A study of static friction between silicon and silicon compounds

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Abstract. This paper presents results from measurements of static coefficient of friction between materials of interest to microelectromechanical systems (MEMS) The materials studied here include silicon, silicon dioxide, and silicon nitride Two measurement techniques have been used in this study In the first technique, static friction between two millimeter-sized flat components was measured in a 10^{-6} Torr vacuum chamber In the second technique, static friction between a three-millimeter radius aluminum bullet coated with a material of interest and a flat substrate was measured in a $\sim 5 \times 10^{-10}$ Torr ultra-high vacuum (UHV) chamber The results show that the coefficient of friction, μ, between silicon and silicon compound contacts is in the range 0 2 to 0 7 The coefficients of friction between silicon dioxide/silicon dioxide and silicon dioxide/silicon contacts increase by 55% to 157% with increased exposure to humidity Additionally, friction between similar materials behaves differently than that between dissimilar materials Furthermore, using the friction measurement in UHV as reference, exposure to nitrogen gas often decreases the coefficient of static friction between silicon compound mechanical contacts, while exposure to oxygen gas increases the coefficient of static friction These results agree well with the results from *in situ* friction measurements in micromotors

1 Introduction

Studies on IC-processed micromotors indicate that frictional effects can be significant, and the operational environment influences the frictional behavior [1–5] The information on frictional behavior between microcomponents is important in understanding the operational characteristics of microelectromechanical systems (MEMS) Because of the large surface to volume ratio as well as reduced sizes and forces involved in MEMS, the frictional behavior of mini or micro components is expected to be different from that of macro components Some important factors that influence frictional behavior of mechanical contacts include surface topography, surface cleanliness, and stray forces For micro components, the effects of stray forces such as electrostatic, chemical, and physical forces on the surfaces may be much more significant

An understanding of the effects of adsorbed gas films on friction is important for understanding the performance characteristics of MEMS For MEMS, due to the smaller dimensions and forces, the influence of the adsorbed gases might be greater than those of macro devices It is of particular interest to understand the effect of environment parameters such as composition of the atmosphere, temperature, and humidity on frictional behavior between mini or micro components Once the

effect of adsorbed gas on friction is understood, techniques for lubrication may be developed

The objectives of this study are (i) to examine static friction measurement techniques, (ii) to compare frictional behavior between similar materials and dissimilar materials, and (iii) to explore the effects of environmental parameters including humidity, nitrogen, oxygen, and argon exposures at various pressures on the frictional characteristics of MEMS The coefficient of friction, μ, of silicon nitride/silicon nitride, silicon nitride/silicon, silicon dioxide/silicon dioxide, and silicon dioxide/silicon mechanical contacts at various gas pressures is presented along with preliminary interpretations

Two measurement techniques were used in this study In the first technique [1], hereafter referred to as experiment A, the friction between two millimeter-sized flat components was measured in a 10^{-6} Torr vacuum chamber, into which different gases could be leaked, and the gas pressure could be controlled from 760 Torr to $\sim 5 \times 10^{-6}$ Torr Test forces on the order of 10^{-5} N were used in these measurements A polyvinylidene difluoride (PVDF) bimorph cantilever was calibrated to generate a small repeatable tangential force from 0 to 8×10^{-4} N The normal force was applied by electrostatic attraction and was in the range of 10^{-3} N The effect of humidity on friction was observed by measuring the coefficient of friction for samples in air before and after baking

In the second technique [6] hereafter referred to as experiment B, static friction between a flat substrate and a three-millimeter radius aluminum bullet coated with a test material was measured in a ~5 × 10⁻¹⁰ Torr ultra-high vacuum (UHV) chamber Exposure of the contact surfaces to three gases including nitrogen, oxygen and argon were studied These gases were leaked into the vacuum chamber one at a time after the measurement system was pumped down and the samples were baked out at 200 C for 20 min The effects of the adsorbed gases at various pressures on the frictional behavior were observed

2 Sample fabrication and preparation

In experiment A, bare silicon, thermally oxidized silicon, and silicon nitride deposited silicon wafers were used as two-inch substrates and diced to form 1 mm × 1 mm test samples For silicon nitride, plasma-enhanced chemical vapor deposition (PECVD) from silane at 300 C was used Aluminum was evaporated on the backside of the samples to provide electrical contact to the samples from the back

In experiment B, the material of interest was deposited on an aluminum alloy bullet and a silicon wafer as shown in figure 1. The bullet had a three-millimeter radius hemispherical tip and was polished with diamond paste down to a 0 25 μm grit on a lathe On the bullet surface, silicon nitride was deposited by PECVD at 300 'C For silicon dioxide coating of the bullet, sputtering from a fused silica (99 99%, SiO₂) target was used The thickness of silicon dioxide and silicon nitride on the bullet was about 2000 Å We have estimated the thickness of the deposited film on the tip of bullet by ellipsometry on flat silicon monitor samples For the flat substrates of experiment B, the 2000 Å silicon dioxide was grown thermally and the 2000 Å silicon nitride was deposited by PECVD at 300 C on silicon wafers

In order to obtain reproducible results in our friction measurements, a critical factor was surface cleanliness, surface contamination from atmosphere or from handling could produce a very large change in friction In our work, all test samples (including bullet samples in experi-
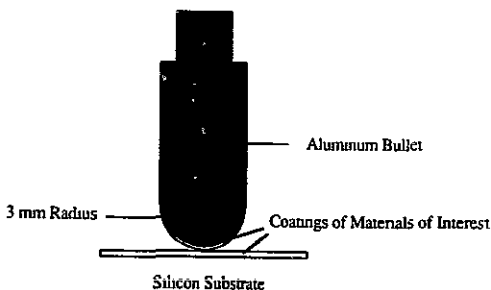
ment B) were cleaned with a standardized procedure before the experiments Samples were cleaned by degreasing in an ultrasonic bath in trichloroethylene (TCE), acetone (ACE), and methanol (METH) for 5 min each They were then rinsed with deionized water and were subsequently dried with nitrogen gas We did not use the RCA standard clean procedure because of the aluminum metallization on the back of the samples for experiment A, and the aluminum bullet coating with a test material were used for experiment B Furthermore, all the measurements were performed in a vacuum chamber, and the samples were baked out in the chamber before the measurements were made

3. Experimental apparatus and procedure

In our experiments, the coefficients of friction, μ, was calculated from the slope of a straight line fit through the tangential force versus the normal force data points as exemplified by figure 2 The tangential force was defined as the force necessary to initiate sliding between the two contact surfaces Data were taken as the normal force was incrementally increased The fitted line through the data points was then determined by least squares linear regression The initial normal force (at 0) was not measured

Figure 3 is a schematic representation of the apparatus for experiment A For this experiment, the vacuum chamber was isolated from environmental vibration The vacuum chamber consisted of a glass bell jar and an aluminum base with feedthroughs for the electrical
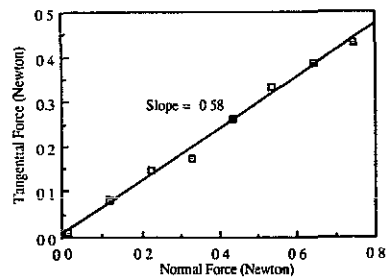
Figure 2 A typical curve of tangential force versus normal force from experiment B The coefficient of static friction was calculated from the slope of a straight line fit through the tangential versus the normal force data points
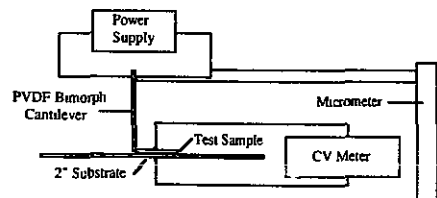
Figure 1. Bullet coated with a test material sliding on a flat substrate for experiment B

Figure 3 Instrumental setup for experiment A

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connections A hot plate with a temperature controller was used to bake the samples in the chamber A calibrated electrostatic clamping force was applied to the samples through a bias voltage Through an electric excitation, a tangential force was generated by the PVDF bimorph cantilever, calibrated to have a repeatable force from 0 to 8×10^{-4} N The CV meter that supplied the clamping voltage to the samples was also used to detect the displacement of the samples When the samples slid over each other, the charge equilibrium at the interface was disturbed, and the air gap between two surfaces was changed due to the roughness of surfaces Thus, a transient charge, corresponding to the displacement of samples, resulted in a sudden change of capacitance indicated by the CV meter For example, a 0 08 micrometer change in the air gap would cause 2 pF change in the capacitance being measured

The electrostatic clamping force was applied using the bias voltage of a high frequency CV meter, and the capacitance was measured simultaneously This electrostatic clamping force was calibrated on each sample before and after baking as well as after the chamber was pumped down Next, an adjustable DC voltage of 0 to 500 V was applied to the PVDF bimorph cantilever to generate the tangential force that pushed the sample forward until a displacement was observed as a sudden change of capacitance indicated by the CV meter

In experiment B, static friction between a flat substrate and a three-millimeter radius aluminum bullet coated with a material of interest was measured in an UHV chamber The measurement system is schematically represented in figure 4 [6] Samples were exposed to different gases by back filling the vacuum chamber with the desired gas The normal force on the bullet was controlled by the position of a 0 908 kg weight rotating on a threaded rod The arm holding the bullet could be translated horizontally by a translation table using a piezoelectric positioning device The push of the piezoelectric positioning device was controlled by a high voltage power supply, supervised by a programmable controller This tangential force on the bullet was measured by a charge mode piezoelectric force sensor

After loading the samples, the vacuum chamber was pumped down and maintained at a pressure of $\sim 5 \times 10^{-10}$ Torr Samples were baked at 200 C for 20 min to achieve reproducible results The measurements were carried out after the temperature of baked samples recovered to room temperature The experiments were made by carefully lowering the bullet onto the substrate, adjusting the normal force onto the bullet in contact with the substrate, and pushing the bullet forward using the translation device until plastic behavior (slippage) was observed on the force versus displacement curve The bullet was then raised

The gas exposure experiments were performed only after all measurements at $\sim 5 \times 10^{-10}$ Torr had been completed Gas exposure was carried out at constant gas pressure while the tip of the bullet was lifted to 2 0 cm above the substrate The highest gas exposure pressure was 1×10^{-6} Torr, the duration of gas exposure varied from 40 to 60 min The product of gas exposure duration and pressure is specified in units of Langmuir (1 Langmuir $= 1 \times 10^{-6}$ Torr s) [7]

After each gas exposure measurement, the chamber was pumped down to near $\sim 5 \times 10^{-10}$ Torr Samples were then baked until they recovered their 'original surface state', as indicated by a return of the coefficient of friction to within $\pm 10\%$ of the UHV values In our experiments, argon was the first gas to be tested, followed by nitrogen and then oxygen This order corresponds to the increasing reactivity of the gases

After a set of experiments, scanning electron microscopy (SEM) was used to measure the apparent areas of contact between the samples and the bullet as well as the trace of movement on the substrate The apparent bullet contact area was estimated to be 0 03 to 0 04 mm^2

Figure 4 Friction measurement apparatus for experiment B

4. Results

Table 1 presents the results from measurement of coefficient of static friction using experiment A The coefficient of static friction for silicon nitride 'silicon nitride, silicon dioxide/silicon dioxide and silicon dioxide/silicon contacts were measured Measurements were made at 760 Torr before and after the samples were baked as well as at 1×10^{-5} Torr after baking All measurements were repeated more than ten times The averages of the measured values and the corresponding maximum deviations are shown in table 1 The data on PECVD silicon nitride/silicon nitride contacts vary somewhat from sample to sample, this is attributed to varying deposition conditions of our PECVD silicon nitride

A comparison of the measurements made before and after baking indicate the effect of water vapor on friction Figure 5 presents typical results for silicon
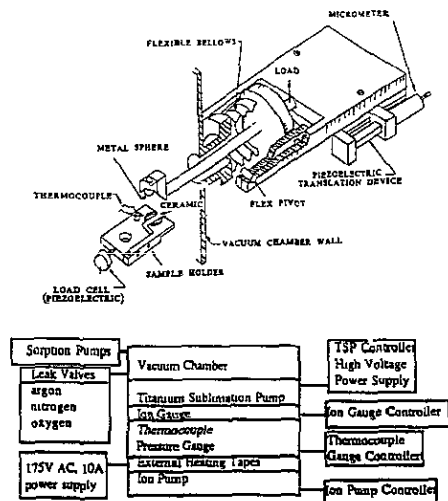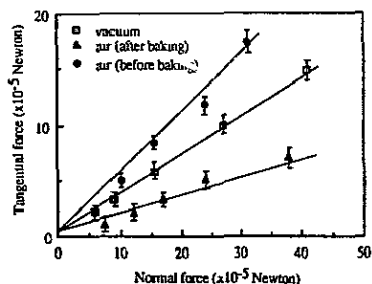
Table 1 Measurement results from experiment A SiN$_x$ PECVD silicon nitride

	SiN$_x$ on SiN$_x$*	SiO$_2$ on SiO$_2$	SiO$_2$ on Si
Air (before baking)	0 62–0 84	0 54 ± 0 03	0 48 ± 0 02
Air (after baking)	0 62–0 84	0 21 ± 0 03	0 31 ± 0 03
10^{-5} Torr (after baking)	0 53–0 71	0 36 ± 0 02	0 33 ± 0 03

*Measured at different locations with maximum deviation ± 0 03

Figure 5 Tangential force versus normal force measured between SiO$_2$/SiO$_2$ contacts in experiment A In air, the coefficient of friction is 0 54 before baking the samples and 0 21 after The coefficient of friction is 0 36 at 10^{-5} Torr after the samples are baked

dioxide/silicon dioxide contacts In air, the coefficient of friction, μ, is 0 54 before baking the samples and 0 21 after baking At 10^{-5} Torr, μ is 0.36 after the samples are baked A similar result is obtained between silicon dioxide/silicon contacts, μ in air is higher before baking than after The humidity experiments on these two groups of components show that the change in μ is between 55% to 157% For silicon nitride/silicon nitride contacts, the frictional behavior was not affected by humidity In this case, there is no significant difference in the coefficient of static friction before and after baking in air

At 10^{-5} to 10^{-6} Torr vacuum, the gas adsorbed on the surface is not removed totally Therefore, after the surface is exposed to one gas, its condition will be different from that of the original surface Even after the chamber is pumped down to 10^{-6} Torr and samples are baked, the original surface conditions cannot be obtained If the sample is then exposed to a second gas, the frictional behavior observed at 10^{-6} Torr varies according to the sequence of the experiment As a result, experiment A was not used to study the effect of gas exposure on frictional characteristics of the surfaces studied in table 1

Table 2 presents the results from the measurement of coefficient of static friction using experiment B The coefficients of static friction for silicon nitride/silicon nitride, silicon nitride/silicon, silicon dioxide/silicon dioxide, and silicon dioxide/silicon mechanical contacts were measured The averages of the measurement values and the corresponding maximum deviations are shown in table 2 The results from experiment B are discussed below and are grouped by the contact materials studied

4.1. Silicon nitride/silicon nitride

The measured μ in UHV between a PECVD silicon-nitride coated bullet and a PFCVD silicon-nitride flat substrate varied widely at different substrate locations It was observed that after the chamber was pumped down to 10^{-6} Torr and before baking, at all test locations, μ fluctuated from 0 55 to 0 85 under different normal forces

Table 2 Measurement results from experiment B SiN$_x$ PECVD silicon nitride

	SiN$_x$ on SiN$_x$	SiN$_x$ on Si	SiO$_2$ on SiO$_2$	SiO$_2$ on Si
Air (before baking)	0 55–0 85	0 40–0 55[a]	0 43 ± 0 05	0 55 ± 0 05
UHV (~5 × 10^{-10} Torr)	0 40–0 70[a]	0 35 ± 0 05	0 20 ± 0 02	0 39 ± 0 04
Ar(< 10^{-6} Torr)	0 40 0 70[a]	0 35 ± 0 05	0 20 ± 0 02	
N$_2$(< 10^{-6} Torr)	Decrease from 0 58 to 0 35[b]	0 35 ± 0 05	Decrease to 0 15 ± 0 02	Decrease to 0 20 ± 0 02
O$_2$(< 10^{-7} Torr)	Increase from 0 44 to 0 68[b]	Increase to 0 45 ± 0 05	Increase to 0 75 ± 0 05	Increase to 0 55 ± 0 04
R N$_2$[c]	~0 6	~1 0	~0 8	~0 5
R–O$_2$[c]	~1 6	~1 3	~3 8	~1 4
R(O$_2$/N$_2$)[d]	~1 9	~1 3	~5 0	~2 7

[a]Measured at different locations with maximum deviation ± 0 05
[b]Measured at the same location with maximum deviation ± 0 05
[c]R- N$_2$ and R -O$_2$ are ratios of the coefficients of friction measured in nitrogen and oxygen to those measured in UHV respectively
[d]R (O$_2$/N$_2$) is the ratio of the coefficients of friction measured in oxygen to those measured in nitrogen

However, after pumping down to 6×10^{-10} Torr and baking, the μ value stabilized Values of μ from 0 40 to 0 70 were measured at different substrate locations This result was consistent with that of experiment A presented in table 1 This behavior may be due to the poor uniformity of our PECVD silicon nitride films In order to observe the effects of gas exposure, all the measurements (except for argon exposure) on silicon nitride/silicon nitride contacts discussed below were made at the same substrate location Argon was leaked into the chamber until the pressure reached 1×10^{-6} Torr and was maintained there for 40 min (2400 L), the value of μ measured was the same as in UHV at same location

The coefficient of friction versus nitrogen exposure pressure was measured At different normal forces, μ was not constant over the range of nitrogen exposure pressures studied For normal forces below 0 2 N, μ was larger than that for normal forces greater than 0 2 N This experiment was repeated three to four times at different nitrogen pressures, the data were repeatable within our measurement error Figure 6 presents typical results of tangential force versus normal force at 240 L of nitrogen pressure Figure 7 shows values of μ versus nitrogen pressure obtained after nitrogen had been leaked to reach the desired pressure for 40 min at the two magnitude ranges of normal force. μ decreases as the pressure increases The effect of nitrogen on the coefficient of friction relates to the nitrogen pressure and can be cycled Figure 8 shows the results of both increasing and decreasing nitrogen pressure sequences After the nitrogen pressure was increased to 10^{-6} Torr for 40 min, the nitrogen pressure was decreased by reducing the nitrogen leak rate to reach the desired lower pressure for 40 min The data were recorded, then the pressure was further reduced in steps After the chamber was pumped down to UHV and the samples were cleaned again, the coefficient of friction returned to 0 55 which was within 10% of its original value

Before oxygen gas exposure, μ at the test location in UHV was 0 44 at 1×10^{-9} Torr This value did not change after 24 L exposure in oxygen and increased to 0 68 after 480 L exposure To avoid excessive contamination of the
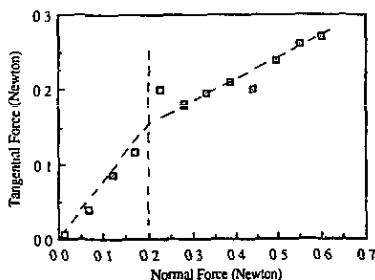

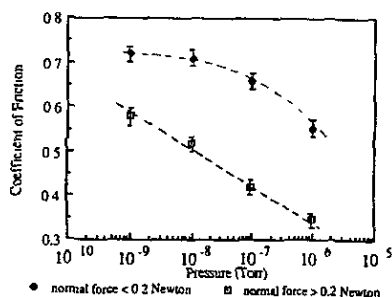**Figure 7** The coefficient of friction versus increase of nitrogen pressure measured between PECVD SiN$_x$/SiN$_x$ contacts The coefficient of friction was measured after nitrogen had been leaked to reach the desired pressure for 40 min at the two magnitude ranges of normal force The coefficient of friction decreases as the pressure increases
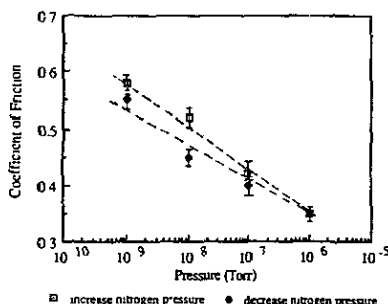

Figure 8 The coefficient of friction versus nitrogen pressure measured between PECVD SiN$_x$/SiN$_x$ contacts The normal force is from 0 2 to 0 6 N The coefficient of friction was measured first with increasing nitrogen pressure from 10^{-9} to 10^{-6} Torr and then with decreasing nitrogen pressure back to 10^{-9} Torr

vacuum chamber by oxygen, extensive oxygen exposure was not performed After this experiment, the chamber was pumped down and samples were baked at 200 C for 20 min μ was measured again, the value was $0 54 \pm 0 02$ This value was higher than the initial value of 0 44 in UHV

4.2. Silicon nitride/silicon

For a PECVD silicon-nitride coated bullet sliding on a single-crystal silicon substrate, μ in air before baking was $(0 40-0 55) \pm 0 04$ at different locations μ in argon was the same as in UHV $(0 35 \pm 0 05)$ After 2400 L exposure of samples to nitrogen, μ did not change This experiment was repeated several times, the results were identical When exposed to oxygen, μ increases but the effect is smaller than that for silicon nitride/silicon nitride contacts

Figure 6 Tangential force versus normal force at 240 L of nitrogen pressure measured between PECVD SiN$_x$/SiN$_x$ contacts For normal forces below 0 2 N, μ was larger than that for normal forces greater than 0 2 N

4.3. Silicon dioxide/silicon dioxide

μ of a silicon-dioxide coated bullet on a silicon-dioxide substrate was 0.43 ± 0.05 after the chamber was pumped down to about 10^{-7} Torr and before baking This value decreased to 0.20 ± 0.02 in UHV after baking. The μ measured was the same as in UHV after argon was leaked into the chamber to reach 2400 L

After 2400 L exposure in nitrogen, μ decreased from 0.20 ± 0.02 to 0.15 ± 0.02 Exposure of the samples to oxygen at 480 L resulted in an increase of μ from 0.22 ± 0.02 to 0.75 ± 0.05 After the chamber was pumped down again to UHV and the samples were baked out at 200 C for 20 min, μ was 0.40 ± 0.02, this being higher than that before oxygen exposure (0.22 ± 0.02)

4.4. Silicon dioxide/silicon

For a silicon-dioxide coated bullet sliding on a single-crystal silicon substrate in UHV, μ is 0.39 ± 0.04 μ decreases to 0.20 ± 0.02 after nitrogen exposure and increases from 0.37 ± 0.04 to 0.55 ± 0.44 after oxygen exposure In contrast to the change of μ due to oxygen exposure on silicon dioxide/silicon dioxide contacts, the increase in μ in this case is smaller

5. Discussion

In experiment A, the results of measurements on silicon dioxide/silicon dioxide and silicon dioxide/silicon mechanical contacts suggest that the removal of the water vapor is the cause of the reduction of μ after baking In experiment B, the measurements made in air and UHV show a decrease of μ in UHV This is evidence that surface contamination is one source of friction Without baking samples, it is known that most residual gases on the surfaces (i e , both the vacuum chamber and the samples) are water vapor and hydrocarbon after pumping down to 1×10^{-7} Torr The measurements made under these conditions suggest that water vapor and native oxide are the major causes of larger μ

There is no effect of argon exposure on the friction between different materials measured. Argon is a noble gas, it is expected to have no effect on the friction In this study, argon was used as the reference gas Nitrogen exposure causes a decrease of the coefficient of friction among the tested materials except for silicon nitride/silicon contacts It is suggested that nitrogen acts as a lubricant with silicon nitrides. The influence of nitrogen on silicon nitride/silicon nitride contacts is discussed below

In figure 6, the coefficient of friction is not constant over the measured range of normal forces, at lower normal forces the coefficient is larger than that at larger normal forces The reason for this behavior is currently not known to us One explanation may be that nitrogen acts as a boundary lubricant According to Rabinowicz [8], shear occurs between the lubricant and one of the surfaces at low hydrostatic pressures Only at high

pressures does shear within the lubricant layer occur One can then postulate that the shear strength between nitrogen and silicon nitride is higher than that between nitrogen layers

Figure 7 shows μ versus nitrogen pressure for PECVD silicon nitride/silicon nitride contacts It is shown that μ decreases as the nitrogen pressure increases For a fixed gas exposure duration, with higher nitrogen pressures, the number of the adsorbed gas atoms or molecules on the surfaces increases The reduction of μ may be caused by a thin layer, perhaps a few monomolecular layers thick, of the adsorbed gas By reducing the nitrogen leak rate to reach the desired lower pressure for 40 min μ increases, but does not recover its initial value, as shown in figure 8 After the chamber is pumped down to UHV and the samples are cleaned again, μ returns to 0.55 which is very close to its original value This phenomenon suggests that the monolayer formed by nitrogen is partly due to physisorption and partly due to chemisorption The physically adsorbed film could be removed by reducing the nitrogen pressure The chemisorbed film could be removed by heating the sample to a temperature above that corresponding to its bonding energy

In contrast to silicon nitride/silicon nitride contacts, nitrogen exposure has no effect on μ of silicon nitride/silicon contacts The reason for this behavior is not known Nitrogen fulfills its expected role as a lubricant between silicon dioxide/silicon dioxide as well as silicon dioxide/silicon contacts. The decrease caused by nitrogen could be interpreted as evidence that some of the interfacial bonds between the oxide surfaces are being replaced by nitrogen

Oxygen exposure increases the coefficient of friction between silicon and silicon compounds The amount of increase varies with the contact materials Oxygen acts as an adhesive in both silicon nitride/silicon nitride and silicon nitride/silicon contacts A possible explanation is that the surface is oxidized and the interaction between the oxide surfaces causes the higher μ value. μ of silicon nitride/silicon nitride contacts does not change after oxygen exposure to 24 L, it increases after oxygen exposure to 480 L Normally, oxidation is not observed on a good silicon nitride film at low temperatures However, the adsorption of oxygen on a nitride film is observed The experimental results could be interpreted as follows The surface is clean at 10^{-9} Torr after the sample is baked If the surface is then exposed to oxygen for sufficient time, it is possible to have layers of oxygen adsorbed on the surface

Exposing silicon dioxide/silicon dioxide and silicon dioxide/silicon contacts to oxygen resulted in an increase in μ The bonding within the oxide films is usually very strong [9, 10] It has been suggested that an intermediate oxide film acts as a transition layer to enhance film adherence [11] The oxygen exposure of silicon dioxide/silicon dioxide contacts increases μ much more than that for silicon dioxide/silicon contacts The difference between these effects may be that the bonding between two oxides in contact is stronger than those interfacial bonds between oxide and silicon

In table 2, we have also summarized the ratio of the coefficient of friction measured in nitrogen and oxygen to those in UHV The ratio of μ in nitrogen to that in UHV for silicon nitride/silicon nitride contacts is about 0 6, while this ratio is about 1 0 for silicon nitride/silicon contacts The ratio of μ measured in oxygen to that in UHV is about 3 8 for silicon dioxide/silicon dioxide contacts, while this ratio is about 1 4 for silicon dioxide/silicon contacts The ratio of μ measured in oxygen to that in nitrogen is about 1 9 for silicon nitride/silicon nitride contacts, about 1 3 for silicon nitride/silicon, about 5 0 for silicon dioxide/silicon dioxide contacts, and about 2 7 for silicon dioxide/silicon contacts These results show that the friction between similar materials behaves differently than dissimilar materials

6. Conclusion

The measured results on silicon dioxide/silicon dioxide and silicon dioxide/silicon contacts show that humidity in air increases the coefficient of friction, μ, from 55% to 157% Exposing the samples to argon results in no change in μ, exposing the samples to nitrogen results in either a decrease or no change in μ, and exposing the samples to oxygen results in an increase in μ Argon is an inert gas, it is expected to have no effect on surface reaction The data suggest that nitrogen acts as a lubricant, and adsorbed oxygen acts as an adhesive between the silicon and silicon compounds

The ratios of the coefficient of friction measured in nitrogen and oxygen to those in UHV agree with the observations in studies of frictional behavior on micromotors [2] where the friction in nitrogen for polysilicon/polysilicon contacts is seen to be about an order of magnitude smaller than in air (oxygen and humidity) The coefficient of friction, reported from in situ friction measurements in micromotors [4, 5], is 0 21 to 0 38 for polysilicon/silicon nitride contacts and 0 25 to 0 35 for polysilicon/silicon contacts Nitrogen has no influence on the frictional behavior of the micromotors made with dissimilar silicon and silicon compounds as the bearing contact materials Those measured results between millimeter components agree well with the results from in situ friction measurement on micromotors

References

[1] Deng K, Ko W H and Michal G M 1991 A preliminary study on friction measurement in MEMS *6th Int Conf on Solid-State Sensors and Actuators (Transducers'91) (San Francisco CA 1991)* (New York IEEE) Technical digest p 213–6
[2] Mehregany M, Phillips S M, Hsu E T and Lang J H 1991 Operation of harmonic side-drive micromotors studied through gear ratio measurements *6th Int Conf on Solid-State Sensors and Actuators (Transducers'91) (San Francisco, CA 1991)* (New York IEEE) Technical digest p 59–62
[3] Lim M G, Chang J C, Schultz D P, Howe R T and White R M 1990 Polysilicon microstructures to characterize static friction *Proc MEMS '90 (Napa Valley, C4 1990)* p 82–88
[4] Tai Y C and Muller R 1990 Friction study of IC-processed micromotors *Sens Actuators* A21-3 180
[5] Gabriel K J, Behi F and Mahadevan R 1990 *In situ* friction and wear measurements in integrated polysilicon mechanisms *Sens Actuators* A21-3 184
[6] Ott J 1988 The shear strength of aluminum-sapphire contacts in ultra-high vacuum *MSc thesis* Department of Material Science, Case Western Reserve University, USA
[7] Zangwill A *Physics at Surfaces* (Cambridge Cambridge University Press) p 227
[8] Rabinowicz E 1980 Friction—especially low friction fundamentals of tribology *Proc Int Conf on the Fundamentals of Tribology (Cambridge, M 4, 1978)* (Cambridge, MA MIT) p 351
[9] Taber D 1981 Friction—the present state of our understanding *J Lubricant Technol* 103 172
[10] Adamson A W *Physical Chemistry of Surfaces* 4th edn
[11] Pepper S V 1976 Effect of adsorbed films on friction of Al_2O_3–metal system *J Appl Phys* 47 2579–83