of chemisorbed monolayers that may be applied to modify the chemistry of the surface, due for example to elevated temperatures or exposure to water vapor.

Other material properties may significantly affect the reliability of future products as MEMS designs become increasingly complex and the number of commercial applications increases. For example, mechanical properties such as anisotropic elasticity in textured or columnar microstructures, strength, toughness, and fatigue may have a strong

influence on performance and reliability. Also of relevance in some potential applications in non-Si devices may be magnetic, capacitive, piezoelectric, and piezoresistive properties.

1.4.2. Qualification and testing considerations

Another barrier to successful development of MEMS products involves test and qualification. In the case of ICs, failure mechanisms are understood to some extent at a fundamental physical and statistical level after three decades of intense, focused study. Qualification of MEMS devices is much more complicated. In addition to the possibility of traditional electrical failure mechanisms, they include mechanical elements that might move, run into each other, or rub against each other. Phenomena such as friction, adhesion, wear, fracture and fatigue, of which the fundamental nature is not well understood at the micrometer scale, become of paramount importance (see Section 3).

The importance of these issues can be seen when we consider reliability taxonomy for MEMS [5,6], as presented in Fig. 2. The simplest are Class I MEMS devices. These have mechanical elements but the elements do not move. Examples include accelerometers, ink-jet printer heads, pressure sensors, and strain gauges. Class II devices are more complicated in that they have mechanical elements

that move, but have no parts that rub or touch. Class III devices are those with moving and touching, or impacting parts. The most complex devices, Class IV devices, include moving, touching, and rubbing surfaces. Most successful MEMS products now in the market are Class I devices. This is a consequence of the high reliability and ease of qualification for such products. Accelerometers are considered Class I devices because in operation a feedback loop applies electrostatic signals to hold the proof mass in a constant position. Acceleration is determined by monitoring the voltage necessary to hold the proof mass stationary. The DMD is the only widespread example of a Class III device successfully introduced into the market, but it was done so only after extraordinary research and development investment. It should also be noted that some of the most exciting MEMS product opportunities are Class IV devices.

It can be seen that fundamental physical and statistical understanding of underlying materials physics must be developed if MEMS are to achieve their full potential. This understanding will enable development of qualification techniques that in turn will enable manufacturers to quantitatively screen their MEMS products with confidence that products will meet their customers' reliability requirements. Improved understanding of MEMS

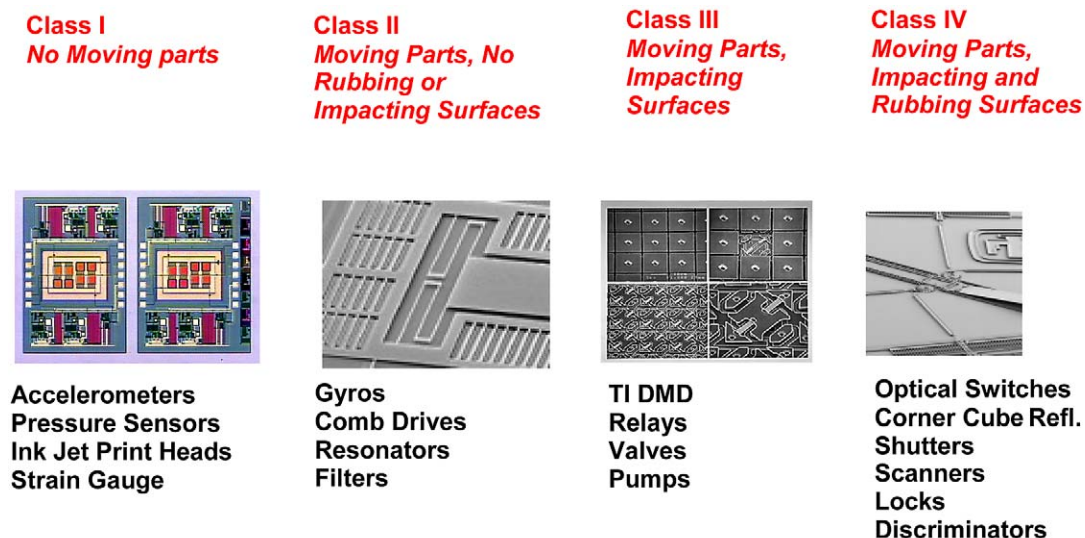


Fig. 2. Taxonomy for considering MEMS performance and reliability qualification: relevant examples.

reliability physics, and the engineering issues associated with MEMS qualification, will enable the field to progress from relatively simple Class I devices to potentially revolutionary Class IV devices.

1.5. Demonstrating MEMS capabilities

Despite the challenges, it is possible to develop high-performance complex MEMS products. MEMX, a Sandia spin-off company, has developed a variety of MEMS-based mirror platforms for telecommunication and other industrial and defense applications. Fig. 3 shows a photograph of an advanced MEMS beam steering system. The mirror is 1.3 mm long, and the electrostatic actuation system is capable of elevating the mirror 2 mm above the surface of the wafer, which enables extremely wide-angle steering of optical signals. The actuation system contains more than 100,000 mechanical fingers that generate an electrostatic force of tens of milli-newtons (mN), which enables precise control of mirror position over a wide sweep range with exceptional stability and reproducibility. Even with this degree of complexity, the devices can be made at affordable cost and with high manufacturing yields.

MEMX's optical mirrors have been used in

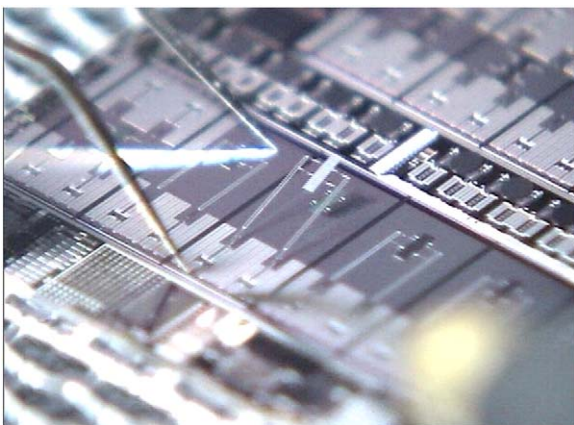


Fig. 3. Optical microscope image showing MEMX beam steering device which contains 100,000 polysilicon mechanical 'fingers', and is capable of producing 2 mm of motion in the 1.3-mm mirror. The next-generation device will have almost 400,000 'fingers'.

optical cross-connect switches for telecommunications applications. More than 15,000 devices were fabricated for this application, and Fig. 4 shows that initial yields of 20% were quickly ramped up to greater than 90% as the manufacturing process was tuned. Fig. 4 illustrates that with proper design techniques extremely complex, five-level surface micromachine chips can be manufactured with yields that rival those of traditional ICs.

2. Surface micromachine fabrication

Surface micromachining technology uses standard semiconductor processing techniques to create microscopic machines on the surface of Si wafers [7–11]. These are created by depositing thin films on the surface of a wafer, photo-patterning the films, and then etching the photo-patterned features into the thin film. Two distinct types of films are used in the process—the structural film eventually becomes the mechanical element, and the sacrificial film serves as a spacer between the structural film and the substrate, or between subsequent structural layers. The sacrificial film is removed at the end of the process to 'release,' or free, mechanical elements patterned in the structural film. Fig. 5 shows a simplified process flow used to create a single-level cantilever. The structural levels are photo-patterned and etched in order to create the mechanical features of the device, and the sacrificial layers are photo-patterned and etched in order to create vias. Each via creates a hole that is filled by the structural film, enabling the structural level to be physically connected to the substrate, or to earlier structural levels. This process flow with a single structural level could be used to create simple microengines, as pictured in Fig. 6, cantilever beams, resonators, diaphragms, accelerometers, and flow sensors, to name just a few. Because semiconductor processes are used, many thousands of mechanical elements can be batch fabricated on a single wafer at the same time.

The device in Fig. 6 is a simple electrostatic microengine, capable of generating motion at the micrometer scale. The center shuttle is suspended by springs slightly above the substrate. The two center banks of fingers are free to be pulled to the

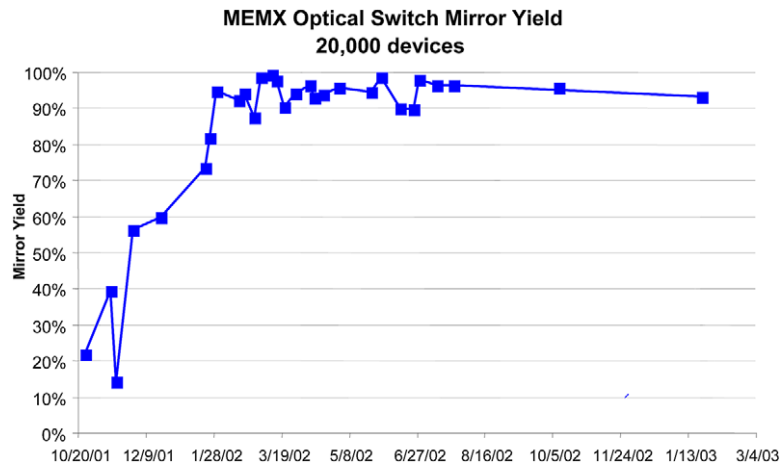


Fig. 4. Manufacturing yields for MEMX optical switch mirrors. Yields above 90% demonstrate that high performance, manufacturable MEMS products can be developed.

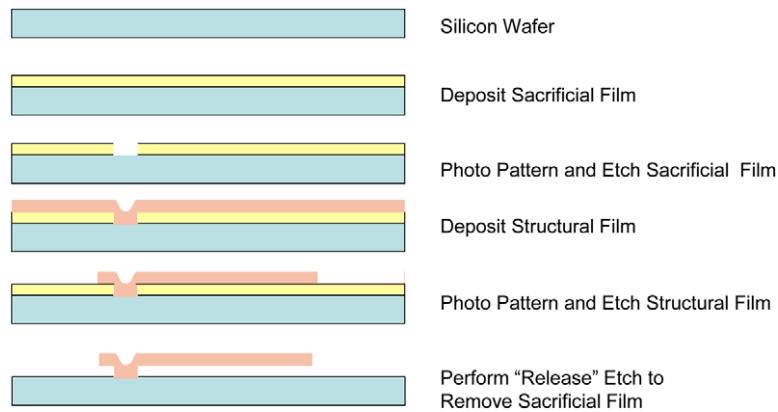


Fig. 5. Illustration of simplified process flow for surface micromachines.

left or right. The spring elements create an elastic restoring force to pull the shuttle back to the center position. If a voltage is applied to the leftmost bank of fingers, an electric field is created that generates an electrostatic force that pulls the shuttle to the left. If a voltage is applied to the rightmost set of fingers, the center shuttle is pulled to the right. By alternately applying a voltage to the left and right set of fingers, the engine will oscillate laterally. While this is the simplest possible design in a single structural level of material, it illustrates the basic concept behind electrostatic microengines.

2.1. Selection of material sets

One can imagine a variety of material sets that could be used as the structural/sacrificial film pair shown in Fig. 5. A number of material issues, however, must be carefully considered in identifying this base material set.

2.1.1. Choice of etchants

For any material pair chosen, there must exist an etchant that will selectively etch one of the materials while not affecting the other. During the

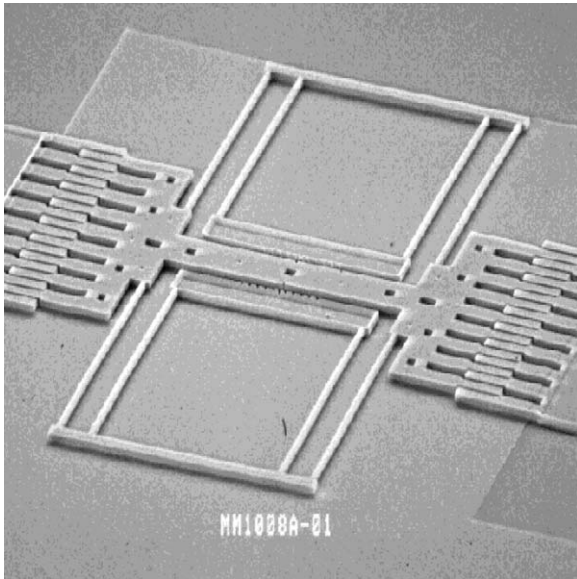


Fig. 6. Scanning electron micrograph of surface micromachined electrostatic engine. Spring elements in this device are as narrow as 1 μm .

final release process, the sacrificial material must be completely removed without affecting the structural material. This requirement alone immediately begins to limit the material combinations that can be used.

2.1.2. Residual stress

In fabrication of traditional ICs, the thin films remain laminated on top of one another, so the technology is somewhat tolerant of stress in the films. However, in the case of surface micromachining, the chemical vapor deposition process produces residual stress in the structural film, causing it to curl after the sacrificial layer is removed since the structural layer is then unconstrained. Many MEMS applications require extremely flat mechanical structures. For optical applications, a radius of curvature of 0.5 m or more may be required. This can translate into an allowance for residual stress of no more than a few MPa. This requirement further limits the available material sets that can be considered.

2.1.3. Thermal effects

High-temperature anneals, approaching the melting point of the structural layer, are often required to relax stress in the structural films and achieve the required flatness. Anneals of 1000 $^{\circ}\text{C}$ or more can be required for Si devices, in some cases. Sacrificial material must be chosen that is compatible with these temperatures. Additionally, the coefficient of thermal expansion of the structural and sacrificial materials must be closely matched in order to avoid cracking or delamination. Mismatch in the coefficients of thermal expansions through the thermal cycles of the process result in film stresses in the deposited films which can cause significant wafer bow. Integrated circuit manufacturing tools have strict limits on the amount of wafer bow that can be tolerated, and the film stresses must be properly controlled to ensure the wafers maintain the flatness required by the manufacturing tools.

2.1.4. IC process compatibility

When considering use of an existing IC manufacturing line to produce surface micromachined devices, compatibility with the IC process is naturally of paramount importance. IC manufacturers are extremely selective of the materials they will consider processing on their lines because many are contaminants to silicon chips.

This issue has prevented a number of novel surface micromachine technologies and concepts from becoming viable products. A typical sequence is: Research facilities have a large degree of flexibility in the materials and processes they can consider. This flexibility allows creative investigation of a variety of materials sets. In response to specific product requirements, a new and novel material set is developed to serve as the structural and sacrificial material pair. This work leads to prototypes that generate interest from a potential customer. Work then begins on finding a production source for the devices. But then IC manufacturers refuse to consider making the device, even though they have the tools that could do the work. The innovator then investigates the costs of establishing a stand-alone manufacturing facility for the device, and finds that the large costs of standing up an IC-like fabrication facility cannot be supported by the

less-than-certain market projections for the new product. Hence, a potentially revolutionary product is not born because of the issue of IC compatibility of the material set.

The IC compatibility issue is not a technical challenge per se, but should be considered in the research stage if the objective is to eventually move the micromachine project into production.

2.2. Polysilicon/SiO₂ processing

After several decades of research in various possible material sets, the approach that appears most practical for most MEMS applications is to use polycrystalline silicon ('polysilicon') as the structural material and SiO₂ as the sacrificial material. This is one of the few sets that can effectively weave its way through the complex list of issues discussed above. Hydrofluoric (HF) acid is an etchant that will remove sacrificial material (SiO₂) without affecting the structural material (Si). The etch selectivity between the two materials can be 10,000:1 or greater. This large ratio in etch rates enables complex devices to be built, and fully released without negatively impacting the structural layers. Properly processed and annealed polysilicon can achieve the low stress levels needed for most optical, as well as other applications. The materials are thermally compatible, and can be taken to temperatures in excess of 1000 °C without the films warping, cracking or delaminating. Since standard IC presently use both SiO₂ and polysilicon, IC manufacturers are not concerned about running these materials in their production lines.

2.2.1. MEMS/CMOS integration

While polysilicon as a structural level and SiO₂ as the sacrificial material has become the material set of choice, a few other material combinations have been successfully implemented. One example is to use photoresist as the sacrificial material and some suitable metal, such as Au or Al, as the structural material. Photoresist is deposited with a spin-on process. Metal films are deposited via sputter deposition or evaporation. Both processes can be done at low temperature, compatible with the photoresist material.

An advantage of this material set is that, since

it can be processed at low temperature, it offers a straightforward path to the integration of MEMS and CMOS on the same piece of silicon. CMOS circuits are formed first, followed by low temperature photoresist and metal processes to form the micromachine structures. The Texas Instruments DMD uses this approach to build millions of individual mirrors, each directly on top of the CMOS circuitry in the underlying silicon used to control it. Polysilicon and SiO₂ MEMS do not offer a straightforward path to integrated CMOS/MEMS devices because the high temperatures (up to 1000 °C, or more) associated with the polysilicon deposition and anneal would damage the underlying CMOS devices. CMOS circuits typically use aluminum as the interconnect material. The aluminum begins to be damaged at about 450 °C.

While the low temperatures of a metal/photoresist micromachine technology offer attractive features when considering integration with CMOS, material properties of the metal films are not generally so good as the polysilicon. Metal micromachine devices are prone to fatigue, plastic deformation, and creep. In addition, metal technologies have yet to achieve the low stress levels achieved in polysilicon devices. This stress results in rather severe curvature in the final parts, severely limiting the types of mechanical elements that can be successfully fabricated.

2.2.2. Multi-level devices

Modern surface micromachine technologies can have 10 or more levels (i.e. 5 polysilicon layers, 4 sacrificial oxide layers, and 1 metal layer). For some advanced applications, design requirements continue to drive the technology to additional levels. The design space expands exponentially with each additional level of structural material.

A major challenge of surface micromachining is the problem of adhesion or 'stiction,' discussed in detail in Section 3.1 of this paper. The term 'stiction,' now used to describe adhesive interactions in MEMS, was borrowed from the magnetic recording industry and actually refers to a special case of adhesion due to adsorbed liquids—water or thick lubricant films—creating capillary forces between surfaces. In MEMS, adhesion is a general descriptor for the fundamental property that small

things tend to stick to each other. Thus the functionality of MEMS devices can be impaired because the adhesion phenomenon causes micromachine devices to tend to stick to the underlying substrate or one another.

Since the stiffness of a mechanical structure increases with the cube of its thickness, adhesion-related failure can be largely mitigated by the stiffness achieved with additional levels of polysilicon. With five-level technology, complex interconnected mechanical systems comprising engines, transmissions, lift elements, mirrors and shutters can be batch fabricated at affordable cost and with high yields. Fig. 7 shows a prototypical complex weapon safing system built with SUMMiT™ V five-level surface micromachine technology. The device requires a 24-bit code to be correctly entered before a series of mirrors can be aligned to complete an optical path that enables transmission of a critical signal. This device shows the degree of mechanical complexity that can be achieved with modern surface micromachine technology.

Fig. 8 illustrates SUMMiT™, a state-of-the-art technology for surface micromachining, in more detail. This illustration shows a CAD drawing of a complex ratcheting actuator. Also pictured is the schematic cross-section, showing how the five levels of polysilicon stack together to form the complex mechanical element. A scanning electron micrograph shows the device when fabricated.

2.2.3. Manufacturing challenges

The advancement of surface micromachine technology to include additional structural levels generates a variety of engineering and materials challenges. One of the most significant of these is associated with maintaining planarity throughout the process. Fig. 9 illustrates a cross-section after a sacrificial SiO_2 layer is deposited over the first patterned polysilicon layer. It can be seen that the sacrificial layer is not flat, but will bear the imprints of the various shapes of the underlying layers. This problem becomes compounded for each additional layer of material, generating untenable manufacturing problems. This fundamental engineering challenge presented an early obstacle

to creating surface micromachine technologies with more than one or two polysilicon levels.

This problem is overcome with the use of chemical mechanical polishing (CMP) to planarize the wafers after each sacrificial SiO_2 deposition. CMP is a mature IC manufacturing technology, used to maintain planarity of IC processes and enable more levels of electrical interconnect. CMP processes produce both local and global wafer planarization. The silicon oxide surface is polished by rotating a wafer under pressure against a polishing pad in the presence of a silica-based alkaline slurry [12].

By adapting the process for MEMS, planarity can be maintained on the wafers throughout the process, enabling fabrication of devices with five or more polysilicon levels [13,14]. Fig. 10 illustrates the effect of using CMP to polish the sacrificial SiO_2 layers. It can be seen that the ‘bumps’ so prevalent in the SiO_2 material in Fig. 9 have been polished off, leaving a smooth, planar surface onto which the next structural level of polysilicon can be deposited.

CMP is a key process in enabling routine manufacture of advanced surface micromachined products with five levels of polysilicon [15]. Research prototype MEMS devices also have been demonstrated with six levels of polysilicon. Fig. 11 shows a SEM photograph of an advanced six-level actuator built with Sandia’s SUMMiT™ VI technology.

CMP offers the promise of a MEMS technology that will continue to migrate in response to designers’ needs. Each additional level of polysilicon enables MEMS designers to achieve higher levels of mechanical sophistication, stiffer devices that are resistant to adhesion, and design features that improve manufacturability and reliability.

2.3. Device processing issues

Impressive progress has been made in the research and development of surface micromachining technologies in the last 20 years. However, the migration of technology from research institutions to successful commercial products has slowed, and several manufacturing challenges have impeded

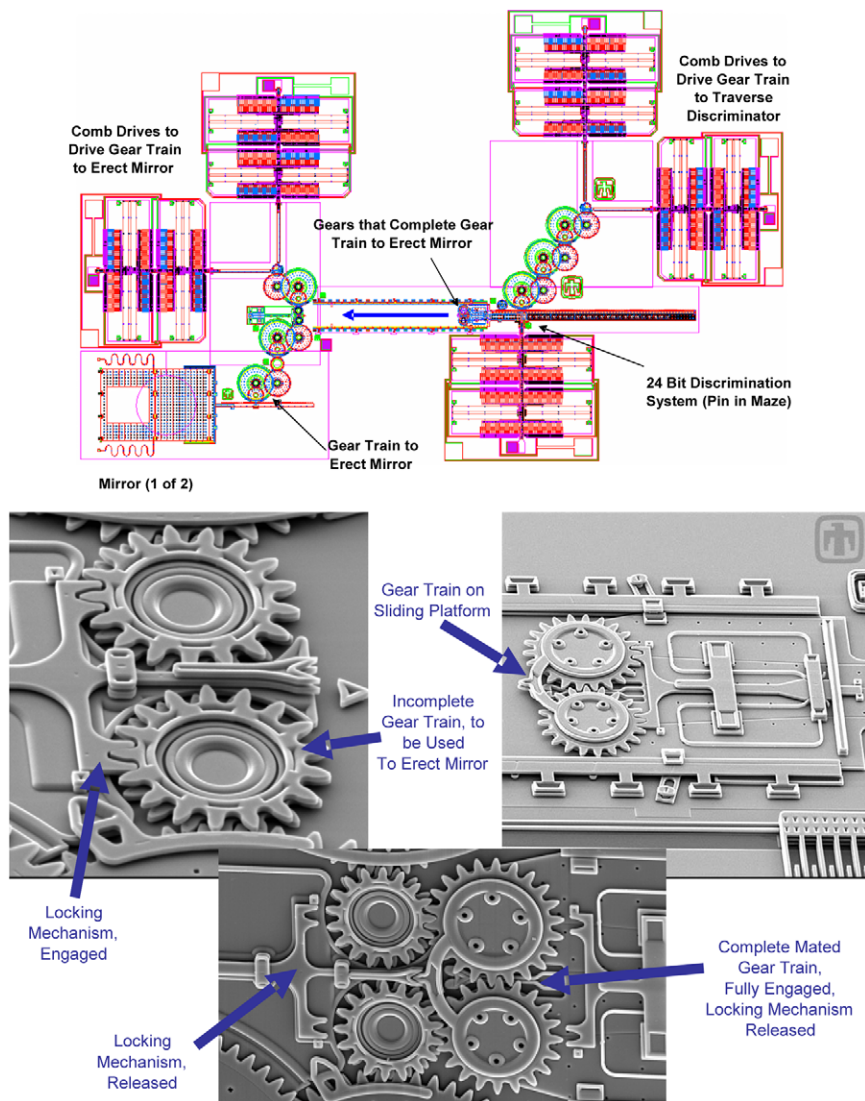


Fig. 7. Illustration of CAD design, and SEMs of individual elements of a prototypical 24-bit weapon safing system. If the correct 24-bit code is entered into the device, a gear train is engaged which enables the alignment of mirrors to complete an optical path that allows the weapon to be armed. The gear teeth pictured are about 7 μm across.

development of products that might otherwise become commercially viable.

One such manufacturing challenge is associated with adhesion in the final release of the mechanical devices, when sacrificial layers are dissolved away to expose the mechanical elements. Following the release process, the wafers must be cleaned and then dried. The problem is that, as the devices dry, surface tension forces generated from the evaporat-

ing liquid menisci can pull the mechanical elements into contact with each other, or with the substrate [16,17]. Once the devices touch, van der Waals forces cause them to adhere to each other, resulting in non-functional devices [18]. There are three solutions that have been identified for this problem: anti-adhesion design, supercritical drying, and hydrophobic surface monolayers.

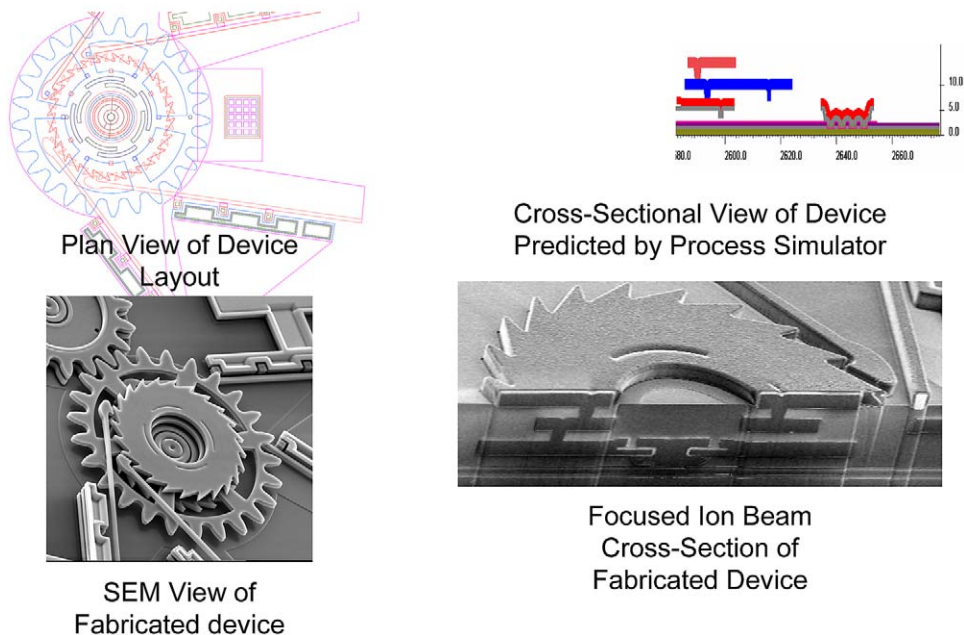


Fig. 8. Illustration of a state-of-the-art surface micromachined device fabricated in the SUMMiT™ V technology. CAD images of the plan and cross-sectional views of the device are shown, as well as SEMs of the actual device after fabrication.

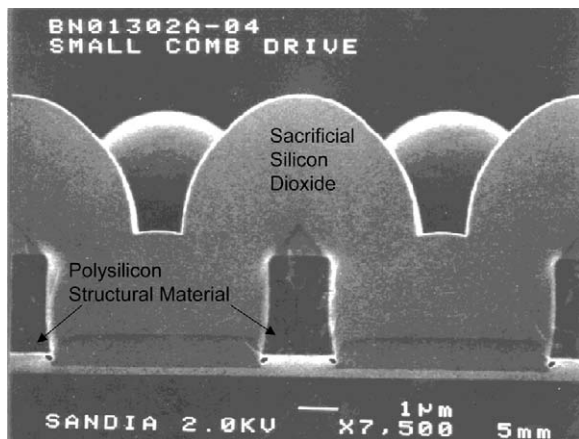


Fig. 9. SEM image demonstrates the challenges of manufacturing multi-level surface micromachine devices. The silicon dioxide sacrificial layer conforms to the shape of the underlying polysilicon, generating a high degree of non-planarity.

2.3.1. Anti-adhesion design

Successfully addressing adhesion challenges such as this requires attention throughout the design and manufacturing effort of a MEMS device. In the case just addressed, design tech-

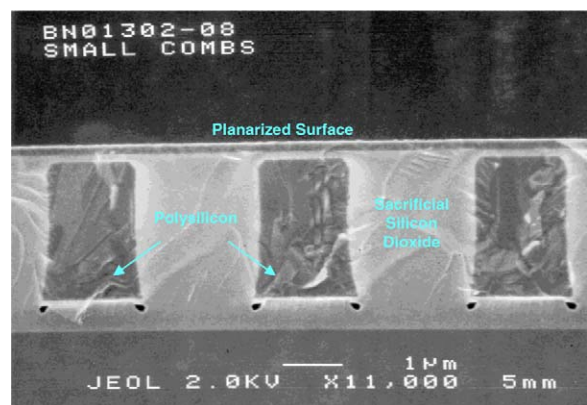


Fig. 10. SEM image showing the effect of CMP planarization of sacrificial silicon dioxide. Planarization of sacrificial silicon dioxide enables subsequent structural material to be deposited on a smooth, flat surface.

niques can be used to create small dimples (vertical stand offs) on the bottom and sides of the mechanical elements. These limit the contact area, and hence the adhesion force. The objective is to limit the contact area, lowering the adhesion forces below the restoring elastic forces of the mechanical

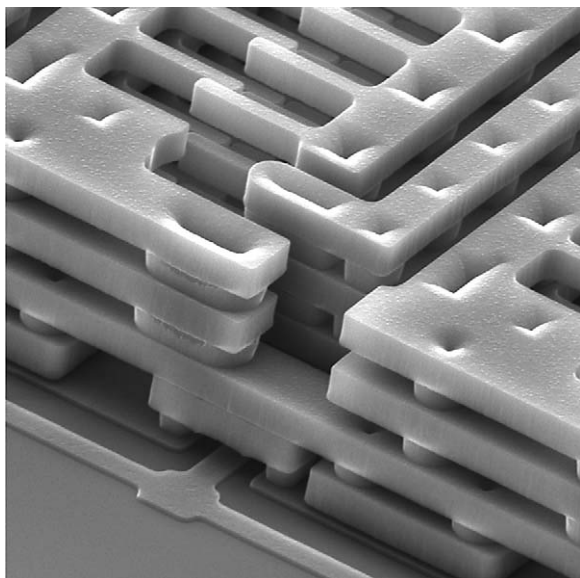


Fig. 11. SEM image showing prototype actuator fabricated in a six-level surface micromachine technology. The polysilicon fingers are 1.25 μm wide.

elements, enabling devices that do not permanently adhere to each other.

2.3.2. Supercritical drying

Supercritical drying techniques applied during the release process can help mitigate the adhesion problem. For example, supercritical CO_2 drying can completely eliminate the liquid–vapor interface. CO_2 is used to displace the liquid on the surface of the wafer, and the temperature and pressure of the system is then taken through the supercritical point of the CO_2 , removing water without generating meniscus or capillary forces [19,20].

While this process prevents adhesion at the point of release, shock, vibration, or other environmental conditions may cause the mechanical elements to touch each other during the normal course of operation, in which case they will still stick together: in this case, generating a field failure of the device.

2.3.3. Hydrophobic surface monolayers

Application of self-assembled monolayers (SAMs) has been investigated to lower the adhesion forces of the surfaces [21]. SAMs are short or long chain molecules with a head group

that reacts with silicon surfaces and a tail group that increases the hydrophobicity of the silicon surfaces. The hydrophobic surface results in H_2O contact angles greater than 90° , and a meniscus that does not pull parts together during the drying process. In addition to improving the yield of devices through the release process, SAM coatings hold some promise of improving long-term device reliability by providing a passivation coating that reduces surface adhesion energy. While SAMs show great promise, some questions remain related to their stability over long-term exposure to temperature and other environments that the MEMS product might experience.

2.3.4. Packaging and sawing

In the case of traditional ICs, the last step of the wafer manufacturing process is to deposit a SiO_2 passivation layer on top of the circuits on the wafer. With this protective layer, the wafers can be diced into individual circuits and then put into electronic packages. It is much more challenging to identify a straightforward way to get MEMS devices into the packages. As discussed earlier, surface micromachined devices are formed by depositing, photo-patterning, and etching thin films on the surface of the wafer. At the end of the process, intricate polysilicon mechanical devices sit on top of the wafer, encased in SiO_2 . The challenge is that if the SiO_2 is removed at this point, fragile mechanical elements will be left exposed on the surface of the wafer. If the wafer were then to be diced, debris from the sawing process would foul the mechanical elements, rendering the MEMS devices useless. One strategy is to saw the wafer prior to the removal of the SiO_2 . Then, once the wafer is diced, individual MEMS chips can be cleaned, exposed to HF to remove the SiO_2 , and put into their packages. It should be noted that at this point the chips are very susceptible to particle contamination, so the packaging must be done in a cleaner environment than that required for traditional electronic circuits.

The process of sawing the wafers first, then releasing the MEMS chips, works effectively for products with low to moderate production volumes. For higher volume products, wafer-level release of MEMS devices is more desirable. While

it is easy enough to remove SiO_2 from the entire wafer, the challenge becomes how to protect the devices during the wafer sawing process. Various companies have developed proprietary methods to ease this problem, but to date no industry standard techniques are readily available. Packaging approaches to overcome these problems include different techniques to protect the fragile MEMS structures during sawing. A popular approach is to cap the wafer prior to sawing with a protective lid. As an example, quartz or silicon wafers can be created with etched cavities, bonded to the MEMS wafer, and then sawn. The bonded capping wafer creates a protective lid for the MEMS device. Typically, companies that have successfully perfected such techniques keep them as closely guarded trade secrets.

2.4. Design and process simulation

Actual design of complex MEMS structures also presents challenges. Few MEMS design and process simulation tools exist, one major reason being that industry standard MEMS technologies have yet to emerge. While commercially successful MEMS technologies have been developed for projection displays and accelerometers, these typically remain proprietary and do not, therefore, enjoy the wide user base that would motivate a CAD developer to create sophisticated design tools for them. Additionally, many exciting MEMS fabrication technologies are available in university laboratories, and hold great promise for the future, but typically do not have the maturity or wide user base that would motivate a CAD developer to create design software.

The lack of industry standard MEMS technologies causes yet another barrier. Since there are no industry standard technologies, design software developers are slow to move into the MEMS business because no one technology has a large user base. At the same time, the lack of powerful MEMS CAD systems precludes more widespread adoption of the technology. Similarly, lack of industry standard MEMS technologies dampens the enthusiasm of traditional IC tool manufacturers for creating MEMS-specific fabrication tools.

3. MEMS performance and reliability

As can be observed from the foregoing commentary, successfully achieving viable MEMS products requires development of an understanding of the physical mechanisms governing the performance and reliability of mechanical devices with micrometer feature sizes. Often, the intuition developed based on macro-scale mechanical devices fails at these small dimensions. For example, the surface area-to-volume ratio of a body is proportional to the reciprocal of its characteristic length. Therefore as the size of a structure is reduced, surface phenomena (van der Waals, electrostatic, capillary forces) dominate the behavior and interaction of structures as compared to volumetric effects (inertia and gravitational forces). A microsystem structure 10 μm long would have a surface area to volume ratio 1000 times greater than a macroscopic structure 10 mm long (although it is not usually practical to scale down a mechanical design directly). In addition, available motive forces in microsystems, such as electrostatic attraction and differential thermal expansion, are limited due to the size of the structures. These factors dictate that surface interactions will dominate the behavior of microsystems.

Several primary factors in determining MEMS performance and reliability concern characteristics of adhesion, friction, wear, film stress, fracture strength and fatigue.

3.1. Adhesion

Adhesion is the most common cause of failure in MEMS devices with compliant structural members. ‘In-process’ adhesion refers to the sticking together of movable elements during back-end-of-line processing, typically due to drying after wet chemical etching of the sacrificial layers. ‘In-use’ adhesion refers to the collapse of initially free movable structures during handling or in operation, and can result when a mechanical shock or actuation force causes unintentional contact of movable structures. Since structures typically contain compliant members to facilitate movement, the restoring force due to elastic energy may be insufficient to overcome the adhesive force and release the structure.

3.1.1. Chemical and capillary forces

In-process adhesion occurs when the sacrificial layers are removed. After rinsing with water to remove residual hydrofluoric acid, silicon is nominally hydrogen-terminated, resulting in a water contact angle near 80°C [22], due to termination of the Si by hydrogen [23]. However, capillary bridges will still form and pull compliant structures into contact. Mastrangelo and Hsu analyzed capillary adhesion and determined the conditions of mechanical stiffness and surface energy necessary to prevent it [24,25]. Alternative approaches are to avoid wet release of structures entirely [26,27] or to avoid the formation of liquid menisci after wet release by supercritical CO₂ [28] or freeze-drying [29,30].

Although these approaches result in structures that are initially free, oxygen or water vapor exposure will result in growth of the natural oxide [31,32], which will ultimately result in a hydrophilic surface. While much research on MEMS adhesion has focused on adsorbed water films, due to the ubiquitous presence of water and the difficulty in removing adsorbed water from Si [33], this is not the only mechanism by which surfaces will adhere. Unsaturated Si bonds on surfaces will cause structures to adhere if these bonds are not passivated prior to contact of the surfaces. Unsaturated Si bonds can be created after fabrication by such processes as contact damage or wear [34].

3.1.2. Other adhesion mechanisms

Other forces that can be manifested at MEMS contacts are electrostatic and van der Waals attraction. Electrostatic attractions may arise in the absence of any applied potential due to charge trapping in dielectrics. Silica and silicon nitride films may trap charge during contact [35]. This phenomenon is responsible for reliability problems in capacitive radio-frequency MEMS switches [36], as charge accumulation alters actuation and release voltages.

Adhesion due to van der Waals attraction occurs between surfaces that are close together but not in contact, and varies inversely with the square of separation distance [37]. Recent research has shown that for hydrophobic surfaces, the dominant adhesion force is from van der Waals attraction

between surfaces that are not in contact [38]. De Boer et al. used adhesion measurements to estimate that for planar surfaces of polysilicon, actual contact occurs over an area eight orders of magnitude smaller than the apparent area, and individual contacts may be tens of micrometers apart [39].

3.1.3. Quantifying adhesion

The adhesive interactions of MEMS surfaces must be quantified in order to assess the merits of treatments to reduce the surface energy. An energy approach developed by Mastrangelo and Hsu [24,25] treats an adhered MEMS structure as a balance between stored elastic energy in the structure and the adhesion energy of the two surfaces. This approach was applied to the specific case of a cantilever beam [40]. The situation is depicted schematically in Fig. 12. From the energy balance, Mastrangelo derived a relationship for the surface energy per unit (apparent) contact area.

$$\gamma_s = \frac{3Et^3h^2}{8s^{*4}}$$

The typical approach is to examine an array of progressively longer beams and determine the length corresponding to the first free beam. Several researchers have estimated the apparent work of adhesion for an oxidized Si surface to be on the order of 20 mJ/m² [38,41].

Another approach uses a fracture mechanics analogy [39]. In this formulation, the gap between the beam and substrate is treated as a crack of length s (see Fig. 12). The problem is treated analytically by equating the energy release rate in the absence of an applied load to the energy of adhesion Γ between the surfaces

$$\Gamma = \frac{3Et^3h^2}{2s^4}$$

In this case, the crack length s is the length of the non-adhered portion of the beam adjacent to the adhered portion, and is experimentally determined using interferometry and modeling.

This technique has been adapted using finite element modeling [39,42] to account for the non-uniform electrostatic force resulting from voltage applied to the actuation pad (Fig. 12), compliance at the support post, and fringing fields at the edges

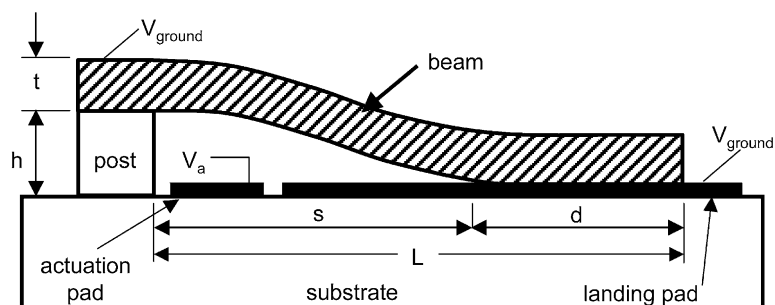


Fig. 12. Schematic illustration of an approach for determining the apparent work of adhesion between silicon micromachined surfaces. The beam may be pulled into contact with the aid of a voltage V_a on the actuation pad.

of the beam. The detection limit for adhesion energy using this approach is estimated to be $3 \mu\text{J}/\text{m}^2$ or better.

3.1.4. Countering in-use adhesion

In-use adhesion can be mitigated by treating the surface to adjust its surface energy or topography, which can also minimize the effects of capillary films during processing and mitigate in-process adhesion.

3.1.4.1. Surface roughening Early attempts to minimize adhesion focused on roughening the surfaces to minimize the real area of contact. Several strategies to modify topography have been explored, including growing a thermal oxide followed by dry etching [43], and heterogeneous oxidation of phosphorus-doped polysilicon due to segregation of the phosphorus to grain boundaries [44]. Modification of surface topography alone was found to decrease the apparent work of adhesion for oxidized silicon by about a factor of 20 to less than $1 \text{ mJ}/\text{m}^2$. Houston et al. [45] developed a process for ammonium fluoride treatment which both roughened the surface and left the surface hydrogen terminated. The combination resulted in an estimated work of adhesion of less than $0.3 \text{ mJ}/\text{m}^2$, but the hydrogen-terminated surface was found to oxidize after about a week in air [45].

3.1.4.2. Chemical passivation By far the most extensively studied surface treatment processes to reduce adhesion involve chemical passivation with coupling agents. These coatings are popular because they can be applied at the back end of the

manufacturing line, thus having no impact on the fabrication process. The coatings are typically one molecular layer thick, and as such do not modify the stress state of the polysilicon layers. Other advantages are that the adsorbed films are self-limiting in thickness, and can penetrate through the liquid or vapor phase to deeply hidden interfaces.

Coupling agent films were first formed by exposing the surface to a solvent containing the precursor molecule in solution [46]. Srinivasan et al. [41] used this approach to form films of octadecyltrichlorosilane ($\text{C}_{18}\text{H}_{37}\text{SiCl}_3$, ODTS) and perfluorodecyltrichlorosilane ($\text{C}_8\text{F}_{17}\text{C}_2\text{H}_4\text{SiCl}_3$, FDTS) on polysilicon MEMS structures. In the simplest description of the surface reaction, the alkylsilane molecule comes in contact with the oxidized Si surface, and the chlorosilyl head groups hydrolyze and chemisorb to the surface, forming Si-O-Si bonds. The head groups will also react with water chemisorbed on the surface, as well as any water in solution, to form aggregates or micelles that may be more weakly attached through hydrogen bonding to the surface [47]. This high reactivity with water, and the difficulty in controlling water on surfaces that are intentionally exposed to water during processing, is responsible for the high irreproducibility of silane coatings [48].

Though variable in nature, hydrophobic surfaces formed in this manner can yield water contact angles of 112° (ODTS) to 115° (FDTS), with apparent work of adhesion less than $3 \mu\text{J}/\text{m}^2$. This is a factor of 6000 less than that for hydrophilic oxidized Si [41]. Values for apparent work of adhesion on the order of $\mu\text{J}/\text{m}^2$ result in the release

of extremely compliant structures, such as cantilever beams 2 μm thick and greater than 1000 μm long, suspended 2 μm above the substrate.

Attempts have been made to improve the reproducibility of monolayer coupling agent treatments. Mayer et al. [49] developed a vapor-phase route for depositing silanes on surfaces. Even if reproducibility is improved, recent work suggests that exposure of these surfaces to high humidity for extended periods can result in reorganization of the monolayer [47], and decreasing hydrophobicity [39]. Vapor deposition also requires that the structures are initially free prior to treatment.

More recently, alternative chemistries have been investigated. Ashurst et al. developed solution deposition routes for octadecene ($\text{C}_{16}\text{H}_{33}\text{CH}=\text{CH}_2$) [50] and dichloridimethylsilane ($(\text{Cl}_2\text{Si}(\text{CH}_3)_2)_2$, DDMS) [51]. These coatings reduce the presence of agglomerates due to polymerization in solution. Octadecene coatings yield work of adhesion and static friction comparable to ODTS, but are not as thermally stable in air. DDMS films are thermally more stable than ODTS, but at the expense of higher adhesion and friction coefficient. The manipulation of Si surface chemistry to yield robust hydrophobic surfaces remains an area of active research. Breakthroughs in this area could enable new applications of microsystems.

3.2. Friction

Control of friction is essential to further development of MEMS technology. Considerable work has been done in the physics of microsystems friction and a number of tools have been developed for surface–surface and sidewall tribometry. However, a number of challenges remain.

3.2.1. Physics of microsystem tribology

Initial investigations of friction in microsystem materials have used techniques applied to macroscopic systems. Measurements of friction between self-mated polysilicon in vacuum [52] and various atmospheres [53,54] yield friction coefficients between 0.2 and 0.8, with the higher values associated with sliding in vacuum or inert atmospheres. Gardos [34] investigated friction of self-mated Si(100) as a function of temperature, and con-

cluded that creation of unpassivated dangling bonds on the surface was responsible for increased friction. At room temperature, in the presence of water vapor or oxygen, surface free radicals are rapidly passivated by adsorption and the friction coefficient remains near 0.2. These measurements were made at an apparent contact stress of several hundred MPa.

Chen and Carman [55] investigated friction between single-crystal silicon surfaces at applied force as low as 100 mN. Results indicated that the friction coefficient increased from about 0.8 at an apparent contact stress of 104 MPa and above, to greater than 2.0 at an apparent contact stress of 10.4 MPa. The increase in friction coefficient at low loads is due to adhesion increasing the true interfacial contact stress.

The existence of adhesive contributions to the contact load is well known [37], and has been described in detail using several theories, including Johnson, Kendall, and Roberts (JKR) [56] for short-range adhesion forces between compliant materials, and Derjaguin, Muller, and Toporov (DMT) [57] for long-range forces acting on stiffer materials. Ultimately the varying degrees of adhesive interaction of surfaces, combined with the geometry and elastic properties of the bodies, affect the real contact area between the solids. The most commonly observed manifestation of this effect is in single asperity friction experiments in the atomic force microscope (AFM). During measurements of friction between Pt-coated AFM tip and a mica surface, Carpick et al. observed finite friction force for negative applied load [58]. Variation of friction force with load conformed to JKR predictions of the real contact area. The JKR theory defines one limit in the actual relationship between contact area and applied load for elastically deforming solids.

At the other limit, we have the long-standing theory of Hertz [59] that assumes no adhesion forces between the solids. The friction force as a function of applied load is plotted for the theories of Hertz, JKR and DMT in Fig. 13, adapted from Carpick and Salmeron [60] assuming unit values for the radius of curvature of contacting asperities, composite elastic modulus, surface energy per unit area and interfacial shear strength.

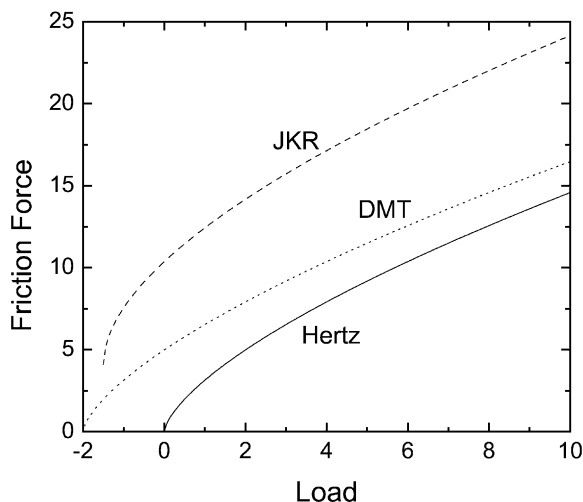


Fig. 13. Variation in friction force with applied load for the theories of Hertz, Johnson, Kendall and Roberts (JKR), and Derjaguin, Muller and Toporov (DMT). Adapted from Ref. [61].

While the variation in friction force with load for real interfaces will fall between the Hertz and JKR limits, since the DMT theory describes interaction of stiff materials, we may expect the interactions for polysilicon surfaces (which are quite hard) to tend toward this type of behavior. The main result for microsystem contacts is that a finite friction force will exist under conditions of zero applied load. The challenge in relating friction force to the interfacial shear strength then becomes determination of the real area of contact between two rough surfaces.

Mechanical properties and the surface topography created by processing govern the real contact area of microsystem materials. At the same time energy dissipation modes, such as phonon scattering and orientation changes in monolayer films, are influenced by the local stress state and the time scale of surface interactions. Experimental techniques that can access the operating parameter space of microsystems are therefore critical to understanding interface behavior.

Scanning probe microscopy has been used to investigate friction at isolated asperity contacts in the presence of liquid films [61,62]. However, the contact pressures are in the range of 1 GPa or above, and interfacial velocity is typically less than

1 mm/s. The surface forces apparatus has been used to investigate the dynamics of confined fluids between macroscopic, atomically flat planes [63], but maximum interfacial velocities are still limited to a few mm/s.

Recently a mechanical probe was combined with a quartz crystal microbalance to permit measurements of energy dissipation at asperity contacts at interfacial velocity of 0.1 m/s [64]. In parallel with advanced experimental techniques for tribology, computational methods have advanced with increases in computational power and the availability of potential functions to describe atomic interactions. Tutien et al. [65] have investigated the friction behavior of diamond surfaces separated by adsorbed hydrocarbons using molecular dynamics simulations. Atomistic simulations have provided some insight into the organization and deformation of monolayer films during sliding [66]. However, explicit atomistic simulations on rough surfaces are still intractable, and investigation of long relaxation time events commensurate with interfacial velocities below 1 m/s require prohibitively long run times.

A comparison of some of these experimental and computational tools is shown schematically in Fig. 14. Pin-on-flat tribology tests, where macroscopic samples of the materials of interest are translated

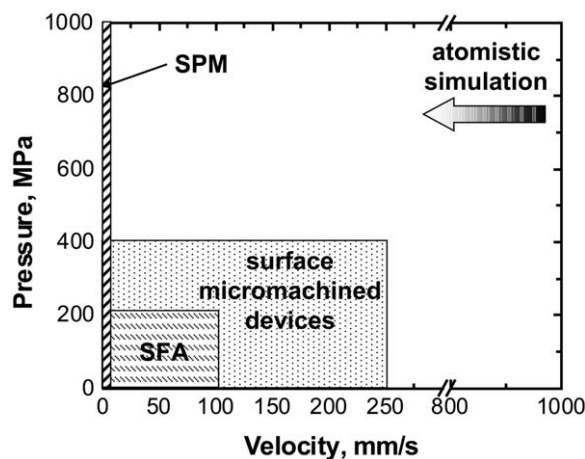


Fig. 14. Comparison of experimental (SPM, scanning probe microscopy; SFA, surface forces apparatus) and computational tools for investigating friction at molecular to atomic scale, relative to the operating parameters of surface micromachines.

in contact under controlled load, can be used to investigate the entire parameter space represented in Fig. 14. However, such tests represent the interaction of rough surfaces with many real points of contact. In addition, the thermal environment at the interface due to frictional heating at the contact points differs from that in microsystems. Microsystem contacts are expected to operate in a more isothermal environment than macroscopic bodies in which the heat generated at the interface is coupled to a large thermal mass.

3.2.2. Tribometric tools

Approaches for measuring friction using microfabricated devices themselves have clear advantages over other experimental tools. The bulk microstructure, surface topography, and chemistry of the surfaces are representative of those in MEMS applications. Further, measurements can be made at an appropriate range of contact force and shear rate. Finally, degradation mechanisms that may have minimal impact on the initial performance of a macroscopic body, such as generation of sub-micrometer wear particles, may be extremely damaging in a microsystem contact.

3.2.2.1. Planar surface friction Lim et al. [67] were the first to develop a MEMS device specifically for measuring friction. The device used an electrostatic comb drive to laterally move a shuttle, and contact occurred between a planar surface and dimples on the bottom of the shuttle. Lim et al. [67] measured the static friction between polysilicon surfaces to be 4.9 ± 1.0 , and between polysilicon and silicon nitride to be 2.5 ± 1.0 , in laboratory air. The main conclusion is that much higher friction coefficients than observed in macroscopic systems are possible as the applied force is reduced, due to the adhesion contributions to the applied load.

3.2.2.2. Measuring sidewall contact friction

Prasad et al. [68] were the first to develop a MEMS device for measuring friction at sidewall contacts. Due to the planar nature of surface micromachines, forces tend to be transmitted between structural elements in the plane of the device. We may therefore expect that most of the

higher stress surface interactions in MEMS will occur between sidewall surfaces. Prasad et al. [68] measured static and dynamic friction in moderate vacuum in a scanning electron microscope, and for self-mated SiO₂ surfaces found static friction coefficient μ_s of 0.5, and dynamic friction coefficient μ_k of 0.45. Although surface roughness was not specified, the roughness of the sidewalls formed by DRIE would probably be greater than that on as-deposited surfaces, thus reducing van der Waals contributions to the applied force. The fact that the measurements were also made in moderate vacuum suggests reduced contributions to normal force by capillary films at points of contact.

3.2.2.3. Continuous sidewall tribometry Senft and Dugger [69] were the first to develop a device that allowed *continuous* measurement of kinetic friction at MEMS sidewall contacts while operating at realistic speeds. This permits investigation of the evolution of interface behavior with use, and is critical to understanding the impact of changes in interface behavior on other functional devices. The device is shown in Fig. 15. Friction forces can be monitored throughout the test by capturing an image of the device at a particular point in the drive signal applied to the electrostatic actuators. Automated image analysis is used to extract displacements of the movable portion of the device, from which forces can be calculated. Using this method, the friction response of MEMS surfaces can be determined over the course of millions of sliding cycles. The MEMS sidewall tribometer [69] has been used to investigate the friction behavior of monolayer coatings in various environments [70], and the tribological performance of conformal hard coatings. An example of the evolution of dynamic friction is shown in Fig. 16. The device treated with an alkylsilane monolayer (FDTs) exhibits consistent friction coefficient below 0.1 in environments without water vapor, in agreement with other measurements using the structure of Lim et al. [67] to determine the dynamic friction coefficient from the movement of the structure after release [71]. In the presence of water vapor, the FDTs coated device exhibits rapid fluctuations in friction coefficient, and becomes stuck at ~150 000 cycles (where the friction coef-

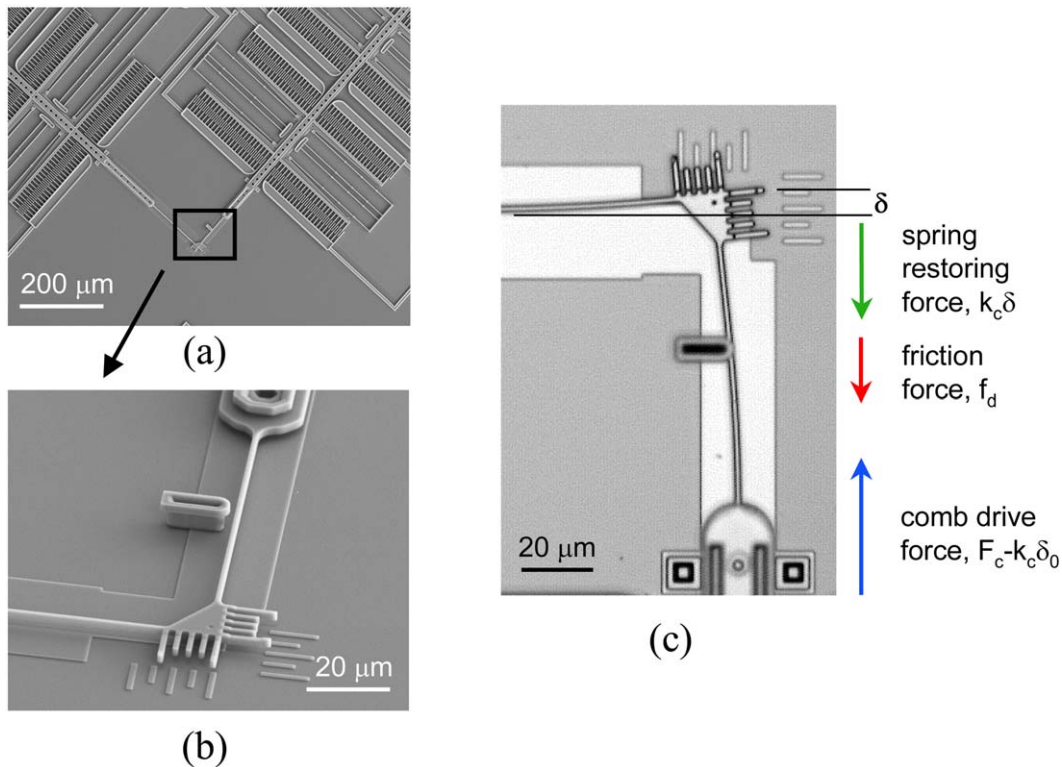


Fig. 15. Scanning electron micrographs of a surface micromachined sidewall tribometer [69], showing the layout of electrostatic actuators (a), the beam and anchored post (b), and a top view during data collection in the optical microscope (c).

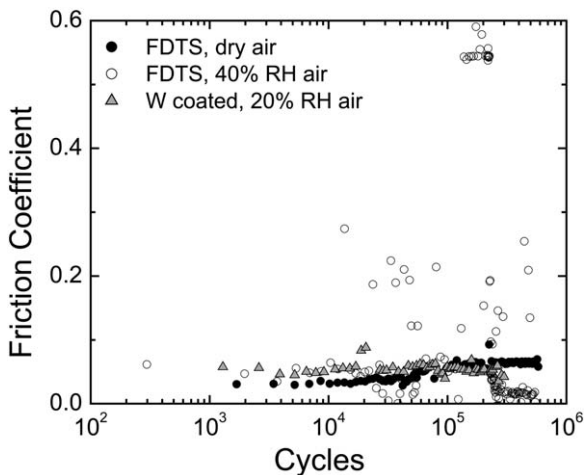


Fig. 16. Evolution of friction coefficient for the sidewall tribometer with a chemisorbed monolayer of FDTs, and conformal tungsten coating, in different operating environments [70].

ficient remains near 0.55). As an alternative to chemisorbed organic monolayers, hard coatings have been investigated for improving the tribological behavior of silicon micromachines. Tungsten may be deposited selectively on silicon micromachines by chemical vapor deposition after removing the sacrificial layers [72]. Fig. 16 shows that the friction coefficient measured for a tungsten treated device in the presence of water vapor remains below 0.1. Chemical analysis of tungsten-coated surfaces indicated that the presence of a mixed tungsten oxide and nitride, which is more resistant to water-assisted cracking than SiO_2 , may be responsible for improved performance. More recently, the sidewall tribometer was employed to investigate the effects of monolayer degradation on static friction coefficient [73]. Both ODTS and FDTs monolayers were found to be stable after radiation exposure to a dose of 500 krad. The monolayers also exhibited no change in surface chemis-

try or hydrophobicity after exposure to 300 °C in pure nitrogen or dry air for 60 min. However, the ODTS monolayers were found to degrade when exposed to ~13% relative humidity at this temperature for 10 min. Photoelectron spectroscopy indicated a loss of coating from the surface, and water contact angle decreased from 110 to below 80°. This change in surface chemistry was also manifested in the static friction response, as shown in Fig. 17. A change in the static friction coefficient due to aging could result in the inability to move a device with the available motive forces from actuators. The kinetics of such degradation reactions must be understood in order to predict the impact of storage on device performance.

3.2.2.4. 'Inchworm' tribometer The latest addition to the suite of devices to characterize friction between micromachined surfaces is an inchworm device developed by de Boer et al. [74]. The device consists of planar polysilicon 'rails' that make contact with a planar track. Uniform contact of planar surfaces is frequently difficult to insure, but in this case multiple levels of polysilicon are used to stiffen the structure and improve planarity. Parallel plate capacitors having relatively large area, and the ability to tailor the size of the contact

pads, enable investigation of a wide range of applied loads.

3.2.3. Further tribometry challenges

Several challenges remain in the area of metrology for MEMS friction. Independent measurement of actuator output force is difficult. Quantification of force now relies on calculation to determine actuator performance. Since dimensions can be affected by processing, and stiffness is proportional to the cube of thickness, some uncertainty exists in the stiffness of beams used to determine load by measuring displacement.

Improved methods to determine the magnitude of intrinsic forces (van der Waals, etc.) are also needed. The MEMS sidewall tribometer [69] can be operated to determine the force required to separate the movable beam from the post, in much the same way that the pull-off force between an AFM tip and a sample can be determined. This provides only a measurement of the total force required to separate the surfaces, and no force vs. displacement from which the work of adhesion and range of interfacial forces can be determined.

Finally, real-time measurement of displacement would enable exploration of dynamic behavior over a single cycle of motion at realistic shear rates. Phenomena such as stick-slip motion, and the transition from static to dynamic motion, could be studied in more detail.

3.3. Wear

Wear has been recognized as a life-limiting failure mechanism for micromachines since Gabriel et al. [75] observed wear in a Si surface micromachined gear spun on a hub at high speed using an air jet. Lee et al. [76] developed a series of 'vibromotors,' in which a disk was pushed around a hub using off-axis impact with a linear electrostatic actuator. The contact in this device was primarily compressive, with limited shear at the impact point. Wear was observed only at high contact stress, estimated at greater than 2 GPa.

3.3.1. Wear-based failure model

The first attempt to relate wear quantitatively to the operation of a MEMS device was made by

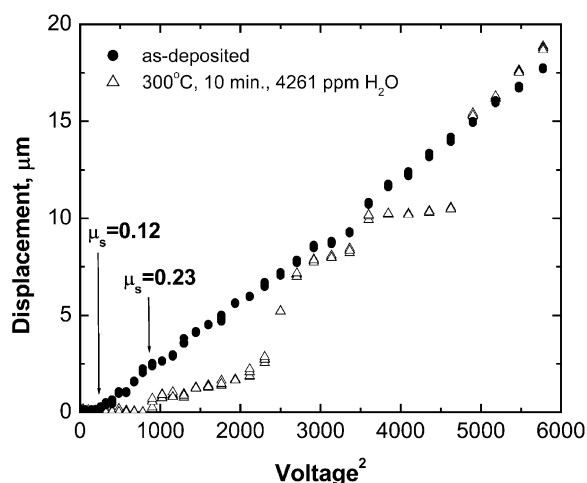


Fig. 17. Displacement as a function of the square of voltage for sidewall tribometers treated with ODTS. The voltage for which slip first occurs is used to calculate static friction coefficient (after Ref. [73]).

Tanner et al. [77]. Failure of the device was caused by wear at sliding surfaces, and a relationship between wear volume and contact parameters was developed to estimate the number of rotations to failure of the device. The wear-based failure model was found to agree with the data on cycles to failure as a function of drive frequency, with a wear coefficient of 1.1×10^{-7} . The wear coefficient relates wear volume to applied force, sliding length and material strength.

Tanner et al. also investigated the effect of operating environment on the reliability of the Sandia microengine [78]. Operation in a dry environment (1.8% relative humidity) was found to produce a wear rate of approximately $0.25 \mu\text{m}^3/\text{Kcycle}$, and this decreased monotonically to $0.10 \mu\text{m}^3/\text{Kcycle}$ as the relative humidity was increased to 40%. Devices operated in dry conditions exhibited a large quantity of wear debris near the pin joint and hub, and increase in gap spacing at these locations. Conversely, very little debris was observed in devices operated at 40% relative humidity.

3.3.2. Wear and environment

The general trend in wear behavior of the Sandia microengine as a function of environment was found to be opposite to that of the sidewall friction device discussed previously [69]. Fig. 18 shows the wear on the post from sliding experiments in dry and humid air. In the case of the friction device, water vapor was found to accelerate the production of wear debris. This contrast illustrates the importance of operating conditions on the wear mechanisms that may be exhibited for a particular sys-

tem. Adachi et al. [79] developed a method for graphically depicting the relationships between competing wear mechanisms and how they changed with operating parameters in a wear map for ceramics, in a parameter space defined by the mechanical and thermal severity of contact. In terms of these parameters, the contacting materials for the microengine and sidewall tribometer are the same so that mechanical severity of contact can be related directly to contact pressure. The thermal severity of contact depends upon the ability of heat generated at the contact to be transported away into the bulk of the structure. A large thermal mass facilitates rapid removal of heat and lower contact temperatures. The estimated contact pressures in the friction tester and microengine are 230 and 63 MPa, respectively. Similarly, the interfacial velocity in the friction tester and microengine are 160 and 22 mm/s. The thin cross-section of the beam in the friction tester, small contact area, higher interfacial velocity and contact pressure, and the fact that the contact area is stationary on one surface as opposed to moving on both surfaces as in the microengine, suggest that both the mechanical and thermal contact severity are greater for the friction tester than for the microengine. These differences in operating conditions result in the two devices operating in regimes of different wear mechanism. At low contact stress polysilicon contacts, Mizuhara and Hsu [80] reported the formation of surface hydroxides which may protect the surface from additional wear at high humidity. At the same time, water is known to promote crack propagation in Si by adsorbing at the crack tip to prevent crack healing [81].

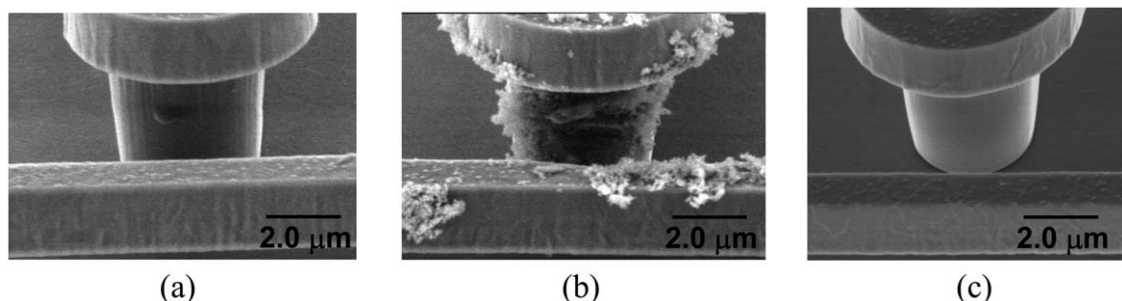


Fig. 18. SEM micrographs of the post from the sidewall friction device when run in air containing less than 100 ppm H_2O (a), and in air at 40% relative humidity (b). The post from a tungsten-coated device run in air at 20% relative humidity is shown in (c).

Clearly wear processes are complex phenomena, and very different mechanisms of material removal can be activated in identical materials when operated under different conditions or in different environments. Metrology challenges in measurement of wear are associated with the small size of devices and difficulty removing debris to permit accurate wear volume measurements.

3.4. Film stress

Residual stress in MEMS materials can cause structural layers to curl out of plane. These deflections can prevent parts from interfacing as they should, for example in a gear train where the teeth must mesh to transmit force, or in an electrostatic actuator where comb finger teeth must remain in the same plane to permit linear actuation. When residual stresses are large they can lead to fracture or delamination either after processing or during the application of sub-critical loads.

While wafer curvature measurements have been used successfully to measure the overall stress state in a thin film deposited on a wafer, this does not provide information on gradients in the film, or local variations in stress resulting from process variation over the surface of a wafer. Jensen et al. [82] have developed an approach to characterize several stress parameters in polysilicon films, using measurements of cantilever beam deflections combined with modeling. While little variation was found in Young's modulus (164 ± 3 GPa), significant variation in beam curvature, $3.28\text{--}3.73\text{ m}^{-1}$, were discovered. This approach, using on-chip structures, enables variation in properties with location on a wafer surface, and with post-release processes, to be determined.

3.5. Fracture strength and fatigue

Design of reliable MEMS devices requires knowledge of the strength distribution of the structural material. In polysilicon devices, strength is determined by the flaw size distribution and hence can be influenced by grain size, microstructure, and etch processes. Glass et al. [83] found that the fracture strength of polysilicon in uniaxial tension could vary from 2.2 to 4.3 GPa, depending upon

the details of the fabrication process. The critical flaws producing these levels of fracture strength are estimated to be in the range of 75–175 nm [84], which is much smaller than the feature sizes of MEMS components. Fracture surface fractography indicates that failure initiated at the surface in all cases.

The presence of flexural elements in MEMS actuators and resonators raises concern about the effects of cyclic loading on material failure. Since Si does not exhibit dislocation activity at low homologous temperature, and there is little evidence for extrinsic toughening mechanisms observed in some brittle materials [85], Si should not exhibit fatigue at room temperature. However, Connally and Brown [86] first reported observations of fatigue in a polysilicon device, and these have been confirmed in subsequent investigations [87]. The resonant frequency of a reversed bending structure was used to monitor crack growth at a notch or precrack. Applied bending stress amplitude was plotted as a function of the cycles to failure to generate fatigue stress-life, or S/N curves. While more than 10^8 cycles to failure were observed at a stress amplitude estimated to be 3 GPa, this was reduced to on the order of 10^5 cycles at a stress amplitude estimated to be 4 GPa. Transmission electron microscopy in the area of stress concentration of devices stopped prior to failure showed a thicker oxide film than in non-stressed areas, and cracks in the oxide. Enhanced oxygen and water diffusivity in the strained, cracked oxide is believed to enhance the oxidation rate. Environment-assisted cracking of the oxide layer, as previously discussed, is then thought to cause crack growth that ultimately leads to failure. Structures coated with an octadecene monolayer, which should bond directly to Si and suppress oxide formation, exhibited a reduced susceptibility to fatigue failure [87]. It is important to note that the levels of stress imposed here to produce the 'reaction-layer' fatigue mechanism are at levels approaching the fracture stress. In typical component designs, where operating stresses are well below 2 GPa, fatigue issues are not a concern. However, in the presence of aggressive environments, environmentally-accelerated fatigue behavior may become important.

3.6. Engineering qualification

Examples of successful MEMS products illustrate the importance of qualification tests in bringing a MEMS product to market. Analog Devices performed extensive reliability tests of ADXL accelerometers [88]. Primary reliability issues were associated with a long-term drift in electrical output when held at 125 °C, variable device-to-device performance under no acceleration, and adhesion of parts after shocks sustained during handling. The first two issues were resolved by redesigning the sensor electrical circuit so that it was less sensitive to surface electrical effects. Adhesion during handling was mitigated using a Si fluid that decomposed during elevated temperature bakeout to leave an organic residue ~0.8 nm thick on the silicon surfaces. In this device, protection from adhesion is required only during handling, since in the air bag modules that use this device these accelerations would only be seen in a crash scenario, and the circuitry is designed to capacitively hold the proof mass in its rest position.

The Texas Instruments DMD is another example of successful application of qualification tests to market a MEMS product [89]. In this investigation, burn-in tests of devices having 778 240 mirrors each were used to evaluate the effects of particular mirror deflection patterns on the rate of mirror failure. In each of several phases of the testing, several thousand devices were evaluated, resulting in more than 10,000 devices used for phase-in and verification of the testing protocols. Weibull plots of accumulated cycles vs. cumulative percent failed are typically used to describe the failure distributions and derive confidence limits for device lifetime.

Of particular concern in applications that involve significant storage time prior to use are changes in surface composition that can affect device performance when it is operated. Surface composition will be influenced by the storage environment for the device, and control of this environment can be extremely challenging. For example, the ability to measure leak rates in packages with small volume limits the degree to which the hermeticity of the packaged environment can be assured.

3.7. Design for reliability

Current knowledge of the importance of MEMS surface interactions and mechanical limits provides some guidelines for reliable designs.

Contacting surfaces should be minimized where possible. Where contact is unavoidable, designs should provide restoring forces that will assure separation of surfaces that come into contact. For untreated SiO₂, for example, devices should provide sufficient restoring force to overcome a work of adhesion of 20 mJ/m².

Rubbing surfaces should also be avoided where possible. The actual normal force between bodies in contact can be on the same order as forces applied with actuators, due to the presence of intrinsic forces, such as van der Waals attraction.

Contact areas should be minimized, and separation distances between planar surfaces kept above 50 nm to minimize the contribution of relatively short range van der Waals forces to the contact force. This is typically achieved using dimples on planar structures to restrict contact to a limited area.

Fracture strength, a statistical property in brittle materials such as silicon, is a function of microstructure and processing, and can exhibit variability from run to run due to process variability. Stress in polysilicon elements should be kept to 10% or less of the measured fracture strength for the material and process in use. Stress values in the range of several hundred MPa appear to be quite acceptable.

Products with significant complexity and high degrees of reliability can be achieved by utilizing these design-for-reliability principles, and the underlying scientific principles that led to their development. Fig. 19 presents reliability data for MEMX's optical cross-connect mirrors, similar to the one pictured in Fig. 3. Each mirror contains more than 100 000 mechanical elements, and is capable of steering an optical beam through a 40° light cone. Fig. 19 represents long-term reliability testing of 300 of these mirrors operated at 70 °C. It can be seen that no failures have occurred in 575 billion accumulated device cycles. Furthermore, upon closer examination of a device with over a billion cycles, there are no measurable differences

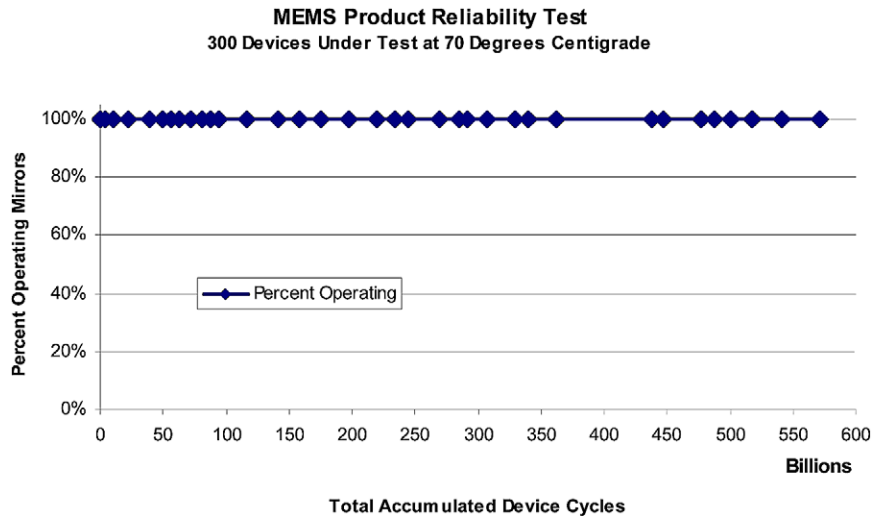


Fig. 19. Reliability data for MEMX's Advance MEMS-based mirrors. Each device contains over 100 000 mechanical elements, and no failures have occurred in 300 devices after 575 billion accumulated device cycles.

in its operational behavior from those of newly-fabricated devices. Hence, using the principles outlined above devices can be built that exhibit virtually fatigue-free behavior.

4. Conclusion

The past decade has seen the emergence of a vast array of promising MEMS research; however, development of successful products has been slow and, for the fledgling industry, painful. Gaps in the fundamental understanding of the physics of performance and reliability have been a major barrier to more successful commercial products, but are being gradually closed by investigations at Sandia National Laboratories and elsewhere. We are learning vital information about the relationship of intrinsic and applied forces at the micro-scale and how, as dictated by surface topography, they reveal themselves in the form of friction and adhesion. It follows that the reliability of MEMS devices with contacting surfaces will be increased greatly as this knowledge enables optimal modification of surface chemistry and topography. Importantly, development of the field (i.e. shortening development cycle and cost) will accelerate as measurements of key materials properties, made with MEMS tools,

become standard methods that can be applied across the community, enabling rationalized comparison of research results. Similarly, while the regrettable lack of industry standards has slowed development, Fairchild Semiconductor's decision to establish a commercial foundry offering SUMMiT™ V technology may help establish the requisite criteria, while enabling the emergence of a new generation of high performance, high impact MEMS products. These positive indicators nurture optimism that the MEMS community, encouraged by the gradual development of a firmer technical infrastructure, will regain the confident path that began with the pioneering commercial products of the 1980s.

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