Wednesday Morning, October 22, 2008

Tribology Focus Topic
Room: 205 - Session TR+MN+NC-WeM

Surfaces and Interfaces in MEMS/NEMS

Moderator: J.A. Harrison, United States Naval Academy

8:00am **TR+MN+NC-WeM1 A Study of Au and Ru RF MEMS Contacts in Controlled Vacuum Environments**, ***M. Walker***, North Carolina State University, *N. McGruer*, Northeastern University, *J. Krim*, North Carolina State University

Studies of RF MEMS switch performance under ultra clean and controlled environmental conditions have to date been extremely limited.[1] Such studies are highly valuable however, as they provide an opportunity to separately examine the impact of various factors such as contamination films, creep, deformation and stiction that plague current RF MEMS switch reliability. We have constructed a custom ultra high vacuum chamber with in situ surface cleaning, variable temperature and gas dosing capabilities in an effort to isolate the multiple variables that impact RF MEMS contact resistance and longevity. This chamber allows us to study switches in atmosphere followed by studies performed in the cleanest environment possible. We have investigated cantilever MEMS devices with both Au on Au and Ru on Ru contacts. Au on Au switches have so far been investigated by the vast majority of studies, and provide baseline material for our studies. Ru on Ru switches are far less studied. Ru is currently our material of interest on account of its harder properties that resists creep and deformation. In atmosphere we observe the resistance of a closed switch over time then open the switch. We pump the chamber to a base pressure of 9 x 10-10 torr followed by measuring the resistance over time then opening the switch. Surface cleaning is performed via in situ oxygen plasma. This is followed by closing the switch and observing the resistance over time. We have observed switches that have initially had infinite resistance in both atmosphere and UHV exhibit tens of ohms contact resistance after oxygen plasma cleaning. The resistance values after oxygen cleaning are closer to the theoretical values for clean contact. We compare these resistance changes to theoretical models[2] that account for creep and deformation of the switch contacts. A study of contact resistance as a function of hydrocarbon uptake is in progress.[3] This work was supported by the DARPA Center for RF MEMS Reliability and Design Fundamentals Grant # HR0011-06-1-0051 and the AFOSR Extreme Friction MURI Grant #FA9550-04-0381.

[1] C. Brown, A. Morris, A. Kingon, J. Krim, submitted to J. MEMS
[2] O. Rezvanian, C. Brown, M. Zikry, A. Kingon, J. Krim, D. Irving, D. Brenner, submitted to J. Applied Physics
[3] H. Koidl, W. Rieder, Q. Salzmann, vol. 22, No. 3, 1999 .

8:20am **TR+MN+NC-WeM2 Bimetallic Nanoparticles as Surface Coatings in MEMS Switch Contacts**, ***M.L. Jespersen***, Air Force Research Laboratories, *S.T. Patton*, University of Dayton Research Institute, *J. Slocik, R. Naik, A. Campbell, A.A. Voevodin*, Air Force Research Laboratories

Microelectromechanical systems (MEMS) switches have a broad range of applications in the aerospace, communications, and electronics industries. However, contact failure, especially during hot switching, prevents widespread implementation of the next generation MEMS devices in new technologies. Few studies have investigated physical and chemical processes that occur on modified MEMS contact interfaces, although one published study used self-assembled monolayers (SAMs) as a switch lubricant.[1] These SAMs thermally decompose in the contact.[1] We also have investigated nanoparticle liquids (NPLs) deposited onto MEMS contacts as nanomaterial-based lubricants, which improved the performance and durability of MEMS contact switches by orders of magnitude.[2] In this study, we investigated bimetallic (Au/Pd) nanoparticles (NPs) as surface lubricants for MEMS contact switches. Bimetallic systems offer enhanced properties for MEMS by taking advantage of the physical characteristics of the individual components. For example, Au has a low contact resistance, while Pd exhibits higher melting temperatures and lower adhesion. Performance of bimetallic NP-lubricated contact surfaces were investigated, using a micro/nanoadhesion apparatus as a MEMS switch simulator with in-situ monitoring of contact resistance and adhesion force. Ex-situ analyses of the chemical and physical processes at the contact interfaces were carried out using SEM, TEM, XPS, and scanning Auger spectroscopy. Bimetallic NPs exhibited orders of magnitude improvement in electrical performance and durability as compared to uncoated and SAM-coated contacts. The observed improvement in performance and reliability results from nanoscale surface roughness extending across multiple nanocontact regions, enhanced thermal and electrical conductivity over SAM coatings, and self-limited nanowire growth that prevents shorting failure in the contact regions, as determined from physical and chemical analyses. Based on these results, bimetallic nanoparticles are promising candidates as surface lubricants for MEMS switch contacts.

[1]S. T. Patton, K. C. Eapen, J. S. Zabinski, J. H. Sanders, and A. A. Voevodin, "Lubrication of MEMS RF switch contacts using self-assembled monolayers," J. Appl. Phys., vol. 102, pp. 024903-1 – 024903-5, 2007.
[2]A. A. Voevodin, et al."Nanoparticle-Wetted Surfaces for Relays and Energy Transmission Contacts." Small, vol. 3, pp. 1957-1963, 2007.

8:40am **TR+MN+NC-WeM3 Contact Mechanics and Lubrication of MEMS Switches: Insights from Atomic and Multiscale Modeling**, ***D.W. Brenner***, North Carolina State University **INVITED**

We have been using a combination of molecular modeling and continuum analysis to understand and predict a range of dynamic processes that occur during the contact of RF and capacitive MEMS switches. The results of these studies are being used in the rational design of new materials and lubrication strategies for enhancing the lifetimes of these devices. In the case of closed RF-MEMS switches, it will be shown that the time-dependent resistance is well described by a power law, and using an asperity creep model that the prefactor and exponent in the power law can be related to the surface roughness and creep coefficient, respectively. For capacitive switches we have used molecular modeling to explore the efficacy of a "bound+mobile" lubrication scheme involving tricresylphosphate molecules diffusing on a octadecytrichlorine self-assembled monolayer. Temperature-dependent diffusion coefficients calculated from the simulations have been used in a scaling relation for liquid lubrication that depends on the ratio of the contact area to the product of the lubricant diffusion coefficient and the switch cycle time. This combination of atomic modeling and multiscale analysis predicts that this molecule-surface combination will only be effective for temperatures greater than ~200K and up to ~MHz oscillation frequencies.

This work was done in collaboration with D. Irving, O. Rezvanian, C. Brown, M. Zikry, A. Kingon, C. Padgett and J. Krim. This work was supported by the Extreme Friction MURI program, AFOSR grant FA9550-04-1-0381 and the Office of Naval Research.

9:20am **TR+MN+NC-WeM5 Sidewall Tribometer Study of Vapor Phase Lubricants for MEMS**, ***D.A. Hook***, *B. Vlastakis, B.P. Miller*, North Carolina State University, *J. Rutledge*, University of California, Irvine, *M.T. Dugger*, Sandia National Laboratories, *J. Krim*, North Carolina State University

Long hydrocarbon and fluorocarbon based monolayers have been widely used in MEMS applications to prevent release related stiction and adhesion. These and similar monolayers, however, have proven ineffective as MEMS lubricants. Indeed, even the most robust of SAM layers fails to protect devices from tribological failure for either normal or sliding cyclic contact.[1] Alternate schemes, such as vapor phase lubrication, must therefore be developed if progress is to occur.[2] The vapor phase of pentanol has recently been reported by Seong et al to extend the lifetime of a MEMS device in a mixture of dry nitrogen and various concentrations of pentanol. Macroscale friction experiments have meanwhile shown the build up of long carbon chain reaction films in identical conditions.[3] In order to probe the effectiveness of pentanol and related alcohols, we have employed a ringdown measurement technique with a specially designed MEMS sidewall tribometer to compare the coefficients of friction of a device before and after introduction of pentanol into a vacuum chamber at one monolayer of coverage. Initial measurements show no change in the coefficient of friction, but subsequent measurements show a progressive decrease. This reflects a formation of a reaction film extremely quickly upon rubbing. Lifetime measurements using the sidewall tribometer were also taken with shorter chain alcohols, namely trifluoroethanol and ethanol, at one monolayer coverage to determine whether amount of carbon present affects the lubricating properties as well as the role of methyl versus trifluoromethyl termination. It has been found that ethanol's ability to lubricate is dependant upon the initial state of the device whereas trifluoroethanol and pentanol will lubricate a device that has previously failed. Work funded by the AFOSR Extreme Friction MURI #FA9550-04-0381.

[1]Hook, D.A., Timpe, S.J., Dugger, M.T., Krim, J., "Tribological Degradation of Fluorocarbon Coated Silicon Microdevice Surfaces in Normal and Sliding Contact" Journal of Applied Physics, in press
[2]Krim, J., Abdelmaksoud, M., "Nanotribology of Vapor-Phase Lubricants" Tribology Issues and Opportunities in MEMS, B. Bhushan, ed. 1998 pp. 273-284
[3]Asay, D.B., Dugger, M.T., Ohlhausen, J.A., Kim, S.H., "Macro- to Nanoscale Wear Prevention via Molecular Adsorption", Langmuir 2008, 24, 155-159.

9:40am **TR+MN+NC-WeM6 Effects of Organic Vapor Adsorption on Nanoasperity Adhesion and Friction – From Fundamentals to MEMS Applications**, ***S.H. Kim***, Pennsylvania State University

As the contact size involved in mechanical device operations decreases, the adsorption of gaseous molecules on the contact surface – which normally

ignored in macroscopic measurements – becomes more important and dominant factors governing the contract properties such as adhesion and friction. Water adsorption can causes high adhesion and severe wear of silicon oxide surfaces. In contrast, alcohol vapor adsorption from the ambient can provide unprecedentedly efficient lubrication effects for operation of microelectromechanical systems (MEMS) with sliding contacts. Atomic force microscopy (AFM) is an ideal tool for studying the adhesion and frictional behavior of nanoscale asperity contacts. The tribological response of a silicon nanoasperity contact was studied with AFM with alcohol vapors as the VPL. Alcohol vapor adsorption on silicon oxide surface readily forms a thin organic film on the surface which mitigates the adhesion and friction forces between the AFM tip and substrate surfaces. The origin of adhesion and friction changes in the presence of alcohol vapor is elucidated through vibrational spectroscopic investigation of the thickness and structure of the adsorbed layers as well as theoretical calculations of their tribological responses.

10:40am **TR+MN+NC-WeM9 Dynamics and Spreading of Pentanol and Other Alcohols for MEMS Applications**, ***B.P. Miller***, *J. Krim*, North Carolina State University

Microelectromechanical Systems (MEMS) have the potential to revolutionize widespread technologies, but friction and other tribological issues are currently preventing commercialization of devices that contain surfaces in sliding contact. Self-assembled monolayers (SAMs), while highly effective against release related stiction, have proven ineffective as MEMS lubricants. Indeed, even the most robust of SAMs fail to protect devices from tribological failure for either normal or sliding cyclic contact.[1] Alternative MEMS lubrication schemes must therefore be developed if progress is to occur. Vapor phase lubrication has been proposed as a solution to the issue of tribological device failure in Micro-Electro-Mechanical Systems (MEMS) with TCP and alcohol vapors attracting much interest as candidate materials.[2] In an effort to understand the basic mechanisms of lubrication we have performed a quartz crystal microbalance (QCM) study of the uptake, sliding friction, and spreading rates of adsorbed ethanol, trifluoroethanol (TFE) and pentanol films on silicon, aluminum and perfluorodecyltrichlorosilane (PFTS) treated substrates.[3] In response to the oscillatory motion of the QCM, pentanol, and also ethanol, exhibit viscoelasticity and/or interfacial slippage when adsorbed on silicon or PFTS, implying that enhanced tribological performance may be expected in MEMS devices. TFE exhibited slippage on silicon but not PFTS. Significantly lower mobility levels were observed for all three alcohols adsorbed on aluminum. This work is funded by AFOSR Extreme Friction MURI Grant #FA9550-04-1-0381.

[1]D. A. Hook, M. T. Dugger, and J. Krim. J. Applied Physics, in press.

[2]J. Krim and M. Abdelmaksoud, in Tribology Issues and Opportunities in MEMS, B. Bhushan, ed. (Kluwer Academic, Dordrecht, 1998), pp. 273-284; W. Neeyakorn et al., Trib Lett. 27 (2007) 269-276; D. B. Asay, M. T. Dugger, S. H. Kim. Trib Lett. 29 (2008) 67-74.

[3]B.P. Miller and J. Krim, Submitted to Langmuir.

11:00am **TR+MN+NC-WeM10 Effect of Fluid Flow on the Sensitivity of Microcantilever Sensors**, ***R. Desikan***, *D. RangaPrasad, A. Passian, R.H. Datar, T.G. Thundat*, Oak Ridge National Laboratory

Microcantilever arrays are emerging as an attractive platform for detection of biomolecules because of their high sensitivity, miniature size, and their ability to work under solution. Selectivity in detection is accomplished by immobilizing receptor molecules on one surface of the cantilever. Interaction of biomolecules with the immobilized receptors results in cantilever bending. In general, the cantilevers are operated under constant flow of the buffer solution. Since cantilevers are sensitive to fluid flow, the flow rate is kept constant during injection of analytes in the flowing buffer solution. In some cases, reference cantilevers are used to eliminate the effect of fluid flow rate. However, we have observed that the interaction of analytes on receptors on cantilever surface is affected by the variations in the flow rate. More analyte molecules tend to bind the receptors on cantilever surface in static condition when molecular interaction is influenced by diffusion, compared to dynamic condition where analyte molecules flow across the cantilever using a flow control system. This work addresses the issues associated with biomolecular adsorption kinetics, flow rate dependence, and cantilever geometry for increasing the sensor sensitivity.

11:20am **TR+MN+NC-WeM11 Self-Affine Fractal Analysis of MEMS Surfaces for Minimizing Adhesion**, *D.-L. Liu*, Worcester Polytechnic Institute, *J. Martin*, Analog Devices Incorporated, ***N.A. Burnham***, Worcester Polytechnic Institute

Differing approaches to studies of the influence of surface roughness on adhesion have recently appeared in the literature. Molecular dynamics has been used to simulate the contact of two surfaces and found that atomic-scale roughness can have a large influence on adhesion, causing the breakdown of continuum mechanics models.[1] Yet a simple continuum model predicted the qualitative behavior of adhesion as a function of root-mean-square surface roughness in the nanometer to tens-of-nanometers range.[2] Although a useful first-order approximation, the assumptions in the latter work were severe; a more descriptive approach is necessary in order to design surfaces that either maximize or minimize adhesion. Self-affine fractal analysis provides a reasonable framework in which to move forward. In addition to the root-mean-square (RMS) roughness, it characterizes surfaces with two more parameters, the roughness exponent and the correlation length. A high roughness exponent and a small correlation length should minimize adhesion for two rough surfaces, as predicted by Chow.[3] Our adaptation of his work shows similar results for the case of a smooth tip of an atomic force microscope (AFM) and a rough surface. Specifically, the surfaces had the same RMS roughness, 0.2 μm, and the same lateral correlation length, 3.0 μm, but their roughness exponents ranged from 0.1 to 1.0. The height-height correlation functions and the height distribution functions were calculated from the surface height data, and the three fractal parameters were extracted for all the surfaces. The adhesion between a smooth AFM tip and the fractal rough surfaces were then calculated based on both the height distribution and the force-distance relationship between one molecule in the AFM tip and the fractal rough surface. The adhesion was found to decrease linearly as the roughness exponent increased. Furthermore, experimental data of the adhesion between AFM tips and MEMS surfaces as a function of the three fractal parameters will be shown and compared with the theoretical predictions. The work presented here should help minimize adhesion in future MEMS devices and progress the understanding of adhesion between the atomic- and macro-scale.

[1] B. Luan and M.O. Robbins, Nature 435, 929-932 (2005).

[2] D.-L. Liu, J. Martin, and N.A. Burnham, Appl. Phys. Lett. 91, 043107 (2007).

[3]T.S. Chow, Phys. Rev. Lett. 79, 1086 (1997).

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