Tribology Concerns in MEMS devices: The Materials and Fabrication Techniques Used to Reduce Them

Final Project
ME381: Introduction to MEMS

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ABSTRACT:

Microelectromechanical systems (MEMS) is an emerging technology with successful applications in areas such as automotive industry and space exploration. Increasing the performance of current devices in the areas of functionality, reliability, strength, device life, and safety will allow MEMS to continue to grow as practical solutions to real problems. Microactuator performance is greatly influenced by the tribological contact of moving parts with other moving or fixed parts. This contact affects the microactuator performance, and a characterization of the tribological properties of friction, adhesion, and wear has been developed to understand how.

Scaling friction to the microscale will have a significant impact on the physics used to design devices. Additionally, scaling the effects of the thermal environment and atmospheric environment on the device during operation is noteworthy. Since adhesion, abrasion, corrosion, surface fatigue, deformation, impact, and fretting wear are the primary failure mechanisms of macroscopic mechanical systems, it can be expected that a specific combination of these mechanisms or new mechanisms will be the dominant wear-out mechanism in MEMS devices.

The close proximity of parts as they wear each other can cause for particulates to break off and further damage the device, which in many cases leads to failure. The characterization of the tribological properties of friction, adhesion, and wear, on the microscale has given engineers and scientists the knowledge to develop strategies to mitigate the undesirable effects of component contact. Two prominent techniques include developing new thin films to be deposited on the contact surfaces of devices and fabricating entire devices with new materials.

To decrease the ability for a MEMS device to fail in these manners, numerous different techniques and materials were been evaluated to strengthen the devices, relieve stiction and lubricate the components. Some common techniques are to design devices with high modulus materials grown at the surface in high worn areas, use materials that lower friction coefficients and coat the silicon based device with organic films to act as a lubricant for the rigid device characteristics.

Some materials that have been used for the strengthening of the device are titanium based structures like titanium carbide and titanium nitride, tungsten films, and diamond. Diamond coatings for instance have been found to reduce coefficients of friction by greater than twenty percent. Since these materials help to reduce unwanted characteristics they are being utilized for fabrication of the device, instead of just relying on slower post-fabrication methods.

One of the most common post-fabrication steps is to deposit organic films and more specifically self-assembled monolayers (SAMs). These layers are a nanometer or two in thickness and can be deposited from liquid phase onto silicon and silicon dioxide surfaces. These layers help to reduce the adhesion between metallic materials, can act as a dielectric to remove the concern of ohmic contact, and can act as a lubricant to keep the rigid materials from rubbing against one another.

Not all of the developments of tribology in MEMS field are directly related to materials breakthroughs. Methods for chemically and mechanically polishing MEMS have been developed, bringing the macro-scale concept of manipulating the surface finish to achieve lower friction to the micro-scale. However, materials research for the fabrication of micro-devices appears to be the logical step for the advancement of MEMS.
1. INTRODUCTION

Microelectromechanical Systems (MEMS) is a broad class of technologies that is being applied to a diverse mix of fields with great success. As MEMS solutions to practical problems continue to grow, the demand for improved functionality, reliability, strength, device life, and safety will increase. MEMS can be broadly divided into sensors and actuators. Actuator design is greatly affected by tribological considerations since contact occurs between two moving parts or a moving and fixed part. A typical challenge when working at the microscale is that intuition gained from studying the macroscale will be of little use to microactuator designers. There has been significant research in the area of microtribology and its application to MEMS actuators. This paper will present the issues of microtribology, which include for MEMS actuators, adhesion, friction and wear, and the solutions to these problems.

A development of microtribology is presented by investigating surface and interfacial forces. Adhesion and friction will be discussed with not only an emphasis on theory, but also a look at experimental tools used to measure these properties in the laboratory, and an explanation of wear in MEMS actuators will follow.

Since failure of MEMS devices is dependent on the tribology of the structures in the system. To decrease the occurrences of failures from these means, materials considerations are described that reduce the adhesion and friction to the system structures. This helps to decrease the wear and asperity formation at the surfaces in the devices. There are two ways that materials can be utilized in this manner. One is to use new materials in the fabrication steps that are tough and resilient, whereby helping to prevent material failure. There are many materials that fall into this category, such as diamond like carbon (DLC), tungsten and titanium carbide. The second way is to coat the silicon based structures with organic molecules that act as a barrier between the structures and help to create a lubricating layer so that the structures don’t wear away as quickly. The most typical organic layer is a self assembled monolayer (SAM) that covalently bonds to the silicon. These new materials will help to correct many of the MEMS failure issues and produce more applications for them.
2. MATERIAL SURFACE MORPHOLOGY

Background
The human finger is an excellent tactile sensor. Humans can distinguish between smooth surfaces, like porcelain, and rough surfaces, like sandpaper. This distinction is only a matter of relative roughness, as there is no truly smooth surface. Examining any surface on increasingly smaller length scales reveals that the surface comprises of a series of hills and valleys. These hills are called asperities and not only vary in both lateral size and height, but also are randomly distributed along the surface. A typical surface roughness profile is shown in Figure 1. This random distribution can arise from a variety of circumstances including a fracture of a solid into two surfaces or several microfabrication techniques such as thin film deposition. Since the asperities are contact spots when two surfaces contact each other, a determination of the probabilistic distribution of asperities is important in understanding the contact mechanics and ultimately the friction and wear properties of the two surfaces.

Figure 1: A typical surface roughness profile.

Morphology of Polysilicon
The surface morphology of a polysilicon MEMS gear was analyzed using atomic force microscopy (AFM). It was discovered that the polysilicon surface consisted of a high density of cylindrical caps on a relatively flat surface. The diameter and maximum height of these cylindrical caps was 200nm and 10nm respectively. The 3D island morphology of the gear is shown in Figure 2. These cylindrical caps are the asperities of the gear surface. If this surface came into contact with another surface, the contact forces would act on these cylindrical caps.

Figure 2: An AFM image of the polysilicon gear.
3. TRIBOLOGY ON THE MICROSCALE

**Background**
There are various tribological forces that act on the contact spots of surfaces. While inertial forces are the dominant contact forces in macroscale surfaces, other forces are the dominant contact forces in microscale surfaces. As the surface area to volume ratio increases, inertial forces become less dominant. From scaling, it is known that interfacial forces scale linearly with a characteristic length whereas the gravitational force scales at best cubically with the characteristic length. Given that most MEMS actuators operate with lightly loaded components on at most the micronewton range, interfacial forces are dominant on the microscale. Interfacial force dominance on the microscale influences both adhesion and friction properties of MEMS. Interfacial forces that cause these effects include capillary forces, electrostatic forces, and Van der Waals forces.

3.1 Interfacial Forces

**Capillary Forces**
The capillary force is an attractive force that arises from the Laplace pressure of curved menisci on two surfaces. The menisci form as a result of condensation of vapor in the environment of the surfaces. The capillary condensation of some liquids, most notably water, on surfaces also gives rise to added effects on the contact zone. If the surfaces contain ions, then these ions will diffuse in the liquid. As the ions build up in this liquid bridge, the chemical composition of the surfaces changes within the contact zone.

In a moderately humid environment, the capillary force is generally the strongest interfacial force in MEMS. Oxidized silicon surfaces are hydrophilic and can adsorb several monolayers of water which promotes meniscus formation. The water that is adsorbed on the surface may be from the ambient air or may be introduced to the surface during microfabrication. For example, water rinsing the MEMS devices during fabrication can introduce water on the surface.

**Electrostatic Forces**
Electrostatic forces arise when two surfaces acquire a charge. A surface charge can be acquired in a variety of situations. For example, a RF MEMS switch relies on electrostatic forces to actuate the switching element which consists of a metallic membrane to contact an electrode anchored to the substrate. During the operating cycle of the device, charge may tunnel through the dielectric and become trapped. These trapped charges develop a surface charge. A surface charge can also be acquired in conjunction with capillary condensation. As the ions build up in the liquid bridge, a change occurs in surface charge giving rise to an electrostatic force.

**Van der Waals Forces**
Van der Waals forces are currently the most well understood interfacial force on the microscale and can be accurately calculated and measured. Van der Waals forces are attractive, long-range forces that act in all environments including vacuum. Van der Waals forces encompass three types of intermolecular forces; the dipole-dipole force, the dispersion force, and the hydrogen-bonding force. Each of these forces exists between neutral molecules. These forces are characterized by the development of a charge distribution over a neutral molecule. The induced
dipoles of the molecules will seek a favorable orientation in accordance with electrostatic principles. Van der Waals forces are of interest in considering interfacial forces in MEMS because neutral molecules of two close surfaces of a MEMS device will exhibit this type of attractive force.

3.2 Adhesion

**Background**
MEMS often operate by intersurface contact; for example, RF MEMS switches operate with a metallic membrane contacting an electrode anchored to the substrate. When two MEMS surfaces contact and the restoring force of the device cannot separate them, adhesion has taken place. Adhesion of MEMS surfaces is often termed stiction. Adhesion is a result of the interfacial force dominance on the microscale. Since adhesion is an important tribological consideration, techniques have been developed to measure adhesion on the microscale, and some environmental conditions have been shown to affect adhesion.

**Adhesion Measurement**
The work of adhesion (mJ/m²) is the common quantitative measurement of the magnitude of adhesion. The work of adhesion is defined to be the free energy change to separate unit areas of two surfaces from contact to infinity. Both in-plane and sidewall adhesion occurs in MEMS actuators. Even though in-plane and sidewall adhesion are different due to surface differences, similar techniques are used to measure both types of adhesion. The most widely used in-plane adhesion measurement device is the cantilever beam array (CBA) shown in Figure 3.

![Figure 3: The cantilever beam array. An orthogonal projection and cross section view with key components labeled.](image)

The CBA consists of a series of cantilever beams of different lengths. These beams are arranged in parallel and are all anchored to the substrate at a common length from an edge of the substrate. An electrostatic force is applied to the CBA so that all of the beams contact the substrate. After the electrostatic force is removed from the CBA, the stored elastic energy in the beams will attempt to separate the beams from the substrate. As a beam is prying from the surface, a crack will propagate under the beam up to some length called the detachment length. While beams shorter than the detachment length have enough energy to completely separate from the substrate, beams longer than the detachment length do not have enough energy to separate and will remain adhered substrate. There is an intermediate beam length where only the tip of the beam will remain adhered to the substrate. Using strength of materials relations, this balance of elastic energy and electrostatic energy can be used to calculate the work of adhesion.
**Environmental Effects on Adhesion**

Both humidity and surface roughness can affect the magnitude of adhesion. As discussed earlier, surface roughness can be influenced by a variety of microfabrication techniques. As surface roughness increases, the number of asperities increases leading to an increase of small gap openings in the surface. This type of coarse topography facilitates meniscus formation. Humidity increases also facilitate meniscus formation. This is because as humidity increases, more water is present in the environment, which can then condense on a surface. These environmental effects on adhesion are shown in Figure 4.²

![Figure 4: The environmental effects of surface roughness and increased humidity influence the adhesion of two surfaces. ²](image)

It has been reported that the work of adhesion values for oxidized polysilicon surfaces vary from approximately 1-100 mJ/m². The influence of humidity on adhesion was verified using the CBA on an oxidized polysilicon surface. At 50% relative humidity (RH) the work of adhesion was 10 mJ/m² and at 99% RH the work of adhesion increased to 140 mJ/m². This value is significant, as it is twice the surface tension of water.²

3.3 Friction

**Background**

Many theories and models have been presented to explain and predict friction. These theories and models may precisely explain frictional effects on one length scale but then give erroneous results as the length scale changes. Currently, there is no one theory or model of friction that applies to every length scale.¹

Perhaps the oldest theory of friction is Amonton’s Law, which states the friction force is proportional to the contact load force. The familiar proportionality constant is the coefficient of friction (COF). Consider two surfaces of substantial roughness in contact by means of a load force shown in Figure 5, where the contact spots of the two surfaces consist of many asperities. As the load force increases, the asperities will reach their yield stress and begin to plastically deform. The contact area is then a ratio of the load force and the yield stress. This current analysis only considers static contact between the two surfaces. When relative motion between the two surfaces is allowed, a friction force opposes the relative motion. This friction force is comprised of two parts, a plowing term and a shearing term. The plowing term accounts for the asperities of the harder surface plowing along the asperities of the softer surface and the shearing term accounts for the shearing at the contact spots. Based on Amonton’s Law, the COF is understood to be the ratio of the shear strength of the contact spots and the yield stress of the asperities¹. While this seems like a simple expression for friction, what is often complicated is determining the shear strength of the contact points and the yield stress of the asperities.
Additional problems exist when studying friction on the microscale. In MEMS devices, surfaces are often difficult to characterize. Surface non-uniformity is a chief contributor to this difficulty. Some microfabrication process techniques lead to non-uniform surfaces. For example, some thin film deposition techniques, such as electron beam deposition, suffer from shadowing which leads to non-uniform thin films on the substrate. Surface non-uniformity leads to COFs taking on a range of values for a given surface. Interfacial force dominance also adds difficulty to studying friction on the microscale. At the microscale, the load force is not the only force acting on the contact zone. The adhesion force is also significantly contributing to the mechanics of the contact zone. In fact, adhesion becomes so dominant in some circumstances that Amonton’s Law falls apart as the experimental COF has been determined to be greater than one. As microfriction can be difficult to predict, several devices have been created that allow investigators to measure both in-plane and sidewall friction.

**In-plane Friction Measurement**

Sandia National Laboratories created the nanotractor to measure in-plane friction shown in Figure 6. The nanotractor operates in a similar way to an inchworm. The nanotractor is anchored to the substrate but relative motion can occur between the device substrate. To achieve relative motion, a large voltage is applied to the leading clamp to fix it in place. Then a voltage is applied to bend the actuation plate toward the substrate. As the actuation plate bends, the free trailing clamp slides some distance. After the trailing clamp has stopped sliding, a large voltage is applied to the trailing clamp to fix it in place. The voltage is then removed from the actuation plate and the leading clamp. The elastic energy stored in the non-linear load spring is released and the nanotractor slides some distance. This actuation cycle is repeated to obtain relative motion. The COF is measured by varying the actuating voltages of the clamps. Using this device it was discovered that the frictional force depends on the load force for load forces of 1 millinewton to 50 micronewtons. As the load force decreased, interfacial forces dominated the contact zone. Amonton’s Law failed as the COF increased.
Sidewall Friction Measurement
Sandia National Laboratories has created a device that measures sidewall friction shown in Figures 7 and 8. The sidewall friction device consists of two comb actuators that are oriented perpendicularly to one another on the substrate and connected by a movable beam. A post is also patterned and created on the substrate that lies near the beam. One comb is actuated with a DC voltage to bring the movable beam in sidewall contact with the post. The other comb is actuated with an AC voltage. This AC voltage causes the beam to slide against the post.

Figure 6: The nanotractor consisting of a load spring, leading clamp, trailing clamp, and actuation plate, measures in-plane static and dynamic friction.

Figure 7: The sidewall friction device consisting of two comb actuators connected to a moveable beam.

Figure 8: A SEM image of the beam and post in the sidewall friction device.
3.4 Wear

**Background**
Wear is caused by the relative motion of two contacting surfaces. As the surfaces move relative to one another, particles from one surface are either transferred to the other surface or the particles are transferred to the environment of the two surfaces. Wear is encountered every day on the macroscale and may not always be unproductive. For example, while bald tires can be considered unproductive wear, writing with a pencil can be considered productive wear. Wear in MEMS actuators is generally unproductive. Particle transfer from one surface to the other surface or transfer to the contact environment generally leads to lower device life.

Investigators at Sandia National Laboratories have done significant work in understanding the wear of MEMS actuators. Using a microengine, also designed at Sandia, these investigators were able to observe and characterize the wear in the device. Additionally, environmental conditions that affected wear in the microengine were observed.

3.4.1 Sandia’s Microengine

**Device Description**
The microengine, shown in figure 9 and designed at Sandia, uses two orthogonal comb drives very similar to the sidewall friction device (Figure 7). The two orthogonal comb drives are connected by a rod that takes on a variety of embodiments that is connected to a drive gear. The comb drives are electrostatically actuated and the elastic energy stored in the device can return the combs back to their original position. The actuation force/restoring force cycle causes the drive gear to rotate around a stationary load gear.

![Figure 9: The microengine consisting of two orthogonal comb drives, a drive gear, and a load gear. The comb drive is expanded to further detail its design and the mesh of the drive gear and load gear.](image)

**Wear Observation**
Significant wear was observed in the microengine as it was driven at cycles above the devices resonant frequency. At the end of the cycle interval, the microengine was slowed to an inspection frequency and examined. A failure was defined as the inability of the drive gear to make one complete revolution around the load gear at the inspection frequency. Throughout the
tests, the failures of the microengine were all caused by wear of various parts of the device. The failures observed either involved sticking of various moving parts and resultant locking of the microengine, or a rocking motion of the drive gear about the load gear through a small angle. The wear debris was identified as only amorphous oxidized silicon, no polysilicon comprised any portion of the wear debris. Wear of the microengine gear is shown in Figure 10.

Figure 10: Wear debris of the driver gear connected to connecting rod tested to failure.

Wear Mechanisms
Two wear mechanism models were developed in order to model the wear of the microengine on an analytical level. These two models make a distinction between the contact forces between surfaces. When the models were fit towards the experimental data, the result showed one model to be dominant; however, it was further thought the two mechanisms cooperate in the wear of the microengine.

For contact forces leading to low contact pressure effects, the adhesive wear mechanism is active. In adhesive wear, as two surfaces move relative to one another, the asperities of one surface cold weld to the asperities of the other surface. This cold welding is a result of the plastic deformation of the asperities leading to the plastic flow of the asperities. As the relative motion of the two surfaces continues, the cold weld breaks and an augmented asperity is formed, consisting of the original asperities of both of the two surfaces. The augmented asperity may remain part of one surface or may become totally liberated from both surfaces and become a loose particle. The adhesive wear model is shown in Figure 12. Notice that this model accounts for both intersurface particle transfer and particle transfer to the contact environment.
Figure 12: Adhesive wear mechanism. (i) Two surfaces contacting at asperities due to a contact force (ii) during relative motion of the two surfaces, asperities of the two surfaces cold welding together and (iii) the cold weld breaking and developing augmented asperities on the upper surface. Note: alternatively, one or both of the augmented asperities could have been totally liberated as a loose particle in the contact environment.

For contact forces leading to high contact pressure effects, the abrasive wear mechanism is active. In abrasive wear, shown in figure 13, a hard asperity gouges or plows another contacting surface. As the gouging or plowing occurs over time, wear tracks result. There are two types of abrasive wear. In two-body wear, the hard asperity causes wear tracks in a contacting surface. In three-body wear, a hard asperity is free from both surfaces. When the loose asperity becomes trapped between the two contacting surfaces it will cause wear tracks on either contacting surface. From micromachining, it is known that as a cut is made into a surface, the particles are removed from the softer surface as a wear track develops chips, which is ignored in the abrasive wear mechanism presented.

Figure 13: Abrasive wear mechanism. A hard, loose asperity plows through a contacting surface. Not shown is the chip formed from the cutting action of the asperity.

As mentioned previously, when the two models were fit to experimental data it was found that while the adhesive model fit the data well, the abrasive model fit the data poorly. This was a surprise because wear tracks were observed in failed micro engines. From this result, it was further thought that the two models cooperate to wear the microengine. A combination of the
two mechanisms would provide for augmented asperities where some remain with one contact surface and some become free from both surfaces. Augmented asperities that remained on one contact surface would contribute to two-body wear, whereas augmented asperities that were free from both surfaces would contribute to three-body wear.9

Environmental Effects on Wear

Some environmental effects have been observed to influence the wear of MEMS actuators. Since interfacial force dominance affects both adhesion and friction on the microscale and wear is related to both adhesion and friction, it is expected that environmental affects that influence interfacial forces, adhesion, and friction will also influence wear.

Thermal cycling was determined to have no influence on wear of the microengine.8 As humidity has been presented to influence interfacial forces and adhesion, humidity also plays a major role on the wear of the microengine. Humidity affected both the volume of wear debris and the morphology of the wear debris. As humidity increases, the volume of the wear debris decreases. This can be explained by considering that the humidity promotes the formation of surface hydroxides that act as a lubricant. Additionally, while the wear debris is elongate and stringy in high humidity, the wear debris in low humidity consists of more individual particles. This can be explained by considering the humidity to promote the agglomeration of augmented asperities as they separate from the contact surfaces.8 The benefit of increasing humidity can only be realized to a finite limit because at a certain humidity level adhesion is too strong and the device would fail through stiction.

The role of humidity was further explored in wear studies conducted by another investigator with another actuator.10 The distinction between wear in vacuum and dry further showed environmental effects on wear. In a dry-air environment, the wear debris was a small agglomeration of particles. In a vacuum, the wear debris was determined to be pulled-out grains from the surface. Even though humidity was not present in the dry-air environment, wear mitigation was observed. As relative motion between the two surfaces occurs, some of the worn surface is exposed to the oxygen in the environment. In oxidizing the worn surface, the oxygen in the environment promotes healing of the surface or passivation to occur.10
4. HARD MATERIALS FOR FABRICATION

Background
Due to all of the tribological problems discussed, new materials are being chosen with high elastic and shear modulus to reduce the amount of friction that occurs. Some materials that have been used are titanium based structures like titanium carbide and titanium nitride, tungsten films, and diamond. These materials can be deposited through different methods of chemical vapor deposition with reactive gas; and atomic layer deposition (ALD), which provides an even covering in the range of tens of nanometers. Tungsten proves a useful candidate due to its high selectivity of growth locations to deposit coatings on the surface of silicon. This helps to shield the silicon from actions that would plastically deform and damage the surface. Diamond coatings have been found to reduce coefficients of friction by greater than twenty percent, and its properties and fabrication will be discussed further. Titanium carbide has also shown proven ability to reduce wear. With these multiple materials helping to reduce unwanted characteristics they are being utilized during the fabrication of the device.

4.1 Diamond

Characteristics of Diamond
Diamond is the hardest allotrope of carbon and serves as one of the best candidates for decreasing friction and wear in MEMS. Since carbon’s other common, naturally occurring allotropes, namely graphite and amorphous carbon (i.e. coal), are significantly soft, the crystal orientation is the cause for diamond’s extreme hardness. The carbon atoms are covalently bonded, forming a tetrahedron, which creates an isotropic, hard crystal. Graphite, which has a sheet structure, is anisotropic and the sheet shearing creates its “soft” structure. For MEMS non-natural diamonds (diamond-like materials) are fabricated with similar hardness to natural diamond, however there is some amount of impurity (i.e. nitrogen or hydrogen) is the structure.

Figure 14: An example of a 3-D diamond crystal. The red lines show the carbon-carbon covalent bonds.
Diamond is not only extremely hard, but chemically inert and thermally and electrically stable. As discussed earlier, limitations have been reached in the field of MEMS because of the shortcomings of silicon. Silicon is the dominant material in MEMS, due to the extensive knowledge of fabrication techniques that evolved from the microelectronics industry. However, silicon does not match the mechanical and tribological properties of diamond. Because MEMS devices are designed with quickly moving parts (rotating, translating, etc.), silicon’s material properties are a major cause of system failure. For this reason, materials such as diamond are more suitable for wear resistant MEMS devices. Also, like silicon, diamond-like carbon (DLC) can be doped. For example DLC doped with a significant amount of boron will behave as a semiconductor.\(^\text{12}\)

<table>
<thead>
<tr>
<th>Property</th>
<th>Silicon</th>
<th>Silicon carbide</th>
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<td>5.3</td>
</tr>
<tr>
<td>Flexural strength (MPa)</td>
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<td>670</td>
<td>2944</td>
</tr>
</tbody>
</table>

Table 1: A material properties comparison of silicon, silicon carbide and diamond to show the mechanical benefits of diamond.\(^\text{12}\)

**Coatings Processes**

Like many other materials utilized at the micro-and nano-scale, diamond must be deposited in a manner consistent with MEMS microfabrication. There are many methods for depositing diamond-like films on silicon; Plasma Enhanced Chemical Vapor Deposition (PECVD) is a highly common method for generating DLC (diamond-like carbon) layers on MEMS devices. For this process, a plasma is made from mixtures of methane, hydrogen and other gases and is induced by a radio frequency (RF) source with a power of 150W at 13.56 MHz. As dissociation of the methane occurs (Equation 1 & 2), DLC films begin to nucleate and grow on the silicon surface.\(^\text{13}\)

\[
2\text{CH}_4 \rightarrow \text{C}_2\text{H}_2 + 3\text{H}_2 \quad \text{(Equation 1)}
\]

\[
\text{C}_2\text{H}_2 \rightarrow \text{C}_2 + \text{H}_2 \quad \text{(Equation 2)}
\]

![Figure 15: DLC film deposition rate (nm/min) as a function of CH4 percentage of total gas flow.\(^\text{13}\)](image)
Diamond-like carbon, while offering significantly better tribological properties than silicon, is still not an ideal candidate for wear and friction reduction in MEMS. Frequently, DLC coatings exhibit large amounts of internal stress, poor adhesion between crystal grains, large grain sizes, and most importantly, poor surface finishes, a particularly problematic characteristic for a material intended to reduce friction and wear in moving systems. Krauss et al., present a microwave plasma method for depositing more “diamond-like” DLC, called ultrananocrystalline diamond (UNCD). The “ultranano” prefix describes the grain size of the diamond crystals, which is between 2nm and 5nm. Traditional DLC films contain random growth which made accurate measurement of grain size difficult. The UNCD process (microwave CVD, 12.56 GHz, 100 torr) focuses on ensuring that the methane fully dissociates in plasma consisting of a mixture of methane and argon. If hydrogen doesn’t dissociate from the carbon, it cannot become part of the depositing diamond lattice. Since hydrogen is present in large quantities after dissociation, C₆₀ gas is introduced within the Ar plasma, to create extra carbon dimers (C₂), which is the building block of the diamond lattice.

The ultra-small grain size created by UNCD allows for a surface finish, more than ten times smoother than films produced from traditional methods as shown in figure 17. Not only are the UNCD peaks considerably smaller, they are also blunt. This helps reduce wear, and friction since asperities are rounded and interlock less easily.

The UNCD process has more benefits than just depositing more tribologically beneficial diamond crystals. A common problem with traditional PECVD methods for depositing diamond is that the resultant films are frequently discontinuous and have a varying density, as shown in figure 18. Naturally, a coating that is not completely conformal will produce tribological problems, as uncoated sections will have physical and material properties (i.e. coefficient of
friction, hardness, wear resistance, etc.) more than an order of magnitude different from the diamond coating. \(^\text{12}\)

**Figure 18:** (a) Conventional CVD diamond coating on three Silicon “microwhiskers.” (b) UNCD coating on one Si “microwhisker”. \(^\text{12}\)

UNCD films are also practically free from residual stresses. The film can be removed from its substrate (usually the Si substrate is etched away with KOH), and it will remain flat, instead of bending as soon as it is freed from the substrate, as a film with internal stress would exhibit. Diamond films created by the conventional methods are unsuitable for free-standing structures because of significant internal stresses. \(^\text{12}\)

**Figure 19:** Microturbines created by depositing UNCD on a silicon substrate, which was etched using KOH. The unsupported turbine “wings” do not bend after substrate removal. \(^\text{12}\)

Disregarding cost, given a choice between conventionally-produced diamond and ultrananocrystalline diamond, UNCD is the obvious choice. The pure diamond offers a twenty-three-fold increase in brittle fracture strength compared to silicon and a projected wear life ten thousand times greater than silicon. \(^\text{13}\) The more diamond-like the carbon is deposited the more beneficial it will be.
5. COATING WITH SELF ASSEMBLED MONOLAYERS

Structure and Formation
To help to lower the wear that occurs in MEMS devices silicon based materials may also be coated with organics that act as a barrier layer for the silicon structure. These organic layers are usually self assembled monolayers (SAMs) and have numerous different structures and chain lengths. There are two more general structures, silane SAMs, which covalently bond to silicon and thiol SAMs, which bond to gold.

SAMs are deposited on the substrate surface through means of liquid deposition. The SAM is mixed with an organic solvent, which helps to disperse the molecules. As a molecule comes in contact with the silicon surface it reacts with the thin layer of water that coats the surface. This reaction causes for the alkylsilane group or the halide silane group to decompose and form silicon hydroxide bonds. This chemical structure then breaks up to attach the SAM molecule to the surface of the silicon through Si-O bonds that mask the surface or any silicon structure, as shown in figure 20. This bonding structure forms a two dimensional network that coats the surface with a monolayer that can either be a densely packed or amorphous structure. This structuring is based on how long the SAM molecule is and the components that are present in its backbone. Components that align will form densely pack structures, while those that have extenuated bond angles will form amorphous structures.

![Figure 20: Deposition of a chlorosilane onto a silicon surface.](image)

Interstitial Layers for Deposition
SAM layers may be used as a bonding layer that helps to coat silicon with a ceramic layer. To attach subsequent layers, a SAM is chosen such that the cover layer has a greater priority to grow on that surface than on top of the silicon surface. One common SAM for this fabrication is 3-mercaptopropyl trimethoxysilane, which has a –SH terminus group. This –SH group can then be oxidized into a –SO$_3$H group, which creates a substrate for the chemisorption of zirconium sulfate, which undergoes enhanced hydrolysis in the presence of HCl, or yttrium nitrate, which undergoes the same process in the presence of urea. The enhanced hydrolysis allows for the deposition of ZrO$_2$ (Figure 21) or Y$_2$O$_3$ onto the surface of the SAM. These ceramic coats can act as a surface protector of silicon and is a product of using SAMs to coat the silicon surface. SAMs also allow for ceramics to be deposited that normally couldn’t be.
Barrier Layers

The SAM layers that are used as barrier layers have two major components to their usage; act as a lubricant to decrease the friction coefficient between the MEMS structures; and act as a hydrophobic surface layer to create an adhesion barrier between the MEMS structures. The SAM molecules that are used tend to be long chained hydrocarbon or fluorocarbon structures that can densely pack onto the surface of the silicon to create a stable wear and/or stiction barrier. These structures for MEMS tend to be hydrophobic, and the two most common ones used are octadecyltrichlorosilane (OTS), which is a long chained hydrocarbon and perfluorodecyltrichlorosilane (FDTS), which is a long chained fluorocarbon.

The benefit of these hydrophobic SAM layers is twofold. The hydrophobicity helps to decrease the adhesive properties of the silicon. A thin layer of water physisorbs to the surface of the silicon oxide because of its high surface energy and helps to lower this surface energy. When two silicon layers come into contact the hydrophilicity of the surface helps to cause for an adhesion or stiction of the surfaces. By adding the hydrophobic SAM this sticking is greatly reduced since the water on the surface, and thereby the silicon, is repelled by the SAM. The second aspect of this hydrophobicity is that it attracts oils that are present in the air. Instead of water sticking to the surface of the silicon, the oils stick to the surface of the SAM. These oils act as a lubricant for the MEMS structures and lower the coefficient of friction and the friction force sustained by the structures.

5.1 Adhesion and Friction Testing

Cantilever Beam Array Technique

There are many techniques used to test the adhesive and frictional forces that occur between two micro- or nano- surfaces in MEMS or NEMS. One of these tests, which only probe the adhesion properties of MEMS, is the cantilever beam array technique. These tests were conducted by Ashurst et al. using a plain silicon oxide surface, an OTS coated and a dichlorodimethylsilane (DDMS, shorter and slightly less hydrophobic molecule than OTS) coated surface to determine the length at which the cantilevers stuck (figure 22). This test found that the more hydrophobic molecules are less adhesive, with OTS being less adhesive. The work of adhesion was calculated based on the detached lengths with the values found to be >8 (150 µm), 0.045 (540 µm), and 0.012 mJ/m² (750 µm) for silicon oxide, DDMS, and OTS respectively. This shows the SAM layer decreases the work of adhesion by over two orders of magnitude, creating much less stiction between the materials.
A similar beam process was conducted by Srinivasan et al. with OTS and FDTS. This process found that both of the SAM surfaces stuck at lengths greater than 600 µm, while the silicon oxide surface stuck at a distance of about 100 µm. As shown in the prior study the adhesion of the SAM surface was much less than that of the oxide surface.

**Proof Mass Wear**

A second method, which tests both adhesive and frictional forces, was conducted by Astrom et al., and utilized the adherence of a proof mass to posts on the surface and proceeded to rub the proof mass along the posts before removal. This scraping action was used to wear the surfaces of silicon oxide or FDTS coated posts. This scraping process created wear flakes that coated the posts and the proof mass, as shown in figure 23. The flakes were found to be about twice as large on the silicon oxide surface as they were on the SAM covered surface under the same condition. This shows that the SAM cover can help to prevent some of the wear that occurs in the device, but won’t fully stop it.

**Contact Mode Cantilever Tip**

A third process used cantilever tips of silicon nitride to produce nanoscale, or silicon balls to produce microscale contact with the surface. This contact with the surface, probes the adhesive properties as the tip is brought in and out of contact with the surface and the frictional force as the tips scrapes along the surface. Both of these processes were conducted on a bare silicon surface, a DLC coated surface and a SAM covered surface. Both Bhushan et al. who tested the microscopic and nanoscopic regimes and Yoon et al. who only performed this technique at the
nanoscale, found extremely similar results though different SAM layers were used. From these experiments it was found that both the adhesive and frictional force decrease between the bare silicon, DLC and SAM layers, as shown in figure 24. This shows some added benefit for the use of SAMs over DLC surfaces for application where stiction is the major problem. For wear failure DLC is more beneficial because of its added strength, though a small amount of frictional force is compromised.

![Figure 24: Comparison of the adhesion force, friction force and friction coefficient that is analyzed by contact mode analysis of the surface with a silicon nitride tip for a bare silicon wafer, DLC coated surface and OTS SAM coated surface.](image)

**Electrostatic Lateral Output Motor**

A similar process to the cantilever scraping was conducted by Patton et al. who constructed an electrostatic lateral output motor, which uses dimples attached to a slider to scrape the surface. A major contribution of this study was the analysis of relative humidity on the system. Most previous studies were conducted at 50% relative humidity, which as shown in figure 25, corresponds to the section in which there is neither failure due to wear nor stiction after billions of cycles. They were also able to show that the devices with low water adsorption failed much quicker than those with higher water adsorption. Finally at high water adsorption stiction became the major failure problem, and for 70% relative humidity, the addition of an OTS SAM layer avoided adhesive failure.

![Figure 25: The status of failure for the electrostatic lateral output motor based on the relative humidity in the system. At low water adsorption the silicon structures rub against each other and wear away. At high water adsorption the silicon structures remain stuck to each other.](image)
6. CONCLUSION

MEMS suffer from tribological issues, which are the major cause of failure. These issues include adhesion and friction, which lead to the wear or stiction of the system. To help relieve the tribology of the system new materials are being used in both fabrication and coating applications. A couple of these materials include; diamond like carbon, which is a smooth, hard material that reduces the wear and friction that occur at the surface, and self assembled monolayers that coat the surface to reduce both friction and adhesion. To test how these materials compare to silicon, MEMS dominant material, devices like the microengine, cantilever beam array, and contact mode of cantilever tips were used. Through these testing methods, one major thing was concluded, the addition of DLC and SAM layers help to lower all of the tribological problems. This decrease in tribological issues helps to prolong the life of the device and give a means to create smoother moving devices.
7. REFERENCES

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8. BIOGRAPHICAL SKETCHES

David A. Brass received a B.S.E. degree in Chemical Engineering and Materials Science & Engineering from the University of Pennsylvania in 2003. He is in his second year, working toward a Ph.D. in Materials Science & Engineering. His research interests lie in polymer and surface sciences. He is a recreational photographer and hopes to build his own darkroom when he finally gets a house.

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