LUBRICATION OF POLYSILICON MICROMECHANISMS WITH SELF-ASSEMBLED MONOLAYERS

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ABSTRACT

We have investigated the lubricating effects of self-assembled monolayers (SAMs) on microelectromechanical systems (MEMS) by measuring static and dynamic coefficients of friction with two polycrystalline silicon (polysilicon) surface-micromachined devices. The contacting elements in the first microstructure are as-deposited surfaces, and in the second device, they are etched sidewalls. Both devices are SAM-coated after the sacrificial layer etch following the procedures reported earlier [1,2]. The microstructures emerge released and dry from the final water rinse without requiring additional drying techniques. Using the first test structure, the coefficient of static friction, μ_s , between as-deposited surfaces was found to decrease from 2.0 ± 0.8 for the standard SiO_2 coating to 0.09 ± 0.01 and 0.10 ± 0.01 for films derived from octadecyltrichlorosilane (OTS) and 1H,1H,2H,2H-perfluorodecyltrichlorosilane (FDTS), respectively. OTS and FDTS SAM-coated structures exhibit kinetic coefficients of friction, μ_k , of 0.07 ± 0.01 and 0.08 ± 0.01 , respectively. These values were found to be independent of the apparent contact area, and remain unchanged after 1 million impacts at an apparent pressure of 26 kPa, indicating that these SAMs continue to act as boundary lubricants despite repeated impacts. Measurements from a FDTS SAM-coated sidewall friction testing structure gave comparable μ_k values of 0.02 at an apparent contact pressure of 84 MPa. After 2100 cycles at this high pressure, μ_k was found to rise to 0.27, suggesting SAM wear. Despite this observation, results suggest the FDTS SAMs prolong device lifetime in comparison to oxide-coated counterparts.

INTRODUCTION

Due to their large surface area to volume ratios, adhesion and friction are critical issues for microactuators which contain contacting surfaces in relative motion [3-5]. High static friction is known to contribute to wear and can cause device seizure, and kinetic friction consumes a significant portion of the motive torque [6,7]. Investigations into the failure modes of electrostatic microengines, for example, indicate that the usual path to failure involves adhesion between rubbing surfaces [8]. In order to operate microactuators with sliding surfaces in high-reliability, long lifetime applications, a robust lubrication scheme which affords precise control of the friction forces is needed.

In MEMS, contacting surfaces are lightly loaded ($\sim \mu\text{N}$), placing friction in a regime where the contribution from adhesion dominates over that from asperity deformation [3,5,9]. While tribological studies have been conducted on untreated and chemically modified silicon surfaces at the nanoscale with atomic

force microscopy (AFM) [10] and at the macroscale using pin-on-disc tribometers [11], there are difficulties in applying these results to surface-micromachined devices. For example, AFM work is generally conducted on smooth Si(100) and mica, whereas the surfaces in MEMS are relatively rough and hence, the real area of contact between them is not easily known. In pin-on-disc tribometer experiments, contact forces are typically on the order of mN over millimeter-sized areas, so that adhesion from capillary condensation – a critical problem in MEMS, is no longer significant. Therefore, in order to conduct friction studies with the contact pressures and surfaces topographies relevant to microactuators, it is desirable to use surface-micromachined test devices for *in situ* measurements.

Lim and coworkers investigated static friction in a micromachined device between polysilicon/polysilicon and polysilicon/ Si_3N_4 interfaces, and reported μ_s values of 4.9 ± 1.2 and 2.5 ± 0.5 , respectively [6]. Kinetic coefficients of friction have been measured by several groups using electrostatic micromotors and microbearings [3,12,13]. Bart *et al.* reported a μ_k range of 0.26-0.4 for polysilicon/polysilicon contacts, and similar ranges have been reported for polysilicon rubbing against Si(100) and Si_3N_4 [3,12,13]. Friction measurements between polysilicon/diamond-like carbon contacts have also been conducted, with reported μ_k of 0.38 ± 0.05 at an apparent contact pressure of 16.1 kPa [3].

Low surface energy organic films may be deposited on the contacting surfaces in microactuators to reduce adhesion and serve as boundary lubricants. SAMs formed from alkyltrichlorosilane precursors have been investigated in this regard [1,2,7,14,15]. The precursor molecules covalently bind to the substrate and each other through siloxane linkages (Si–O–Si) to form a dense monolayer. With thicknesses of 1-2 nm, these conformal coatings do not affect bulk material properties significantly, and are therefore well-suited to MEMS [15]. When applied to micromachined polysilicon surfaces, hydrocarbon- and fluorocarbon-based SAMs have been shown to reduce the adhesion energy by over three orders of magnitude [1,2]. In addition, these coatings show exceptional solvent and chemical resistance, wear and durability, and stability at the elevated temperatures encountered in MEMS packaging processes [1,2,7,16].

In microactuators, sliding friction can arise between etched sidewalls or laterally sliding as-deposited surfaces. These two types of surfaces have different topographies and possibly different chemical compositions due to their distinct processing histories. In this paper, we describe two surface-micromachined test structures designed to study friction between these types of contacts. Static and dynamic friction coefficients derived from OTS-, FDTS-, and oxide-coated test structures are presented. In addition, wear between FDTS SAM-coated surfaces in repetitive

normal impact and sliding situations is examined using friction measurements and SEM.

EXPERIMENTAL

Lateral Friction Test Structure. Fig. 1 shows SEM micrographs of the lateral friction test structure after the design of Lim *et al.* [6]. The microstructure consists of a shuttle with bumpers on its underside, maintained 2 μm above the ground plane by a folded beam suspension. The shuttle is attached to an electrostatic comb drive which is used to determine the spring constant of the folded beam suspension. An underlying electrode is used to pull on the shuttle and bring its bumpers into contact with an electrically separate, grounded landing pad.

Figure 1. SEM micrographs of a) the lateral friction testing microstructure, consisting of a spring-suspended shuttle attached to an electrostatic comb drive used for spring characterization, b) the underside of the shuttle, and c) a close-up of a $10 \times 10 \times 1 \mu\text{m}^3$ bumper.

These test structures were fabricated at UC Berkeley using low-stress, low-strain gradient polysilicon films according to the deposition conditions in [17]. The 1 μm deep bumper molds are defined in the sacrificial oxide layer using a timed BHF wet etch. To assess frictional dependence on contact area, microstructures with varying numbers of bumpers and surface area per bumper were fabricated. A Topometrix atomic force microscope was used to image the contacting surfaces and study their textures.

Fig. 2 shows a schematic of the microstructure during the testing procedure [6]. First, the spring-suspended shuttle is laterally displaced a distance of Δx_1 using a tungsten probe tip. Then, the shuttle's bumpers are electrostatically brought into contact with the grounded landing pad by applying a voltage to the underlying electrode. (For the SAM-coated devices, this clamping voltage was 50 V; for the oxide-coated structures, 20 V was used since with higher voltages, the shuttle would often not move even after the clamping voltage was reduced to below the pull-in voltage, V_p .) When the lateral force is removed, static friction between the contacting surfaces maintains the displacement. The electrostatic clamping force is decreased slowly until the lateral suspension force can overcome the static

frictional force, and the shuttle begins to move towards its equilibrium position. The shuttle slides a certain distance and stops at a residual displacement Δx_2 .

Figure 2. Top and side views of the lateral friction testing microstructure in a) its equilibrium position and b) displaced and clamped.

The coefficient of static friction, μ_s , is calculated using a force balance as in eq. 1 [6]:

$$\mu_s = \frac{F_t}{F_n} = \frac{k_x \Delta x_1}{F_n} \quad (1)$$

where F_t and F_n are the normal and tangential forces exerted on the shuttle at the point of slippage, respectively. F_n is composed of the electrostatic clamping force minus the spring suspension's restoring force in the z-direction, and can be calculated according to eq. 2, where α_z is a correction factor to account for fringing effects (taken as 1.1), l and w are the length and width of the underlying electrode, z is the gap distance, ϵ_0 is the permittivity of air and V_s and V_p are the potentials at which the shuttle begins to slip and where it can overcome the spring's z-restoring force, respectively.

$$F_n = \frac{\alpha_z \epsilon_0 w l (V_s^2 - V_p^2)}{2z^2} \quad (2)$$

The lateral spring constant, k_x , used to calculate F_t is computed empirically by resonating the electrostatic comb drive and using Rayleigh's method [6,18]. With dimensions and masses substituted in, eq. 1 can be rewritten as follows:

$$\mu_s = \frac{0.2 f_o^2 \Delta x}{V_s^2 - V_p^2} \quad (3)$$

where f_o is the resonant frequency of the spring suspension.

The difference in the shuttle's potential energy between its starting and stopping positions is due to dissipation to kinetic friction. Therefore, assuming μ_k is constant in this range, it can be derived from an energy balance and is given by:

$$\mu_k = \frac{1}{2} \mu_s \left(1 + \frac{\Delta x_2}{\Delta x_1} \right) \quad (4)$$

For the results reported here, testing is done in air ($RH \approx 30\%$) at room temperature. For each test structure, f_o , Δx_1 , Δx_2 , V_s and V_p are measured and μ_s and μ_k are computed. The reported data is taken from chips from one wafer. For normal impact tests, 30 V square waves at a frequency of 10 Hz are applied to the electrode underneath the shuttle to repeatedly impact the bumpers with the grounded landing pad while the device is in the equilibrium position. FDTD SAM-coated devices are subject to 1 million impacts at an apparent contact pressure of 26 kPa. Coefficients of friction are monitored periodically.

Sidewall Friction Test Structure. The sidewall friction test device shown in Fig. 3 is driven by two sets of electrostatic comb drives, X and Y, which are used to reciprocate a beam back and forth against a rounded post. Each comb drive set can push and pull with a maximum force output of $\approx 10 \mu\text{N}$. This microstructure was fabricated at Sandia National Laboratories using the SUMMiT process from four layers of polysilicon – one electrical and three structural layers [4, 19].

Figure 3. a) An SEM of the sidewall friction testing device showing two sets of electrostatic comb drives 90° to each other b) close-up of the boxed area in a) showing the contacting elements.

A high-magnification SEM of the contact geometry is given in Fig. 4. This geometry is used to maintain a constant contact area regardless of beam tilting. The beam is $2.5 \mu\text{m}$ high and $1.8 \mu\text{m}$ wide. The post is $4 \mu\text{m}$ high with a $2 \mu\text{m}$ thick cap, and sits on a grounded electrical polysilicon layer integral with the ground plane of the comb drives. As fabricated, there is a $3 \mu\text{m}$ clearance between the beam and the post.

Figure 4. SEM (6000 $\times$ magnification) of contacting elements in the sidewall device. The beam rubs on the lower vertical sidewall of the post, and the cap on the post prevents the beam from sliding off.

The testing procedure is as follows. First, the force exerted

by comb drive Y is calibrated with the beam not in contact with the post. Square waves are used to drive the comb drive, and the resulting amplitude of the beam's motion, δ_o , is measured by capturing images using a strobe light synchronized with the drive signals. Since the moving parts have little inertia, the motion in response to the square wave occurs in less than 0.3 ms, leaving the part stationary for the remainder of the half-cycle [19]. The moving part advances until a force balance is achieved between the comb drive force (F_c) and the spring restoring forces of the comb drive's suspension ($k_c \delta_o$) and beam x ($k_b \delta_o$), as in eq. 5:

$$F_c = (k_c + k_b)(\delta_o) \quad (5)$$

Then, comb drive X is used in the pulling mode to bring the beam into contact with the post and exert a normal force between the two. Square waves are applied to comb drive Y to move the beam back and forth, and the amplitude of motion is measured. Due to frictional dissipation, this amplitude, δ , is less than δ_o . A force balance is achieved at the endpoints of motion, with the comb drive force balanced by the spring restoring forces and the kinetic friction force, F_k , yielding:

$$F_k = (k_c + k_b)(\delta - \delta_o) \quad (6)$$

where F_k is assumed to be constant.

The normal force exerted between the beam and post is calibrated in a separate step. Comb drive X is driven in the pushing mode to move beam y in the direction away from the post. This deflection is used with the spring constant of beam y to determine the force exerted by this comb drive. The dynamic coefficient of friction is then computed by dividing the frictional force, F_k , by the applied normal force.

In these experiments, a DC voltage of 70 V was applied to comb drive X resulting in a normal force of the beam on the post of $1.3 \mu\text{N}$ and a Hertzian contact pressure of 84 MPa [19]. Square waves 44 V in amplitude with a frequency of 100 Hz were applied to comb drive Y. The spring constants for beams x and y were calculated to be 0.087 N/m and 0.37 N/m, respectively, using dimensions measured with SEM and a value of 160 GPa for the Young's modulus. The spring constant for the comb drive suspension, derived by measuring beam deflection as a function of the comb drive voltage squared, was found to be 0.071 N/m, as confirmed by resonant methods [24].

SAM Coating Process. The structures were released in concentrated HF and then coated with SAMs. The procedure for SAM-coating microstructures is summarized in Table 1 [1]. The iso-octane, hexadecane, and chloroform used in the SAM coating are anhydrous (Aldrich), and the remaining chemicals are standard solvent grade.

Table 1. SAM coating procedure for polysilicon microstructures. Solvent changes are accomplished by dilution rinses for the water soluble steps, and by quickly moving the wafer pieces to the next solvent for the organic solvent changes. The duration of each rinse step is ten minutes and the chips were immersed in H_2O_2 and the SAM solution for 15 minutes.

1. Sacrificial Oxide Etch:	HF
2. Surface Oxidation:	H_2O rinse, H_2O_2 soak, H_2O rinse
3. Bulk Water Removal:	IPA rinse ($\times 2$), Iso-octane rinse ($\times 2$)
4. SAM Formation:	SAM solution
5. Excess Precursor Removal and Dry:	Iso-octane rinse ($\times 2$), IPA rinse ($\times 2$), H_2O rinse

The OTS SAM solution consists of 0.5 mM octadecyltrichlorosilane ($\text{CH}_3(\text{CH}_2)_{17}\text{SiCl}_3$, Aldrich, 95% purity) in a 4:1 vol. mixture of hexadecane and chloroform. This solution was prepared and used under a fume hood. The fluorinated SAM solution, 1 mM FDTS ($\text{CF}_3(\text{CF}_2)_8(\text{CH}_2)_2\text{SiCl}_3$, PCR Chemicals, 98% purity) in iso-octane was mixed and used in a glovebox ($\text{RH} \approx 10\%$) to prevent bulk polymerization caused by its highly water-sensitive headgroup. The oxide-coated microstructures used as a benchmark for the friction studies were released in HF, reoxidized with H_2O_2 , and dried using supercritical CO_2 . The surface treatments were done at UC Berkeley.

Contact angle measurements were taken with a Ramé-Hart goniometer with water and hexadecane as test liquids. Time-of-flight secondary ion mass spectroscopy (TOF-SIMS) using a PHI-TRIFT spectrometer was used to study the quality of the SAM coatings and confirm that the coverage is the same for both test devices.

RESULTS

Lateral Friction. Contact angle measurements on SAM-coated polysilicon with water ($\approx 110^\circ$ for both SAMs) and hexadecane (38° for OTS, 68° for FDTS) confirm that well-packed coatings were formed [1,16]. Atomic force microscopy of the ground plane polysilicon gives an rms roughness of 5 nm [1].

Table 2. Average normal and tangential forces (F_n , F_t) and static and dynamic friction coefficients (μ_s , μ_k). The total bumper area is $300 \mu\text{m}^2$ (three $10 \times 10 \mu\text{m}^2$ bumpers) and the shuttle displacement is $12 \mu\text{m}$.

	$F_n (\mu\text{N})$	$F_t (\mu\text{N})$	μ_s	μ_k
Oxide	0.48	1.1	2.0 ± 0.8	-
OTS	8.6	0.77	0.09 ± 0.01	0.07 ± 0.01
FDTS	7.6	0.76	0.10 ± 0.01	0.08 ± 0.01

Table 2 shows μ_s and μ_k values and the normal and tangential forces at the onset of shuttle slippage for measurements taken with an initial displacement of $12 \mu\text{m}$. Data from test structures with different total bumper areas (300 and $144 \mu\text{m}^2$) is shown in Table 3. Each friction coefficient represents an average of at least 30 data points. Static friction measurements were also taken at different initial displacements between 4 and $12 \mu\text{m}$ corresponding to varying tangential forces. SAM-coated devices gave constant friction coefficient values at three different measurement positions. For oxide-coated structures, initial displacements of 9.5 and $12 \mu\text{m}$ gave similar μ_s values of 2.10 ± 0.8 and 2.0 ± 0.7 , respectively. Tests using smaller initial displacements were unreliable due to stiction – often, the shuttle remained clamped to the substrate even when the applied normal force was reduced to zero.

Table 3. Static coefficient of friction data taken from test structures with four $6 \times 6 \mu\text{m}^2$ and three $10 \times 10 \mu\text{m}^2$ bumpers (total areas of $144 \mu\text{m}^2$ and $300 \mu\text{m}^2$, respectively).

	$\mu_s (A = 144 \mu\text{m}^2)$	$\mu_s (A = 300 \mu\text{m}^2)$
Oxide	2.3 ± 0.8	2.0 ± 0.8
OTS	0.09 ± 0.01	0.09 ± 0.01
FDTS	0.11 ± 0.01	0.10 ± 0.01

At a ramp-down speed of 1 V/s for the clamping force, the movement of SAM-coated structures was a mixture of continuous sliding and stick-slip motion. At higher ramp-down speeds (5 V/s), motion appeared continuous.

FDTS SAM-coated lateral friction testing devices subject to 1 million impact cycles at an apparent contact pressure of 26 kPa showed no degradation in μ_s and μ_k values.

Sidewall Friction. A plot of the sidewall friction coefficient as a function of the number of wear cycles at 84 MPa is shown in Fig. 5. For the first ~ 800 wear cycles, the friction coefficient is 0.02. Then, after ~ 2100 cycles μ_k is observed to increase to an average value of 0.23. After 3.7×10^5 cycles, stick-slip predominates, indicated in Fig. 5 by the oscillation between high and low friction coefficient values. Friction coefficient values of ~ 0.9 result when the force of the comb drive is insufficient to move the structure. In this case, the plotted value of 0.9 is a lower bound to the actual friction coefficient. The test was continued for 2.3×10^7 cycles with the number of sticking events reduced after 5 million cycles and μ_k slowly rising to 0.28.

Failure of the device is taken as the point where sticking first occurs, giving a lifetime of 3.7×10^5 cycles. In comparison, oxide-coated structures show a lower lifetime of 1.9×10^4 cycles [19]. The uncoated structure ceased moving altogether after 7.7×10^4 cycles, whereas the FDTS-coated sidewall device was still operating when the test was terminated at 2.3×10^7 cycles. The factor of 20 difference in cycles to onset of sticking, and factor of more than 350 before complete seizure, suggests that SAMs prolong lifetime even though the initial μ_k of 0.02 is only maintained for ~ 800 cycles.

Figure 5. The friction coefficient measured by the sidewall device during sliding friction. The large friction values intermittently measured after 3.7×10^5 cycles are due to sticking of the surfaces.

After the wear test, the contacting surfaces were imaged by SEM as shown in Fig. 6. A buildup of material, presumably wear

Figure 6. SEM examination of the contacting surfaces of the sidewall device after 2×10^7 wear cycles shows a buildup of wear debris on the post and a horizontal scratch on the beam.

debris, can be seen on the surface of the post. The surface of the beam shows a horizontal scratch and agglomerations of wear particles, each particle ~10 nm in size. SEM photos of unworn structures do not show evidence of particles or scratches.

DISCUSSION

Lateral Friction. Large differences in the static friction force are seen between structures coated with SAMs and SiO₂. The experiments performed on the lateral friction test structures give μ_s of 0.09 ± 0.01 and 0.10 ± 0.01 for OTS and FDTS films, respectively. These values are approximately 20 times lower than μ_s for the standard oxide coating, 2.0 ± 0.8 . The results in Table 3 indicate that in this testing situation, these coefficients do not depend on apparent contact area, as expected from Amonton's law [6,20].

Since friction in MEMS arises from localized adhesion at the points of real contact, the high μ_s values for the oxide coating can be attributed to strong capillary forces between the surfaces. These attractions seem to be exerting a force between the contacting surfaces of comparable magnitude to the applied normal force. The dramatic reduction in μ_s with SAMs can be explained by the lack of capillary attractions between the hydrophobic SAM surfaces. Tests on cantilever beam arrays on the same chip support this—the apparent adhesive energy between the polysilicon surfaces is reduced by four orders of magnitude due to FDTS SAM films most likely through the elimination of capillary condensation [1].

The dynamic coefficients of friction ($\mu_{k,OTS} = 0.07 \pm 0.01$ and $\mu_{k,FDTS} = 0.09 \pm 0.01$) coincide well with literature results taken at the macroscale with pin-on-disc tribometers. Published values of μ_k for OTS SAM-coated Si(100) range from 0.07 [21] to 0.12 [11]. For the fluorinated monolayers, DePalma and Tillman report higher friction coefficients ($\mu_k = 0.16$) despite their lower surface energies [21]. This has been attributed to greater adhesion hysteresis between the fluorinated films caused by the lower packing density of the fluoroalkyl chains [22]. The dynamic coefficients derived here are similar to those reported from Teflon-coated microengines (0.07) [23], and lower to those obtained for polysilicon/diamond-like carbon contacts under similar apparent pressures [3].

Using similar test structures, Lim and coworkers reported higher μ_s values of 4.9 ± 1.2 for oxide-coated polysilicon contacts [6]. The difference in μ_s may be due to the lower normal forces used (0.08 μ N in [6] vs. 0.48 μ N here), thus increasing the importance of adhesion between the surfaces. Also, different drying techniques were used, i.e., methanol rinse followed by air drying by Lim, *et al.* versus supercritical drying with ultrapure CO₂ in this paper. The high standard deviations in μ_{oxide} data given here as well as by Lim, *et al.* can be explained by considering that high surface energy oxide films favor the adsorption of polar contaminants from the ambient atmosphere, resulting in a highly variable surface layer. In contrast, low standard deviations in the friction data for the SAM films reflect improved reproducibility of these low energy surfaces.

With our test structures, the FDTS SAM film does not show degradation in friction coefficients after 1 million impacts at an apparent pressure of 26 kPa. Due to the rough nature of polysilicon surfaces, the real pressure between contacting asperities is expected to be significantly higher than the apparent pressure. An estimate for the real contact area between these surfaces can be made using an apparent adhesion energy of 23 μ J/m², measured between OTS SAM-coated polysilicon surfaces [1]. (This value was obtained using surface-micromachined

cantilever beam arrays fabricated on the same chip as the friction testers, and hence, with the same polysilicon topography.) Since the real adhesion energy between perfectly smooth, chemically identical surfaces is twice the surface energy, or ≈ 40 mJ/m² for OTS SAMs, the ratio of real to apparent area can be estimated as a ~ 0.001 . Thus, the actual pressure between contacting asperities may be on the order of tens of MPa. In AFM experiments, OTS SAMs have been shown to be able to withstand local pressures in the tens of GPa [25].

Sidewall Friction. The initial μ_k value of 0.02 from the FDTS SAM-coated device is 7–10 times lower than that derived from an oxide-coated structure [19]. This friction coefficient is comparable to that measured using the lateral friction device. The factor of five difference may arise from the different surface topography encountered in the sidewall friction measurements.

The friction coefficient of 0.28 after ~ 2100 wear cycles at an apparent contact pressure of 84 MPa is consistent with prior measurements between oxide surfaces [19]. Due to the roughness of the reactive ion etched sidewall surfaces, the actual pressure at contacting asperities may be significantly larger than 84 MPa. SEM examination of the worn surfaces reveals wear debris and scratching at this pressure, possibly due to fracture of the underlying oxide and polysilicon surfaces [26]. The configuration of this test structure reproduces the sidewall contact found in some MEMS applications. The contact pressure is in the same range as the contact pressures calculated for Sandia microengine hub and pin joints, 27 and 140 MPa, respectively [27].

It is interesting to note that despite the increase in μ_k after ~ 800 cycles, the FDTS SAM-coated structure had a significantly longer operational lifetime than its oxide-coated counterpart [19]. The reason for this behavior is under investigation. Current work includes wear characterization of OTS coatings, which have shown superior wear properties to fluorocarbon SAMs [21,22].

CONCLUSIONS AND FUTURE WORK

Friction has been investigated between two types of contacts found in MEMS using surface-micromachined test devices. The results presented here show that nanometer-thick SAMs can serve as effective boundary lubricants of microactuators. Static friction coefficients between as-deposited contacts are reduced by a factor of 20 with respect to the standard oxide treatment. Dynamic friction coefficients are similarly low, and agree well with literature results taken at the macroscale. Measurements from the sidewall friction test device give a comparable μ_k , which is 7–10 times lower than that obtained with oxide-coated contacts. Impact tests indicate fluorocarbon SAMs can withstand 1 million cycles at an apparent pressure of 26 kPa without an increase in friction coefficients. Preliminary sliding wear experiments between FDTS-coated sidewall contacts at 84 MPa apparent pressure show increased friction after 800 cycles. Despite this observation, results suggest that these SAM coatings prolong device lifetime. Future work involves a systematic characterization of wear between SAM-treated surfaces, quantification of chemical and physical changes to the contacting surfaces during wear, and investigation into the effects of topography on friction.

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