Tribology of MEMS

M.P. de Boer and T.M. Mayer

Because of large surface-to-volume ratios and low restoring forces, unwanted adhesion and friction can dominate the performance of microelectromechanical systems (MEMS) devices. To guarantee the function and reliability of MEMS devices, tribologists must understand the origins of adhesion, friction, and wear over a broad range of length scales from the macroscopic to the molecular. In this article, we present an overview of challenges, successes, and initial steps toward a fundamental understanding.

Polycrystalline silicon (polysilicon) is the material of choice in surface-micromachined MEMS because it is compatible with integrated-circuit technology, can be stress-relieved to less than 10 MPa, and deposits conformally by low-pressure chemical vapor deposition (CVD), allowing the fabrication of sophisticated hub geometries.[1] (For more on the technique of surface micromachining, see the article by Mehregany and Zorman in this issue.) However, silicon oxidizes readily to form a hydrophilic surface, making it susceptible to adhesion. Most metals also oxidize, so the problem is relevant to other micromachining technologies. Oxide surfaces are also prone to accumulating static charge, which can interfere with capacitive-sensing circuitry. Given these surface properties, we must consider aspects of device design, materials selection, and processing, and specific surface modifications to minimize the effects of adhesion, friction, and wear.

Even in applications where contact is never intended, adhesion arises as a significant problem. For example, in accelerometers and gyroscopes, compliant mechanisms are freely suspended above the substrate. During fabrication, a sacrificial material surrounds the structural films and must be removed to render the films freestanding. Sacrificial films are etched or dissolved in liquid in a so-called release step. To avoid capillary collapse,[2] a supercritical carbon dioxide drying process has been developed to circumvent the associated surface tension.[3] However, strain gradients through the thickness of the films can cause structural members to curl and contact the substrate, resulting in adhesion. Proper deposition and annealing sequences[4] must be implemented to guarantee that freestanding films exhibit low curvature, and sufficient design tolerance must be built into the device to avoid contact and adhesion due to handling after release of the freestanding structures.

Contacts are often inherent to the function of a device. Optical switching devices require rapid contact and disengagement, creating a dynamic adhesive interface. Microrelays have conflicting demands of low contact resistance and low adhesion. In some applications, switches may remain in contact for extended periods. In all of these, long-term changes in adhesive energy due to the stability of the interface and environmental factors are of great concern.

Low-surface-energy, hydrophobic coatings applied to oxide surfaces are promising for minimizing adhesion and static-charge accumulation. Typically, these are very thin or monolayer organic coatings, either physisorbed or covalently bound to the surface. Nonpolar organic groups on the surface exhibit low adhesive energy and low static-charge accumulation; in some cases, they are self-healing. In addition to exhibiting low surface energy, coatings must be compatible with subsequent device processing, including packaging processes involving thermal treatments of 400–500°C. Examples of coatings that have been successfully introduced to commercial MEMS products include Texas Instruments' report of a perfluorodecanoic acid coating on structural aluminum that self-heals damaged areas[5] for their Digital Micromirror Device™. Analog Devices has patented nonpolar phenylsiloxane coatings for accelerometers that resist charge buildup and also survive packaging temperatures as high as 500°C.[6]

Coatings must not introduce stress gradients and must coat even the most inaccessible surfaces, so line-of-sight deposition techniques of hard materials are not likely to work. Therefore, much effort has been focused on organic monolayer films, such as the silane coupling agents octadecyltrichlorosilane ($C_{18}H_{37}SiCl_3$, ODTS) and perfluorodecyltrichlorosilane ($C_8F_{17}C_2H_4SiCl_3$, FDTS).[7] These films are typically deposited from nonaqueous solution after the release step in MEMS fabrication. While this process is already much studied, its introduction into the MEMS fabrication sequence has been problematic, due to the requirements of controlling trace amounts of water on the surface and in the solution, stability of the precursor solutions (the organic compounds tend to agglomerate in the bulk solvent), and stability of the resulting films to temperature and humidity. Hydrolysis and condensation reactions in the solvent compete with surface reactions, leading to micelle deposition rather than monolayer deposition.[8] The morphology of the coating strongly affects release yield.[9] According to contact-angle measurements, films of ODTS thermally degrade in air or oxygen below 200°C, but survive to 400°C in vacuum or nitrogen, while FDTS survives in air to 400°C.[10] However, FDTS films have also been reported to degrade in high-humidity environments (>80% RH for extended periods), perhaps due to film restructuring to form surface micelles or water adsorption at defects.[11]

Alternative CVD processes using volatile fluoroalkylsilane precursors alleviate some of the problems encountered in solution-based processes.[12] Precursor chemistry is easily controlled in the gas phase, efficient transport at low pressure ensures coating of high-aspect-ratio structures, and self-limiting surface reactions lead to conformal monolayer coverage. Plasma-enhanced deposition has also been used to form thin fluorocarbon films with low surface energy,[13] but issues of conformal coating, coverage of inaccessible surfaces, and control of film properties remain unresolved.

Organic films directly bonded to silicon (without a surface oxide present) are also being explored with alkenes forming Si–C linkages to the surface[14] and amines forming Si–N linkages[15] emerging as candidates. The structure, performance, and stability of such organic films have yet to be thoroughly investigated.

The most sophisticated MEMS devices employ sliding contacts in rotary- or linear-motion devices. None have yet been commercialized, but they have great appeal because of the high functionality at low cost that can be achieved with gears, linear racks, rotating platforms, and pop-up mirrors.[1] In these devices, issues of friction and wear become important in addition to adhesion. Organic monolayer films are again the focus of efforts to develop lubricants for MEMS. These films have low friction coefficients, and their performance naturally depends on the chemical nature and/or structure of the films. For example, ODTS films show a lower initial friction coefficient than shorter-chain fluorinated FDTS films, presumably due to higher packing density and ordering of the hydrogenated alkyl groups.[16,17] The friction coefficient of organic film-modified surfaces increases after moderate periods of applied shear force, and the surfaces exhibit significant wear.[18,19] These observations suggest that organic monolayer films may not be robust enough to serve as lubricants in devices requiring extended sliding contact. Other hard coatings may be necessary to prevent extensive wear in sliding contacts. A self-limiting conformal CVD of tungsten on polysilicon to form a hard coating shows superb resistance to wear.[20]

To develop robust materials and processes for MEMS devices, *in situ* microtribology tools are needed to quantify properties of adhesion, friction, and wear on as-fabricated MEMS parts. Figure 1 shows a microtribological laboratory on a chip that is being developed at Sandia National Laboratories.[21] Test structures, metrology, and mechanics models are integrated to enable high-resolution mechanical and interfacial property measurement. Deflection of electrostatically loaded cantilevers, measured by interferometry (Figure 1a), can be compared to finite-difference models to determine Young's modulus to 5% accuracy.[22] Residual strain can be measured to $\sim 10^{-6}$ resolution and $\sim 10^{-5}$ accuracy with electrostatically loaded fixed–fixed beams (Figure 1b).[23] Cantilevers (Figure 1c) are simple but powerful structures to measure interfacial adhesion[24] and adhesion hysteresis,[11] lending themselves to studies of the interplay of adhesion with interfacial roughness, humidity, and coatings. For example, adhesion of hydrophilic surfaces increases exponentially with relative humidity. This observation can be explained by a single-asperity model.[25] Friction is being studied as a function of pressure and velocity by use of a cantilevered hinged-pad test structure (Figure 1d).[26,27] Although the properties of interest can be determined to high resolution, the test fixtures occupy only a small percentage of the wafer area. This is important because most of the available wafer area is dedicated to MEMS devices.

At the more fundamental level, the challenge to understanding the tribological properties of MEMS devices extends down the length scale from micrometers to angstroms. As seen in Figure 2, macroscopic contacts in MEMS devices are composed of a distribution of small-area contacts at nanometer-scale asperities. The characteristics of surface morphology and properties of single asperity contacts can be studied by techniques such as atomic force microscopy.[28,29] The characteristics of these nanometer-scale contacts are in turn strongly affected by the atomic-scale chemistry and physics of the surfaces and films coming into contact. Adhesion, friction, wear, and stability of surface films are dependent on molecular structure, end-group chemistry, molecular orientation, defects, and energy-dissipation mechanisms, which are not yet well understood.[30,31] Van der Waals forces between noncontacting portions of the surfaces also contribute strongly to adhesion.[11] Linking these length scales from the macroscopic to the atomic will be necessary in order to develop a fundamental understanding of the adhesion and friction values measured for MEMS devices.

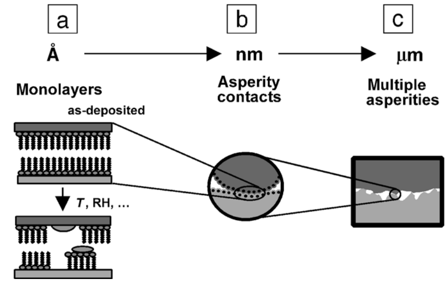

Figure 2. Length scales that must be linked to understand micromachine device performance include (a) as-deposited and potentially degraded coatings (angstrom scale), (b) local adhesion measurement (nanometer scale), and (c) asperity interaction influencing micromachine deflections (micrometer scale).

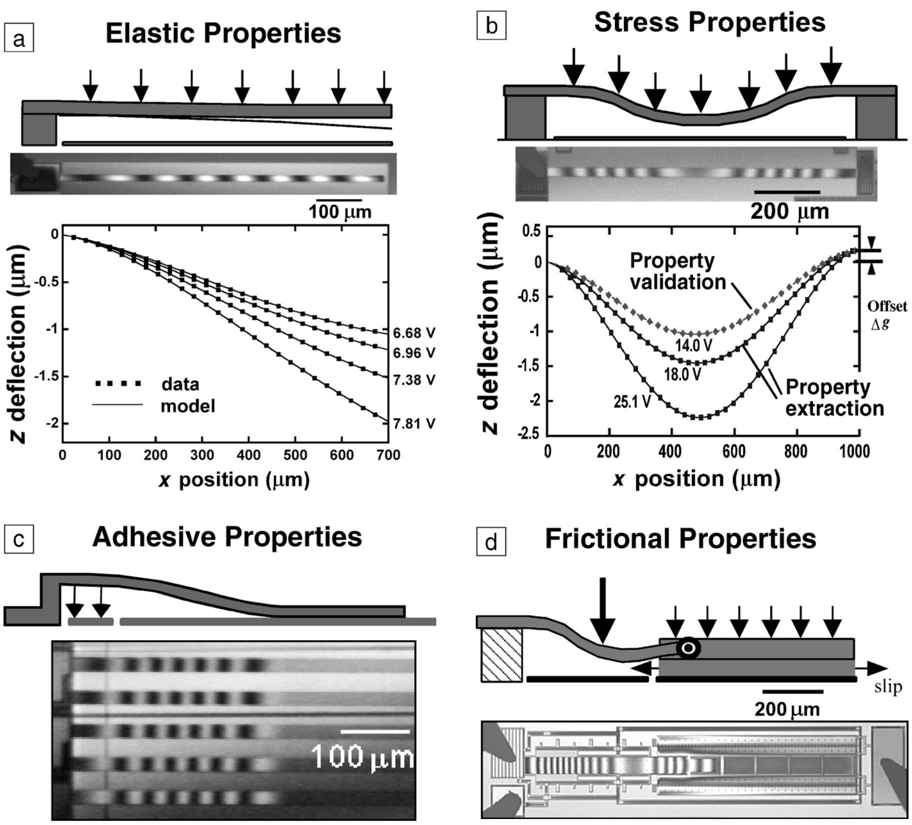

Figure 1. Microtribology laboratory on a chip. Integrated interferometry and finite element modeling in concert with optimized test structure design are used to determine thin-film and interfacial properties. See text for description of (a)–(d).

It is likely that no single technical approach will address all of the problems of process compatibility, charging, adhesion, friction, and wear, and their interactions with environmental factors. Therefore, a given MEMS application and packaging technology must be carefully considered in the context of which tribological issues need to be resolved. The fundamental study of tribological coatings through processing, surface characterization, and modeling will be necessary to bring a wider class of MEMS to the market.

Acknowledgment

Sandia National Laboratories is a multi-program laboratory operated by Sandia Corp., a Lockheed Martin company, for the U.S. Department of Energy under contract No. DE-AC04-94AL85000.

References

1. J.J. Sniegowski and M.P. de Boer, *Annu. Rev. Mater. Sci.* **30** (2000) p. 297.
2. C.H. Mastrangelo and C.H. Hsu, *IEEE/ASME J. MEMS* **2** (1993) p. 33.
3. G.T. Mulhern, D.S. Soane, and R.T. Howe, in *Proc. 7th Int. Conf. on Solid-State Sensors and Actuators (Transducers '93)* (IEEE Electron Devices Society, Yokohama, Japan, 1993) p. 296.
4. H. Guckel, D.W. Burns, C.C.G. Visser, H.A.C. Tilmans, and D. Deroo, *IEEE Trans. Electron Devices* **35** (1988) p. 800.
5. S.A. Henck, *Tribol. Lett.* **3** (1997) p. 239.
6. J.R. Martin and Y. Zhao, U.S. Patent No. 5,694,740 (1997).
7. R. Maboudian, *Surf. Sci. Rep.* **3** (1998) p. 209.
8. B.C. Bunker, R.W. Carpick, R. Assink, M.L. Thomas, M.G. Hankins, J.A. Voigt, D.L. Sipola, M.P. de Boer, and G.L. Gulley, *Langmuir* **16** (2001) p. 7742.
9. J.G. Kushmerick, M.G. Hankins, M.P. de Boer, P.J. Clews, R.W. Carpick, and B.C. Bunker, *Tribol. Lett.* **10** (1–2) (2000) p.103.
10. U. Srinivasan, M.R. Houston, R.T. Howe, and R. Maboudian, *IEEE/ASME J. MEMS* **7** (1998) p. 252.
11. M.P. de Boer, J.A. Knapp, T.A. Michalske, U. Srinivasan, and R. Maboudian, *Acta Mater.* **48** (2000) p. 4531.
12. T.M. Mayer, M.P. de Boer, N.D. Shinn, P.J. Clews, and T.A. Michalske, *J. Vac. Sci. Technol., B* **18** (2000) p. 2433.
13. B.K. Smith, J.J. Sniegowski, G. LaVigne, and C. Brown, *Sens. Actuators, A* **70** (1998) p. 159.
14. W.R. Ashurst, C. Yau, C. Carraro, R.T. Howe, and R. Maboudian, in *Proc. Solid-State Sensor and Actuator Workshop* (Transducers Research Foundation, Cleveland, 2000) p. 320.
15. X.-Y. Zhu, V. Boiadjiev, J.A. Mulder, R.P. Hsung, and R.C. Major, *Langmuir* **16**(2000) p. 6766.
16. V. DePalma and N. Tillman, *Langmuir* **5** (1989) p. 868.
17. J.D. Kiely, J.E. Houston, J.A. Mulder, R.P. Hsung, and X.-Y. Zhu, *Tribol. Lett.* **7** (1999) p. 103.
18. R.R. Rye, G.C. Nelson, and M.T. Dugger, *Langmuir* **13**(1997) p. 2965.
19. U. Srinivasan, J.D. Foster, U. Habib, R.T. Howe, R. Maboudian, D.C. Senft, and M.T. Dugger, *Proc. Solid-State Sensor and Actuator Workshop* (Transducers Research Foundation, Cleveland, 2000) p. 156.
20. S.S. Mani, J.G. Fleming, J.J. Sniegowski, M.P. de Boer, L.W. Irwin, J.A. Walraven, D.M. Tanner, and D.A. La Van, in *Materials Science of Microelectromechanical Systems (MEMS) Devices II,* edited by M.P. de Boer, A.H. Heuer, S.J. Jacobs, and E. Peeters (Mater. Res. Soc. Symp. Proc. **605**, Warrendale, PA, 2000) p. 135.
21. M.P. de Boer, N.F. Smith, N.D. Masters, M.B. Sinclair, and E.J. Pryputniewicz, in *ASTM STP 1413* (2001) in press.
22. B.D. Jensen, M.P. de Boer, N.D. Masters, F. Bitsie, and D.A. La Van, *IEEE/ASME J. MEMS* (2001) in press.
23. B.D. Jensen, M.P. de Boer, and F. Bitsie, in *Proc. SPIE Materials and Device Characterization in Micromachining,* Vol. 3875, edited by Y. Vladimirsky and C.R. Friedrich (SPIE—The International Society for Optical Engineering, Bellingham, WA, 1999) p. 61.
24. M.P. de Boer and T.A. Michalske, *J. Appl. Phys.* **86** (1999) p. 817.
25. M.P. de Boer, P.J. Clews, B.K. Smith, and T.A. Michalske, in *Microelectromechanical Structures for Materials Research,* edited by S. Brown, J. Gilbert, H. Guckel, R. Howe, G. Johnson, P. Krulevitch, and C. Muhlstein (Mater. Res. Soc. Symp. Proc. **518**, Warrendale, PA, 1998) p. 131.
26. M.P. de Boer, J.M. Redmond, and T.A. Michalske, in *Proc. SPIE Materials and Device Characterization in Micromachining,* Vol. 3512 (SPIE—The International Society for Optical Engineering, Bellingham, WA, 1998) p. 241.
27. B.T. Crozier, M.P. de Boer, J.M. Redmond, D.F. Bahr, and T.A. Michalske, in *Materials Science of Microelectromechanical Systems (MEMS) Devices II,* edited by M.P. de Boer, A.H. Heuer, S.J. Jacobs, and E. Peeters (Mater. Res. Soc. Symp. Proc. **605**, Warrendale, PA, 2000) p. 129 .
28. R.W. Carpick and M. Salmeron, *Chem. Rev.* **97** (1997) p. 1163.
29. M. Salmeron, *CHEMTECH* (September 1998) p. 17.
30. E. Barrena, S. Kopta, D.F. Ogletree, D.H. Charych, and M. Salmeron, *Phys. Rev. Lett.* **82** (1999) p. 2880.
31. H.I. Kim, M. Graupe, O. Oloba, T. Koini, S. Imaduddin, T.R. Lee, and S.S. Perry, *Langmuir* **15** (1999) p. 3179. □

MRS FALL 2001

NOVEMBER 26 - 30

BOSTON • MA

Exhibit and research tools seminars

For additional meeting information, visit the MRS Web site at

www.mrs.org/meetings/

or contact:

MRS

Member Services
Materials Research Society

506 Keystone Drive
Warrendale, PA 15086-7573
Tel 724-779-3003
Fax 724-779-8313
E-mail: info@mrs.org

Abstract Deadlines — In fairness to all potential authors, late abstracts will not be accepted.

June 5, 2001: for abstracts sent via fax or mail ◆ **June 19, 2001:** for abstracts sent via the MRS Web site

2001 MRS FALL MEETING

www.mrs.org/meetings/fall2001/

New
- *Materials Development*
- *Characterization Methods*
- *Process Technology*

SYMPOSIA

Inorganic Electronic Materials and Devices
A: Materials Issues in Novel Si-Based Technology
B: Materials Science of Microelectromechanical Systems (MEMS) Devices IV
C: Ferroelectric Thin Films X
D: Polarization Dynamics in Ferroic Materials
E: Materials for High-Temperature Superconductor Technologies
F: Spintronics
G: Thermoelectric Materials 2001—Research and Applications

Photonic/Optoelectronic Materials and Devices
H: Progress in Semiconductor Materials for Optoelectronic Applications
I: GaN and Related Alloys
J: Materials Engineering for Solid-State Lighting
K: Microphotonics–Materials, Physics, and Applications

Thin Films and Surfaces
L: Thin Films–Stresses and Mechanical Properties IX
M: Surface Science and Thin-Film Growth in Electrolytes
N: Current Issues in Heteroepitaxial Growth—Stress Relaxation and Self Assembly
O: Complex Oxide Heteroepitaxy
P: Advances in Surface Engineering—Fundamentals and Applications

Materials Science, Processing, and Evaluation
Q: Rapid Prototyping Technologies—Tissue Engineering to Conformal Electronics
R: Electrically Based Microstructural Characterization III
S: Combinatorial and Artificial Intelligence Methods in Materials Science
T: Statistical Mechanical Modeling in Materials Research
U: Advanced Fibers, Plastics, Laminates, and Composites

Nanoscale Materials and Processes
V: Nanophase and Nanocomposite Materials IV
W: Nanoparticulate Materials
Y: Nanopatterning—From Ultralarge-Scale Integration to Biotechnology
Z: Making Functional Materials with Nanotubes
AA: Self-Assembly Processes in Materials

Organic/Biological Materials and Devices
BB: Organic Optoelectronic Materials, Processing, and Devices
CC: Advances in Liquid Crystalline Materials and Technologies
DD: Polymer Interfaces and Thin Films
EE: Electroactive Polymers and Their Applications as Actuators, Sensors, and Artificial Muscles
FF: Physical Characterization of Biological Materials and Systems
GG: Polymeric Biomaterials for Tissue Engineering
HH: Bio-Inspired Materials—Moving Towards Complexity

Materials and Society
II: Materials Issues in Art and Archaeology VI
JJ: Scientific Basis for Nuclear Waste Management XXV
KK: Design, Characteristics, and Properties of Cementitious Materials
X: Frontiers of Materials Research

MEETING ACTIVITIES

Symposium Tutorial Program

Available only to meeting registrants, the symposium tutorials will concentrate on new, rapidly breaking areas of research.

Exhibit and Research Tools Seminars

Over 225 international exhibitors will diplay a full spectrum of equipment, instrumentation, products, software, publications, and services. Research Tools Seminars, an educational seminar series that focuses on the scientific basis and practical application of commercially available, state-of-the-art tools, will be held again this fall.

Publications Desk

A full display of over 700 books, plus videotapes and electronic databases, will be available at the MRS Publications Desk.

Symposium Assistant Opportunities

Graduate students planning to attend the 2001 MRS Fall Meeting are encouraged to apply for a Symposium Assistant (audio-visual assistant) position.

Employment Center

An Employment Center for MRS meeting attendees will be open Tuesday through Thursday.

01-0024

The 2001 MRS Fall Meeting will serve as a key forum for discussion of interdisciplinary leading-edge materials research from around the world. Various meeting formats—oral, poster, round-table, forum and workshop sessions—are offered to maximize participation.