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IMPACT – Center for Advancement of MEMS/NEMS VLSI

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Summary of Research Progress

I. Mechanical Domain Characterization and Modeling

Our mechanical characterization and modeling activities emphasize the experimental investigation at the micro- and nano-scale of the mechanical properties of materials used in MEMS, and their accurate quantitative description in terms of models compatible with multi-physics, stochastic computational techniques, to be used for device functionality assessment and trustworthy device performance degradation analysis. The following are highlights from research accomplishments during Q4.

Characterization of Stress Relaxation Behavior of Metal Films in RF MEMS Capacitive Switches

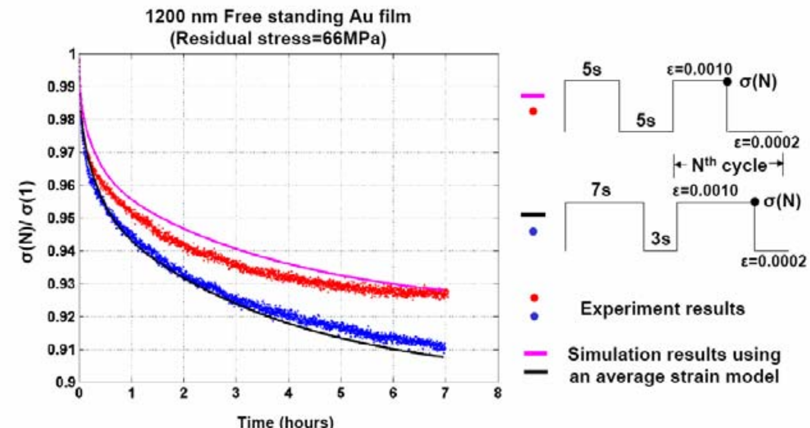
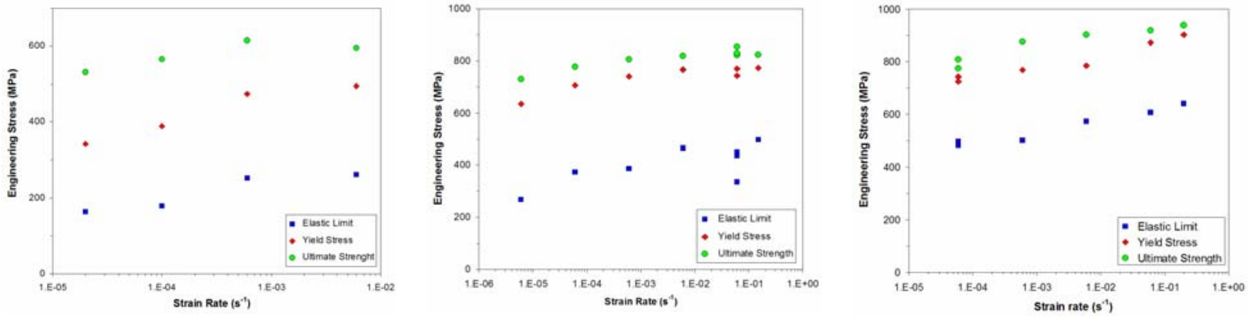


Figure 1.

This research is carried out at Lehigh under the supervision of Professors Rick Vinci and Walter Brown, and in collaboration with Professor John Papapolymerou at Georgia Tech. In order to understand and improve the mechanical behavior of metal films used in RF MEMS capacitive switches, a gas pressure bulge testing system was adapted in Q3 to study the stress relaxation behavior of metal films under constant strain. In Q4 the equipment was further modified for strain cycling to simulate the pull-down and release of a switch component. Free-standing Au films with the thickness of 1200 nm were fabricated and characterized. As shown in the plot in Figure 1, the load cycling frequency is 0.1Hz. Experiments with two different duty cycles were carried out, and the stress of the film at the end of the "on" state in each cycle (σ(N)) was measured. We have found that even when the strain is cycled rapidly compared to the characteristic relaxation time, the restoring force available for opening a switch decreases over times of minutes and hours. This decrease is due to the non-zero average strain experienced by the switch; the larger the average strain, the bigger the decrease. Simulations based on an average strain model represent reasonably well the time dependence of the releasing stress and the difference in that stress for the two duty cycles measured. This model predicts that the decrease in restoring force is independent of the period of a single cycle, as long as the period is short compared to the typical relaxation times. This allows prediction of relaxation in complex loading cycles based on characterization of simple monotonic stress relaxation under constant strain conditions.

Mechanical Response of Au Films at Fast / Slow Actuation Rates for Large Displacement MEMS

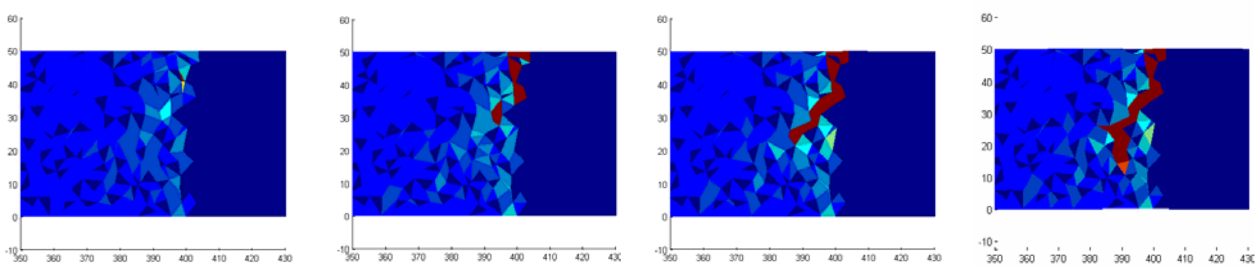
In parallel to the above mechanical characterization activity, Professor Ioannis Chasiotis' group at the University of Illinois, with support by Prof. Peroulis group at Purdue, has investigated the mechanical response of Au films of two different thicknesses: 830 nm and 1760 nm. Films with a third thickness of 500 nm have also been planned. The three film thicknesses are typical for the RF-MEMS applications of interests. This is the second round of fabrication since the initiation of this project, which resulted in improved Au films with more tolerance to stresses and smaller propensity for plastic deformation. Specifically, Figures 2(a-c) show our results of the new tensile tests compared to the first fabrication run. It is noteworthy that the elastic deformation limits (elastic limit) and failure properties (yield and failure strength) of the new Au films are improved. The unusually large strength and yield properties are attributed to the very small grain size that does not promote dislocation-driven plasticity. The grain size, as measured by XRD is 38 nm, which places this Au in the grain boundary controlled plasticity regime that is mostly diffusional and is characterized by slow creep. Differences in the mechanism of damage accumulation in the material at the different loading/actuation rates were investigated also. At the slow strain rate, shear localization resulted in extensive plasticity, which is typical in macroscale testing of bulk Au, with attendant formation of large voids inside the cross-section. At strain rates 6×10^{-2} s^{-1}, or faster, plasticity was of similar extent but the loading rate limited the effect of material relaxation and therefore micro-cracking and formation of surface voids occurred. On-going work focuses on the completion of these experiments on strain rate, extending the loading rates in the range possible by our instrumentation. Subsequently, the creep response of this Au and its relationship to film thickness and, if possible, grain size, will be investigated.



(a) (b) (c)

Figure 2. Critical material properties as a function of loading/actuation rate for three different Au films: **(a)** 2,000 nm Au fabricated in the beginning of the project, **(b)** 1,760 nm Au, and **(c)** 830 nm Au. The improvement in the elastic limit (the largest stress that can be applied before the material deforms plastically) is attributed to the small grain size.

Stochastic Grain-Scale Fatigue Modeling of Large-Displacement MEMS Devices



N = 8708 cycles
Crack Initiation

N = 8894 cycles

N = 8934 cycles

N = 8937 cycles
Failure

Figure 3. Damage accumulation in terms of numbers of cycles.

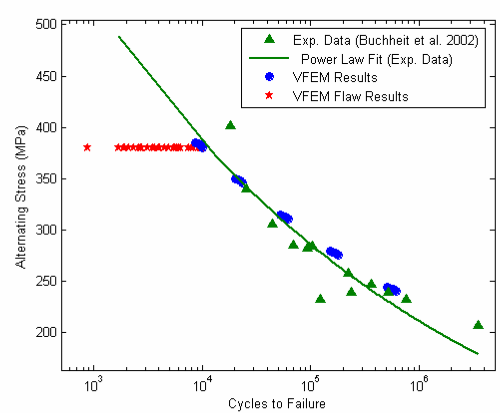


Figure 4. S–N diagram comparison of experimental & analytical results.

The aforementioned experimental mechanical characterization activities were complemented by mechanical modeling efforts at Purdue and the University of Illinois. At Purdue, under the supervision of Professor Farshid Sadeghi, a damage mechanics model was incorporated into the group's Voronoi finite element method (VFEM) and discrete element method (DEM) models to investigate the fatigue life of MEMS. In damage mechanics model, there is damage variable 'D' which can range from 0 to 1. D = 0 means there is no damage in cross section and D = 1 means cross section failed completely. Also, other formulas relating the damage variable to effective stress and alternating stress to damage accumulation rate are used for high cycle fatigue. The damage model enhanced VFEM was applied to 32 tensile specimens with randomly generated microstructures to obtain their fatigue lives. A completely reversed stress with alternating stress equal to 350 MPa was employed. The damage accumulation (crack propagation) in terms of number of cycles is shown in Figure 3 for the considered domains. As shown, most of the fatigue life was spent before crack initiation. The obtained average life, equal to 9285 cycles, is in very good agreement with the experimental results. By considering the homogeneous material properties, a Weibull slope equal to 19.99 was obtained, indicating that there is a good correlation between the fatigue lives. Two different kinds of inhomogeneity: 1) random Young's modulus, 2) random resistance stress, were applied to the samples to investigate the effects of non-uniform material properties on the fatigue life. In both cases, inhomogeneity reduced the average fatigue life and increased the scatter between fatigue lives. Also, a randomly located initial crack was introduced in each sample. Such initial cracks can cause a dramatic decrease in fatigue life and a significant increase in fatigue life scatter. The obtained stress – life diagram is shown along the experimental data in Figure 4. Good agreement is observed.

Multiscale modeling of MEMS materials

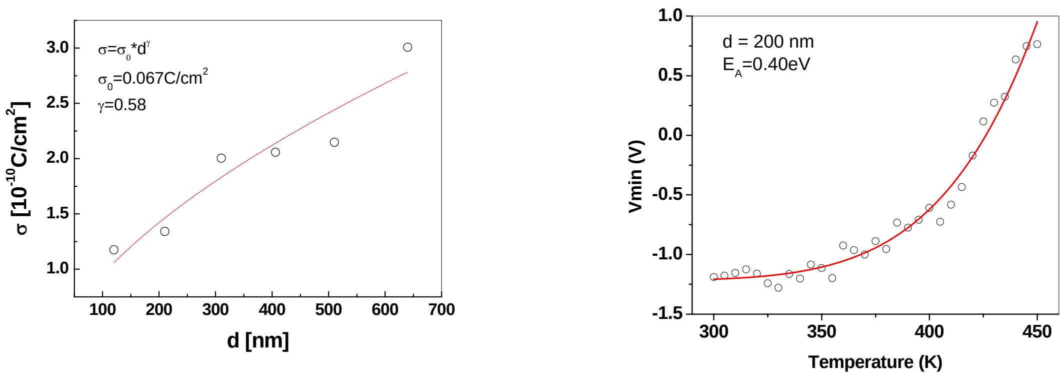
The structural response of MEMS devices is often affected by the granular microstructure of the material. This is particularly true for NEMS and for micron-size features of MEMS devices (such as notches and anchors) with dimensions of the order of grain sizes. Professor Philippe Geubelle's group at the University of Illinois is pursing the development and implementation of a multiscale numerical tool based on the finite element method to extract the effect of the granular microstructure on the constitutive and failure response of MEMS materials. More specifically, the project is focused on creep response of nano-crystalline Au films. Over the last three months, progress has been made in the ability to simulate the effect of intergranular failure on the macroscopic response of polycrystalline materials. The intergranular failure process is modeled with the aid of cohesive (interfacial) elements placed along the grain boundaries. These cohesive elements are characterized by an exponential cohesive model, defined primarily by a failure strength and a fracture energy, accounting for the competition between shear and tensile failure of the grain boundaries. The multiscale finite element framework is able to capture the heterogeneity of the micro-scale solution (in terms of the displacement jumps across the grain boundaries and the associated stress field) and its effect on the macroscopic stress-strain relation. The quantified form of such a relation is important for performance degradation modeling at the MEMS device level. Besides the deterministic analysis, the variance of the homogenized elastic properties due to variations on the grain arrangement and grain orientation was investigated. For this purpose, auxiliary tools have been developed, capable of automatic generation of a number of grains arrangements, also supporting meshing and the assignment of randomized grain orientation. Applying the same multiscale framework, the Young's modulus standard deviation can be computed as a function of the number and orientation of the grains inside the unit cell. Current activities involve the development of a cohesive model to represent creep mechanisms observed in nano-crystalline Au films. This model will account for rate dependent grain boundary sliding and will be validated through comparison with creep experiments being conducted in Prof. Chasiotis' group.

II. Electrostatic Domain Characterization and Modeling

Our electrostatic characterization and modeling activities emphasize the advancement of more accurate models for the quantitative description of dielectric charging in RF MEMS capacitive switches. The following are highlights from research activities and findings during Q4 2007.

Experimental Investigation of Dielectric Layer Thickness on Dielectric Charging

In Prof. John Papapolymerou's group at Georgia Tech, a variety of capacitive RF MEMS switches and MIM capacitors were fabricated in order to characterize the dielectric charging effect. The thickness, *d*, of the SixNy dielectric layer was varied from 200 nm to 500 nm. Capacitance-voltage (CV) characteristics were performed for the RF MEMS switches. The capacitance was monitored in the temperature range of 300K to 450K. To provide for approximately constant electric field, the electric field dependence of $E\sim V/d$ was used to set the maximum voltage value for different thicknesses. MIM capacitors were also fabricated in an analogous way to the RF MEMS switches. The dielectric film was PECVD Si_3N_4 deposited at 150°C. Capacitors with dielectric film ranging from 100 nm to 600 nm and symmetrical or asymmetrical contacts were fabricated. The charging process was investigated by applying the TSDC method. This allowed the calculation of stored charge, the analysis of various charging mechanism and their dependence on the film thickness, bias polarity, and metal insulator contacts. From the TSDC measurement of the MIM capacitors the total stored charge was calculated and results are shown in Fig. 5a. Assuming that in the absence of dielectric there must be no stored charge, an empirical equation for the dependence of the stored charge, σ, on the dielectric layer thickness, d, was obtained, $\sigma(d) = \sigma_0 d^{\gamma}$, where $\sigma_0 = 0.067$ C/cm^2 and $\gamma = 0.58$. This suggests a square root dependence of the stored charge on the dielectric thickness. The capacitance-voltage descending voltage minimum variation with temperature in RF MEMS capacitive switches is thermally activated also. This arises from the fact that the voltage minimum (Vmin) is proportional to the dielectric stored charge. The voltage minimum shift was fitted with an exponential function, with $V_0 = -1.22$ V and an activation energy of 0.40 eV, and is presented in Fig. 5b. The higher activation energy may be attributed to the fact that in MIM capacitors the top electrode is deposited by evaporation while the dielectric charging in a MEMS switch occurs through mechanical contact through a rough surface that is present on both the dielectric surface, due to the electroplated waveguide, and the contacting bridge, due to the sacrificial layer. More measurements are currently under way to further evaluate and model this effect for different nitride thicknesses.



(a) (b)

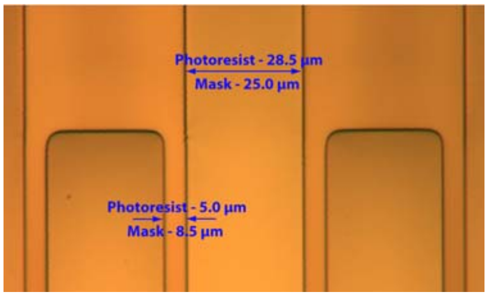
Figure 5. a) Dependence of total stored charge on film thickness; b) CV descending voltage min. variation with temperature.

<u>Compact Modeling of Dielectric Charging</u>

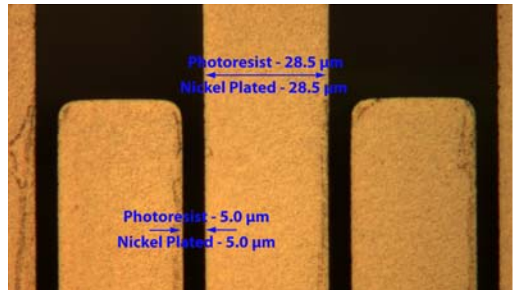
Under the supervision of Professors Andreas Cangellaris and Narayan Aluru at the University of Illinois, a compact model was proposed and demonstrated for dielectric charge build-up and evolution in RF MEMS capacitive switches. The proposed model relies on experimentally-obtained data, using the dielectric charging measurement protocols developed in Professor Hwang's group at Lehigh, for the definition of its parameters, thus allowing for non-linearities in material electrical properties to be incorporated in its definition. The compactness of the model lends itself to the efficient and accurate simulation of dielectric charging under complex control voltage waveforms. It is easily cast in the form of a SPICE equivalent circuit, which can be used to expedite the computer-aided assessment of the impact of dielectric charging on the performance of the switches. In addition, because of its physics-based description, the proposed model should be found useful for incorporation in the electro-mechanical models for MEMS switches used in system-level MEMS simulation tools. The details of the proposed model and demonstration of its accuracy can be found in [1].

III. Test Devices for In-Situ Process Characterization

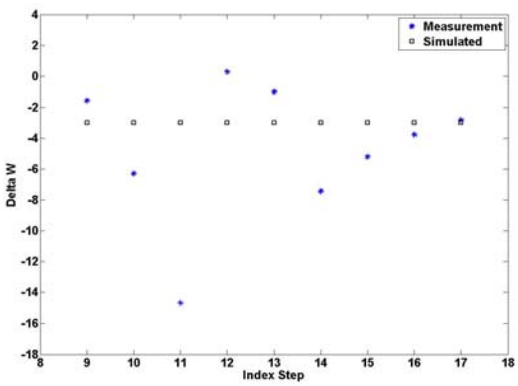
In Professor Dimitri Peroulis' group at Purdue the first experimental results were demonstrated of a new process, called ***Electro-Micro Metrology*** (EMM) for quantifying process variations related to material and geometrical properties. This newly proposed EMM Measurement Protocol (EMM MP) measures changes in capacitance of electro-actuated comb structures. As discussed in the last quarterly report, two comb structures are designed, each of different beam widths, and placed adjacent to each other. If the geometry changes during fabrication, because of the close proximity, the geometry differences of these two structures are expected to be the same. The changes in capacitance of each fabricated structure are measured and used to compute the geometry change during fabrication. The computed average change in geometry from measurement was ~4.67μm. A Sigma-Delta low capacitance measurement method was used to detect changes in the femto regime. In this proof-of-concept experiment, a visual comparison is made of the geometry of the lithography mask, the photoresist electroplating mold, post electroplating structure and final process structure. Visual inspections are made using optical microscope and scanning electro beam microscope. The observed geometry change from lithography mask to photoresist mold is ~3.5µm. No changes were observed during electroplating and final processing. On-going activities include the measurement of more structures and improvements of the model used for extracting geometry change from measured capacitance values.



Photoresist Geometry: Geometry change of 3.5µm difference between mask and photoresist pattern



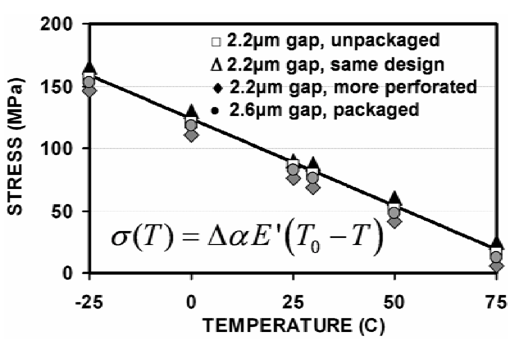
Nickel Plated Geometry: No geometry change during electroplating.



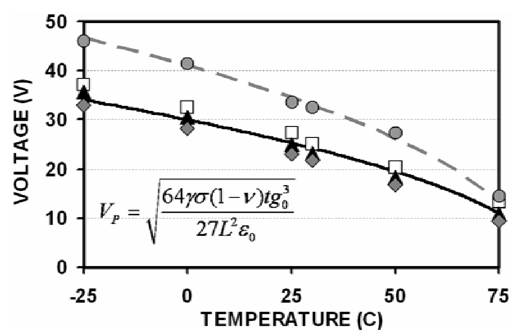
- Negative value of Δw means fabricated geometry is smaller than design geometry.
- Optical microscope and SEM inspected change in geometry is –3.5 µm.
- Averaged change in geometry, Δw, from measurement is –4.67µm.

Figure 6. Preliminary results from the application of EMM for MEMS process variation measurements.

IV. Methodology for monitoring the residual stress in RF MEMS devices



(a)



(b)

Figure 7. Measured (symbols) vs. (curve) modeled (a) residual stresses and (b) pull-in voltage as a function of temperature for (□, Δ, ♦) unpackaged and (•) packaged RF MEMS capacitive switches.

The ability for in-situ measurement of residual stress is essential for accurate predictive assessment of MEMS switch degradation and life testing. Toward this objective, in Professor James Hwang's group at Lehigh a microwave intermodulation technique was used for the first time to measure the mechanical resonance directly on packaged and unpackaged RF MEMS capacitive switches with quality factors approaching unity due to air damping. The result is validated by similar measurements in vacuum with much higher quality factors. From the measured resonance frequencies, the residual mechanical stress of the fixed-fixed membrane of the switches is derived and its temperature dependence is analyzed (Fig. 7a) and correlated (Fig. 7b) with that of the pull-in voltage. The present technique offers a convenient means for monitoring the residual stress in RF MEMS devices in both manufacturing and operation. It also allows mechanical and electrical degradation effects to be conveniently separated during life testing of the switches. Details of the methodology are presented in [2].

V. Computational Framework for Stochastic Multi-Physics Modeling

Research continued under the leadership of Professor Aluru at the University of Illinois toward the development of a fully-coupled, electro-mechanical stochastic modeling framework for electrostatically-actuated MEMS, accounting for uncertainties in geometric/material properties and loading conditions. In addition an effort was initiated toward the efficient modeling of the physics of thermal and electrical failure of these devices through arc formation in metal-to-metal contact switches. This phenomenon involves, at a microscopic and atomistic level, coupled transport of heat, charge and matter in the interstitial plasma and at the metal-plasma interface.

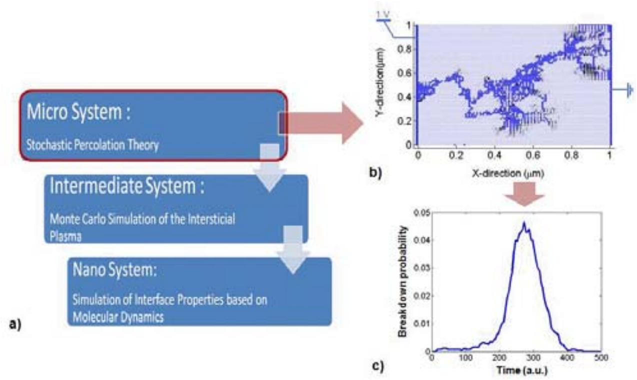


Figure 8. Multiscale framework for the modeling of arcing at metal-to-metal contacts.

A multiscale simulation framework has been developed (Fig. 8a) to model the coupled effects leading to arc failure. An implementation of the highest level of this framework, while assuming linear output of the lower levels, has been provided in adaptable software aiming at simulating the failure dynamics for various device shapes and materials. The current version of the software has already shown the ability to describe the apparition of electrical arcs (Fig. 8b) between the plates. It furthermore outputs statistical data that can be correlated against experimental data to refine the models (Fig. 8c).

Most recent work focuses on the implementation of the lower levels of our framework and the inclusion of non-linear interfaces.

Patents
None

Publications & Conference Presentations
[1] P. S. Sumant, N. R. Aluru, and A. C. Cangellaris, "A Compact Model for Dielectric Charging in RF MEMS Capacitive Switches," paper under preparation. **(PDF attached to this report)**

[2] C. Palego, et al, "Microwave Intermodulation Technique for Monitoring the Mechanical Stress in RF MEMS Capacitive Switches," submitted to *2008 IEEE International Microwave Symposium*. **(PDF attached to this report)**

[3] R. Daigler et al, "Effect of Dielectric Film Thickness on Dielectric Charging of RF MEMS Capacitive Switches," submitted to *2008 IEEE International Microwave Symposium*. **(PDF attached to this report)**

[4] G. Papaioannou, et al, "Dielectric Discharging Processes in RF-MEMS Capacitive Switches," presented at the *2007 IEEE Asian-Pacific Microwave Conference,* Bangkok, Thailand, December 2007.

[5] J.C.M. Hwang, "Reliability of Electrostatically Actuated RF MEMS Switches," *2nd IEEE International Workshop on Radio-Frequency Integration Technology*, Dec. 9-11, 2007 in Singapore. **(PDF attached to this report)**

[6] R.P. Vinci, T. Bannuru, T. Humplik, S. Narksitipan, and W.L. Brown, "Evaluation of Novel Metal Contacts for Wear-Resistant MEMS Switches," *Mat. Res. Soc. Symp.,* Nov. 2007.

[7] X. Yan, W.L. Brown, Y. Li, J. Papapolymerou, R.P. Vinci, "Stress Relaxation in Metal Films and Associated Loss of Restoring Force in RF MEMS Switches," *Mat. Res. Soc. Symp.,* Nov 2007.