

Micromachined RF Switch with High Mechanical Reliability

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1. INTRODUCTION

Micro-electro-mechanical systems (MEMS) have significant attention for radio frequency (RF) applications because of their inherent size, cost and micro-scale functions. RF MEMS switches have many advantages compared with integrated circuit (IC) based switches for the following reasons; low insertion loss, low crosstalk, high contrast ratio, and low power consumption [1-5]. Various MEMS structural designs such as cantilevers [6-10], membrane structures [4,5,9-13], and lateral contacting switches [14,15] have been demonstrated. Additionally, various actuation systems including electromagnetic, electrostatic, and thermal-electric have been used for those designs [16-20]. They exhibit good RF performance, however, the contact lifetime is not good enough for high-end RF applications. In particular, resistive (metal-to-metal) contact switches, which can be widely operated from DC to RF frequency, lack mechanical reliability due to physical contact between metal and metal¹. Whereas we recognize that many researchers have proposed to increase the reliability by either robust bulk micromachining/wafer-to-wafer bonding structures [21-23], studying contact materials [24-26], or chemical treatment [27], their approaches have not provided satisfactory solutions for long life reliability. The reason is that a total RF switching system optimization has not been carried out in our understanding.

In this project, we propose mechanical switching approaches to realize a new RF MEMS resistive (metal-to-metal) switch, which has both high RF performance and reliability. Applying our new MEMS structural optimization method called MEMS Early-Stage Analysis (MESA), two kinds of new mechanical approaches, tri-state multi-contact switch and push-pull switch, are proposed [28,29]. The tri-state multi-contact switch was successfully designed, analyzed and fabricated through Metal MUMPs process, and the details of obtained results are reported [30]. Moreover, the push-pull switch concept was created based on the MESA results of cantilever shape switch and multi-contact switch. The concept and design of switch are described.

¹On the other hand, capacitive switches typically use a thin layer of dielectric material to separate two conducting electrodes. The dielectric layer prevents mechanical contact problems because of its low Young's modulus and insulation.

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14. ABSTRACT For this project, MESA (MEMS Early-Stage Analysis) was implemented to develop ,"tri state multi-contact" switch. The switch was designed and processed to enhance mechanical and RF performance compare to the conventional RF MEMS switches. The switch was successfully fabricated using Metal MUMPs (Thick Metal deposition) process. It demonstrated 107 cycles of switching and 0.5 dB insertion loss. This RF MEMS can be further developed for future advanced RF communications systems for the space based and superior air applications.					
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2. PROBLEM DEFINITION

Figure 1 shows a conventional electrostatically-actuated RF-MEMS switch. The switch is a bilayer cantilever beam that consists of stiff layer (i.e., SiO₂, Si, and Ni) and electrode/contact thin layer such as gold. Applying voltage to the electrodes, the electrostatic force pulls down the cantilever beam toward the bottom electrode and signal switching is made at the contact surfaces of beam edge. In micro scale, the contact metal surface is very rough and the real contact area is much smaller than the apparent contact area. Therefore, large contact force and some plastic deformation are required to obtain low contact resistivity. However, both large force and deformation cause the temperature increase of the contact surface. It is reported that the generated thermal energy is strongly associated with adhesion or stiction [31]. In addition, one paper reports that micro welding occurs at every switching due to RF signal power and impedance mismatch. This also roughens the contact surface and quickens the adhesion [32]. On the other hand, it is assumed that large impact force degrades the contact surface and causes cracks [33]. In general, switching lifetime is proportional to impact force from the metal fatigue life point of view. Although the details of the adhesion and degradation problems are not well-understood, both problems should be solved to achieve high reliability in RF MEMS switches. Many researchers have tried to enhance the reliability of the cantilever RF MEMS switches with improvement of contact material and fabrication process. The cantilever switch, however, has inherent design trade-offs and it is difficult to keep compatibility of reliability and RF performances without total switching system evaluation.

In our design of RF MEMS switches, we adopt our optimization method called MESA to establish new switch structures [28,29]. The MESA supports numerical evaluation of MEMS structures based on simple clarification of the relation between system performance and design factors. In RF MEMS switches, the desired performance of the switching system are good contact resistivity, RF isolation, high switching speed, and mechanical reliability and so on.

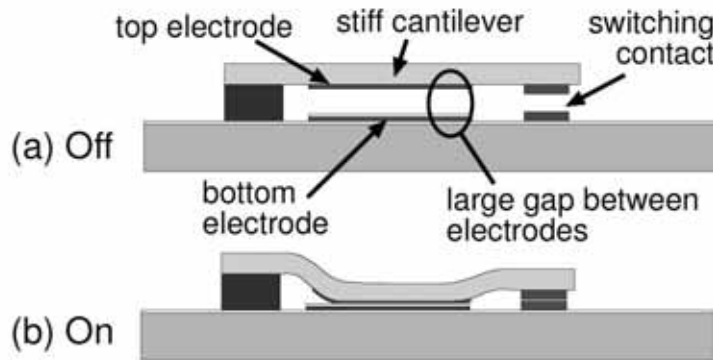


Figure 1. A conventional electrostatically-actuated RF-MEMS switch
(a) Off-state (b) On-state [31]

These system characteristics are decided by the design parameters such as spring constant, actuation voltage, electrode shape and distance. The relation is calculated by the system governing equations, for instance, equations of cantilever dynamic/static motions, electrostatic-mechanical equilibrium conditions, and contact surface physics [1, 2].

In the MESA, the sensitivity s_{ij} represents the relation and it is expressed as

$$s_{ij} = [\pm] \frac{\log(C_{ij,2}/C_{ij,1})}{\log(d_{j,2}/d_{j,1})} \quad (1)$$

where C_{ij} is the system performance and d_j is design factors. The sensitivity shows the effect of the design factor for the system performance. Visualizing the relation of design parameters and system performances by using the matrix, design information is shown to MEMS designers.

Applying the MESA for the cantilever shape RF MEMS switch, the clarification of design factors and system performance is conducted. Through the MESA, the structural problems of the switch are defined and new switching structures will be created. In the RF switch, 6 system performances are considered as the MESA system characteristics; (a) reliability: restoring force (related with stiction), (b) reliability: impact force (related with degradation), (c) contact resistivity, (d) switching speed, (e) RF isolation, and (f) size. The performances (a) and (e) are larger-is-better characteristics, and (b), (c), (d) and (f) are smaller-is-better characteristics. As design parameters, 5 variable factors are chosen; (i) cantilever spring constant, (ii) electrode gap, (iii) actuation voltage, (iv) electrode area, and (v) contact area. Based on the governing equations of the cantilever shape switch, the sensitivities are calculated and 5×6 MESA matrix can be created as shown in Table 1. The all design factors are assumed to vary within twofold range. Arrows next to the design factors indicate that the varying direction of design factor is "↑:ascent" or "↓:descent". In Table 1, all design factors are arranged with the ascent directions. Arrows next to the sensitivity values in the matrix shows that the change of design factors are "↑↑:desirable" or "↓↓:undesirable" for each performance.

The sensitivities show the effects of design factors against the system performances. The desirable/undesirable arrows represent whether the design tradeoffs exist or not in the system. In Table 1, it appears that many tradeoffs exist in all design factors. Focusing on one of design factors, for example the electrode distance, it affects all system characteristics. It is shown in the MESA matrix that the ascent change of electrode gap is desired for large restoring force and high RF isolation but it is undesired for impact force, contact resistivity, switching speed and size. Turning now to reliability, which is defined by restoring force and impact force, there are three tradeoffs regarding the design of spring constant, electrode distance and contact area. The design tradeoffs are inherent and they are difficult to be removed.

The system score S , which indicates the "rough" total system performance, can be calculated from

$$S = \sum_i^m \omega_i \sum_j^n s_{ij} \quad (-1 \leq S \leq 1) \quad (2)$$

where ω_i is a weight value for the system performance C_i . Using equal weight ($\omega_i = 0.2$) for 5 system characteristics except "size" ($\omega_i = 0$), the system score S_0 for cantilever switch becomes $S_0 = -0.13$. This system score is very bad and it indicates that cantilever structure is not suitable as a mechanically reliable switching system. Whereas we recognize that material approaches are effective for reliability improvement, it is concluded that material improvement is not a thorough approach under many design tradeoffs shown in Table 1. Thus, a mechanical approach is our primary solution to enhance the reliability in our design of RF switches. Based on the MESA information, two RF switch structures are proposed instead of discussing material and contact surface issues.

Table 1. MESA matrix of cantilever RF MEMS switch.

Performance Design parameters	reliability		contact resistivity	switching speed	RF isolation	size
	stiction (restoring force)	degradation (impact force)				
spring constant	↑ +0.17	↓ -0.14	↓ -0.13	↑ +0.00		
electrode distance	↑ +0.17	↓ -0.29	↓ -0.25	↓ -0.40	↑ +0.5	↓ -0.33
actuation voltage	↓ -0.33	↓ -0.29	↑ +0.25	↑ +0.40		
electrode area	↓ -0.17	↓ -0.14	↑ +0.13	↑ +0.20		↓ -0.33
contact area	↓ -0.17	↑ +0.14	↑ +0.25		↓ -0.5	↓ -0.33

↑ : desirable ↓ : undesirable

3. TRI-STATE MULTI-CONTACT SWITCH

3.1 Switching Concept

The cantilever switch evolves uncancelable tradeoffs as shown in Table 1. The dominant problems are that all design factors are complexly related with several system characteristics. Moreover the design factors cannot be adjusted because their influences are different to each system characteristic. Our first mechanical approach derived from the MESA information is "tri-state multi-contact" in order to solve such problems. Figure 2 shows a schematic of a lateral switch with tri-state multi contacts. The switch consists of contact fingers, stationary contact pads and two comb-drive actuators. The switch can move both I and II directions for two ON

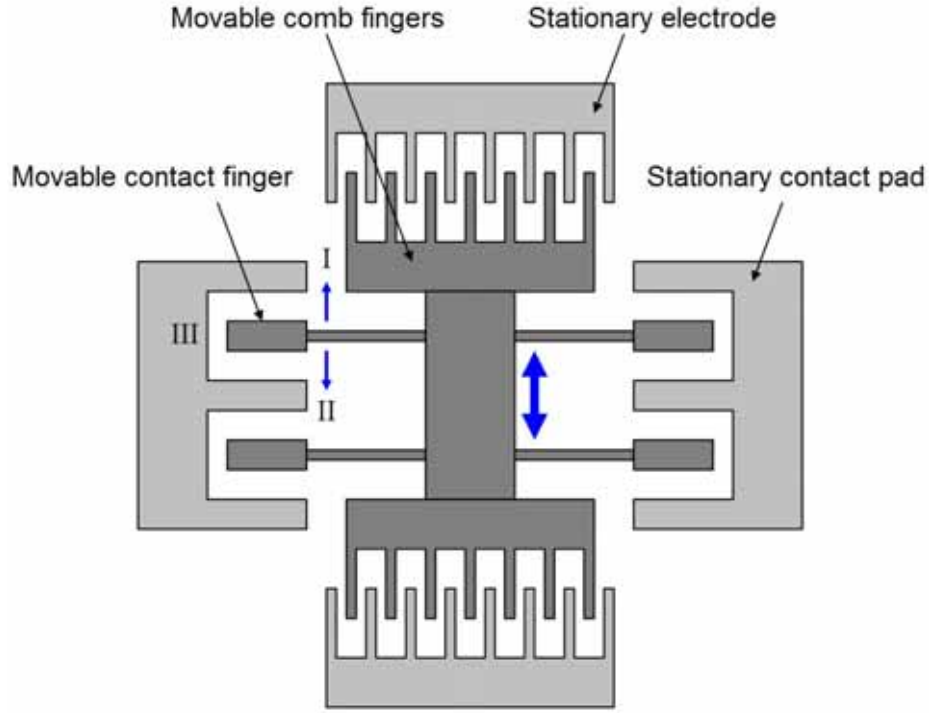


Figure 2. A schematic of tri-state multi contact switching concept.

states and neutral position is II as an OFF state. The contact fingers alternatively impact two sides of the stationary pads and the multi-contact fingers are designed based on a fail-safe concept. The two comb-drive actuators, which are adversely arranged, function as generating not only the switching force but also adverse force against the stiction. In the conventional cantilever switch, the counterforce of stiction is only the restoring force accumulated in the cantilever beam. In that case, if strong stiction at the interface occurs and the stiction force is larger than the restoring force, the cantilever beam cannot be returned back. On the other hand in our RF switch, the active electrostatic adverse force by the comb-drive actuator can overcome the stiction without increase of the impact force and spring restoring force. Thus, the design parameters such as the spring constant and electrode gap are assumed as independent from the design of restoring force.

The MESA matrix for the tri-state multi-contact switch is shown in Table 2. The new switch structure releases the restoring force from the effects of design factors. It results in the removal of the design tradeoffs between the restoring force and the contact resistivity. By the adjusting the characteristic varying directions of design factors, many of the system characteristics can be designed with desirable change by the design parameters. The system score of this switch S_1 becomes $S_1=+0.23$ and it shows that the new switching structure is better than the cantilever RF switch. The degradation is inevitable in relay structure that two surfaces impact each other. However, tri-state multi-contact concept reduces the number of impacting the surface. Therefore, the chance of degradation becomes smaller than conventional switches and the

influences of design factors to the impact force are minimized. It is concluded that the reliability of new switch will be enhanced without the degradation of RF performance.

Table 2. MESA matrix of tri-state lateral multi-contact switch.

Performance Design parameters	reliability		contact resistivity	switching speed	RF isolation	size
	stiction (restoring force)	degradation (impact force)				
spring constant		↑ +0.14	↑ +0.13			
electrode distance		↑ +0.29	↑ +0.25	↑ +0.40	↓ -0.5	↑ +0.33
actuation voltage		↓ -0.29	↑ +0.25	↑ +0.40		
electrode area		↓ -0.14	↑ +0.13	↑ +0.20		↓ -0.33
contact area		↑ +0.14	↑ +0.25		↓ -0.5	↓ -0.33

↑ : desirable ↓ : undesirable

3.2 Design and Fabrication

Based on the switching concept, tri-state multi-contact switch was designed and successfully fabricated by using Metal MUMPs [30]. The Metal MUMPs provide 20μm electroplated nickel layer that is used as a primary structural layer. Gold overplate can be used to coat the sidewalls of nickel structures with a low contact resistance material. The top view of fabricated switch and the contact finger at ON and OFF states are shown in Figure 3 and 4 respectively. The switch is composed of two comb-drive actuators arranged at opposed position, rectangular shape springs supporting the movable frame, 10 input/output contact fingers connected with the movable frame, and stationary contact pads located on the input/output signal lines. The dimension of contact fingers is 20μm width × 80μm length. The gap between the contact finger and the stationary contact pad is 10μm. The switching voltage for 10μm traveling is experimentally confirmed as a 120V. A 125μsec switching speed and a 280μN contact force are expected from the FEM analysis.

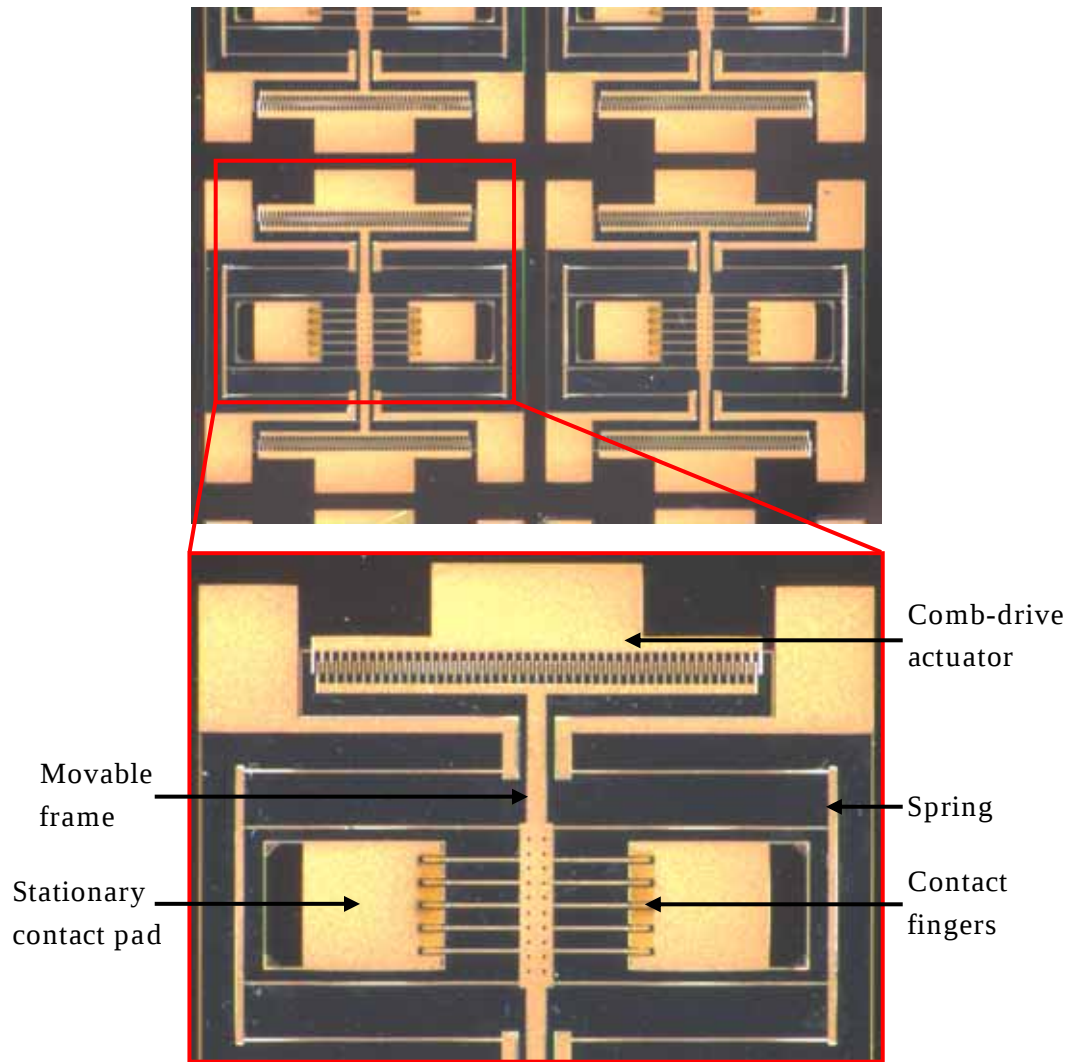


Figure 3. Top-view photo of tri-state multi-contact switch.

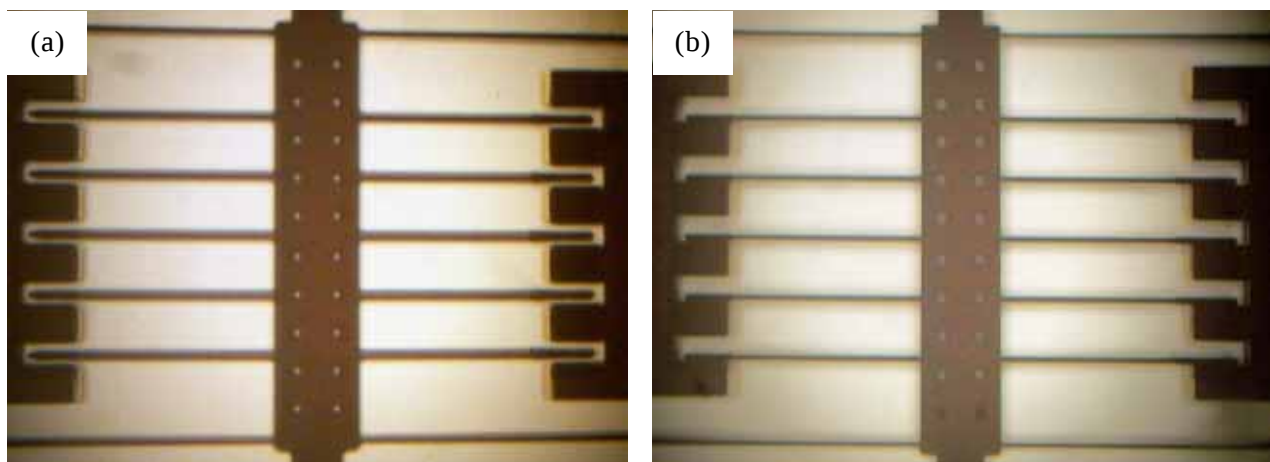


Figure 4. Behavior of contact fingers at (a) OFF state (b) ON state.

3.3 RF Characterization

RF analyses of the multi-contact switch are conducted. To reduce the simulation time, only the parts of the switch shown in Figure 5 were considered. When the switch is in the OFF state, there are two capacitances to be considered for the switch, as shown in Figure 5 (a). Analysis options called MEM Henry and MEM Electro of CoventorWare was used to find the capacitance between the switch pads and the conductors [34]. The capacitance between the movable frame and the each outside stationary contact pads is 0.03546pF. With that information, Agilent Advanced Design System (ADS) was used to find the return loss, and RF isolation for the switch. The results are shown in Figure 6. From these simulation results, it can be concluded that the switch provides reasonable RF performance better than 20dB up to 10GHz.

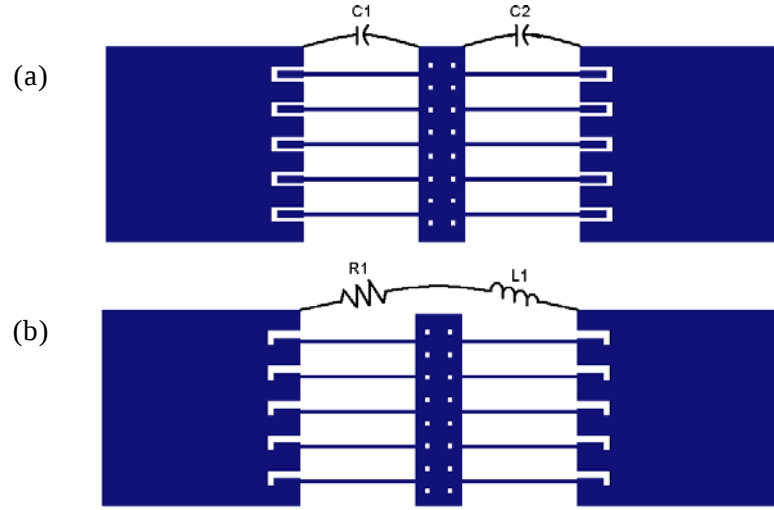


Figure 5. Simplified analysis model of multi-contact switch (a) OFF state (b) ON state.

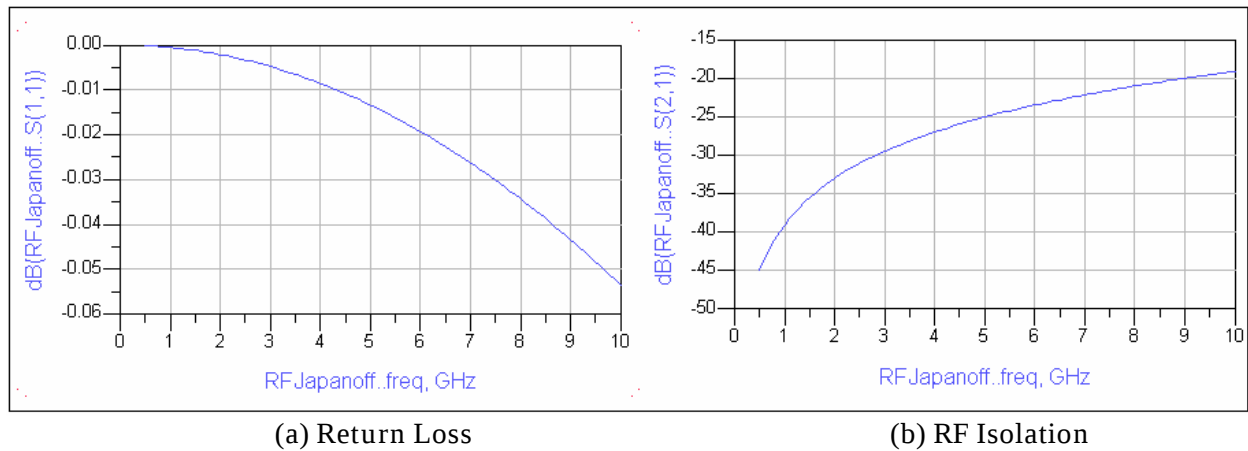


Figure 6. RF simulation results of the switch at the OFF state..

When the switch is in the ON state, the switch will have a resistance and an inductance as shown in Figure 5 (b). These resistance and inductance were found to be 0.1577Ω and 1.081nH respectively. With that information, Agilent ADS was used to find the return loss and insertion loss for the switch as shown in Figure 7. The insertion loss is less than 0.5dB up to 5GHz . From these results, it can be concluded that the switch has reasonable performance in the frequency range up to 5GHz .

In addition, the effect of multi-contact structure is investigated. Figure 8 shows the insertion loss with different number of contact fingers from 5×5 to 1×1 . It is shown that the insertion loss change is only 0.1dB at 5GHz if 60% contact fingers work. Therefore the fail safe function of multi-contact structure can be effective and it helps the enhancement of the switch reliability.

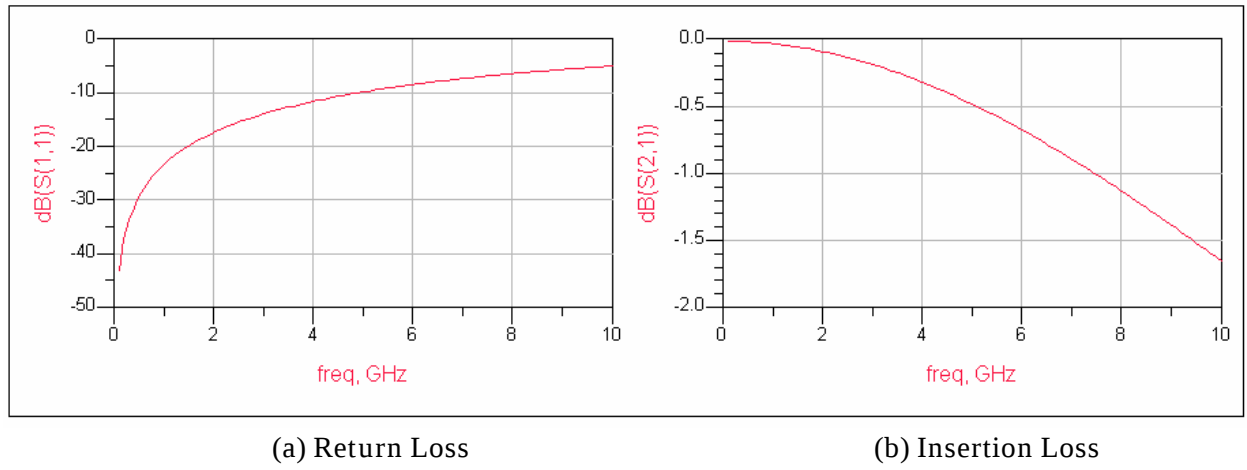


Figure 7. RF simulation results of the switch at the ON state..

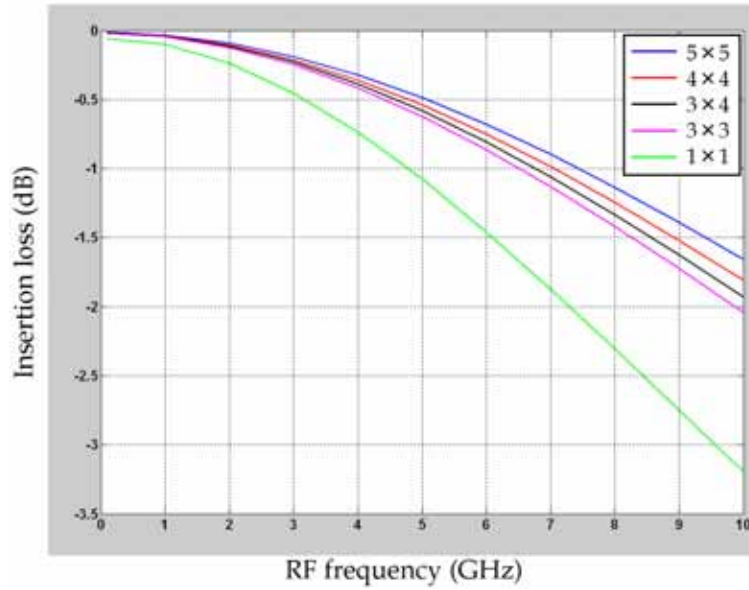
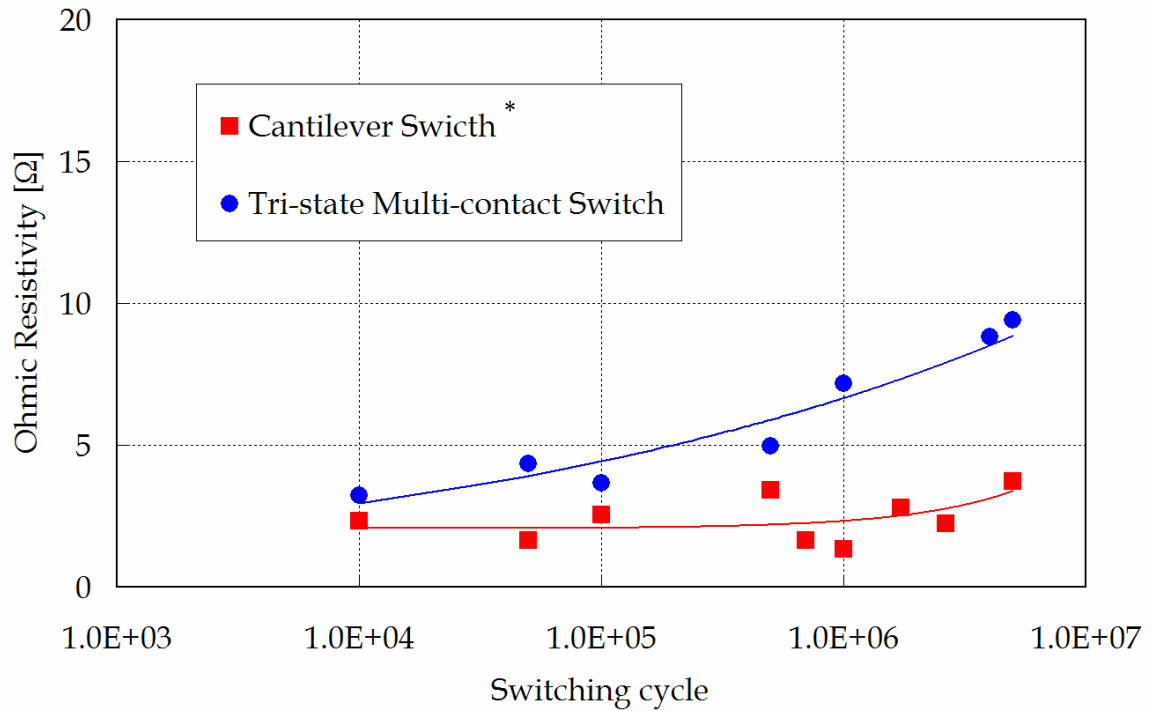


Figure 8. Insertion loss at ON-state for different finger configuration.

3.4 Mechanical Reliability

Reliability testing of both cantilever switch and tri-state multi-contact switch up to 10^7 actuation cycles (with no degradation or failure) has been demonstrated. Experiments have been conducted with 2Hz-10Hz switching frequency and measurement of ohmic contact resistivity in the ON state. Figure 9 shows the reliability testing results. The lateral cantilever switch is prepared with the same configuration of tri-state multi-contact switch. Both switches have no resistive difference and clear mechanical reliability advantage of tri-state multi-contact switch has not been observed. One different phenomenon of the fatigue life experiments of two switches is that stiction to the bottom surface (not to the contact pad) has been observed in the cantilever switch. The failure is not a switching structure issue but experimental circumstance (temperature, humidity, or particles) issue. However, the cantilever switch does not have active adverse stiction force and cannot avoid the circumstance influence. Note that the fatigue life testing of cantilever switch intermittently continues with release of the stiction.

Figure 10 shows the microscope photo of switching parts of (a) switch before testing (b) cantilever switch after 10^7 cycles (c) tri-state switch after 10^7 cycles, respectively. Critical changes of surface condition such as cracks and failure are not observed up to 10^7 cycles. Future test could be carried out to test reliability up to 10^{10} cycles. Many DC contact RF switches have been tested up to 10^8 - 10^9 cycles with no mechanical failure due to metal fatigue or fracture.



* Stiction is observed during the experiment.

Figure 9. Reliability experimental results.

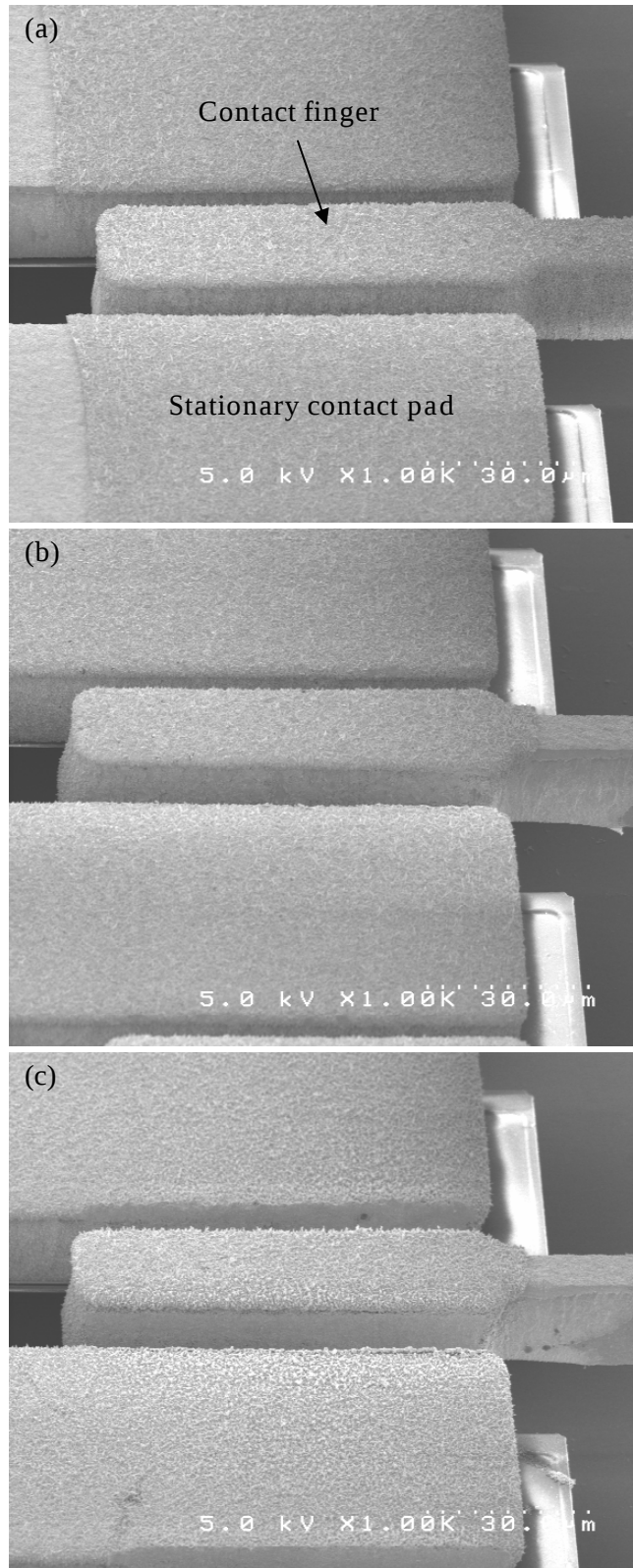


Figure 10. Scanning microscopic photos of switching parts (a) before testing (b) cantilever switch after 10^7 cycles (c) tri-state switch after 10^7 cycles.

4. PUSH-PULL SWITCH

4.1 Switching Concept

The second mechanical approach for enhancing the RF MEMS switch performance is led based on the MESA analysis of tri-state multi-contact switch. As shown in Table 2, RF isolation is worsened by the change of design parameters. The small electrode gap and large contact area (total area of multi-contact fingers) will be causes of poor RF isolation. However, these tow parameters are difficult to be adjusted because they influence degradation and contact resistivity etc. This design tradeoff should be solved to achieve higher switch performance.

We propose new switching concept called "push-pull" switching. Figure 11 shows the schematic of the concept. The switch adopts two-step actuation mechanism to achieve compatibility between high RF isolation and less degradation. In the OFF state, a contact finger is at the offset position away from a contact pad. When the switch is ON state with applying voltage, the contact finger horizontally slides above the pad and then vertically moves to touch with the surface of contact pad. When the switch moves back to the OFF state, the switch is pulled off from the contact pad by the spring restoring force and the active electrostatic force of actuators. Therefore the offset layout of the contact finger will result in high RF isolation and

Table 3 MESA matrix of push-pull switch.

Performance Design parameters		reliability		contact resistivity	switching speed	RF isolation	size
		stiction (restoring force)	degradation (impact force)				
spring constant	↓		↑ +0.14	↑ +0.13			
electrode distance	↓		↑ +0.29	↑ +0.25	↑ +0.22		
actuation voltage	↑		↓ -0.29	↑ +0.25	↑ +0.22		
electrode area	↑		↓ -0.14	↑ +0.13	↑ +0.11		↓ -0.33
contact area	↑		↑ +0.14	↑ +0.25			↓ -0.33
push-pull distance	↑				↓ -0.22	↑ +1.00	↓ -0.33
push-pull voltage	↑	(↑)			↑ +0.22		

↑ : desirable ↓ : undesirable

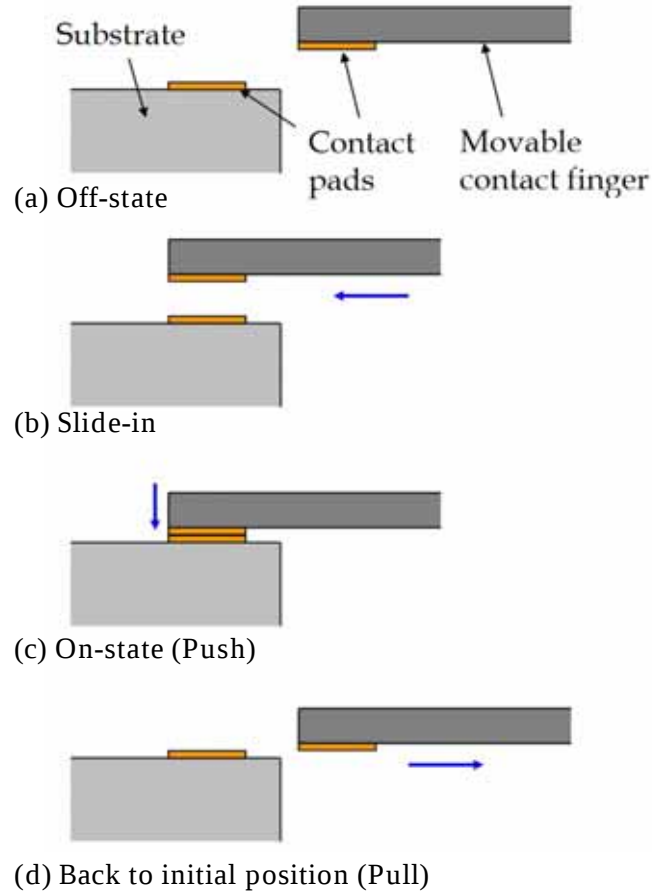


Figure 11. Contact finger behavior of push-pull switching concept.

two-step actuation minimizes the degradation without the change of electrode gap. Moreover, the peeling-off concept by pulling the contact finger makes restoring force independent from the design factors.

The push-pull concept is analyzed by the MESA as well as the first approach and the result is shown in Table 3. Due to the structure change, the number of design factors is increased. The RF isolation becomes independent from the original design factors and the most design tradeoffs are removed compared with the conventional cantilever switch. Although the actuation voltage and electrode area affect the degradation, the electrode gap can be designed as much as small due to the two-step actuation, and the influences of design parameters to degradation will be minimized in this concept. The system score of the second approach becomes $S_2=+0.63$. Since the good total system score is obtained, it is expected that the two-step actuation mechanism leads both high reliability and good RF performance.

4.2 Design and Fabrication

In order to demonstrate the push-pull switching concept, a new electrostatic comb-drive actuator form two-step actuation is designed. Figure 12 shows a schematic of push-pull switch. The two-layer comb-drive actuator consists of stacked two-layer stationary electrodes and mono layer movable electrodes. Applying the voltage on the upper layer, the comb-drive actuator shows horizontal movement. Additionally applying the voltage on the lower layer, the actuator moves downward and the switching state is changed from OFF to ON. Therefore the switching gap between the contact fingers and the contact pad keeps large in the OFF state, and the impact force is lesser than that of the conventional switches. We currently plan to design and fabricate the switch by using UV-LIGA process. The UV-LIGA process provides two 30 μ m thickness nickel layers which sandwich a dielectric layer. Mechanical and RF performance analysis will be also conducted through the design and fabrication.

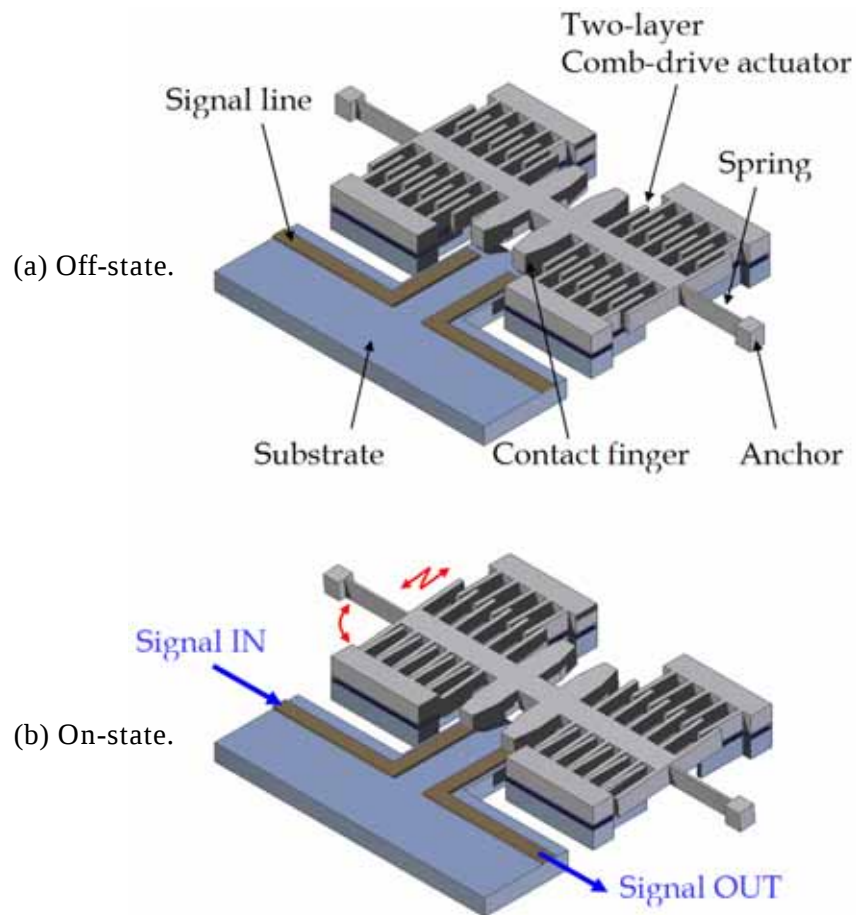


Figure 12. Schematics of push-pull switch with off and on states.

5. CONCLUSION

We proposed new switching concepts thorough the MESA. Analyzing the cantilever shape switch, problems in the RF MEMS switch are defined. The MESA clearly shows the inherent design tradeoffs and clarifies the relation between the design factors and the performances. Based on the MESA information, we created the first generation, "tri-state multi-contact" switch. With the removal of the design tradeoffs, the tri-state switch can have compatibility with mechanical reliability and RF performance. The switch was successfully fabricated by using Metal MUMPs process. The reliability evaluation is an ongoing experiment and finished up to 10^7 cycles without failure. The switch has 0.5dB insertion loss and 25dB isolation which are reasonable performance as an RF switch. In addition, we proposed the second switching concept called "push-pull" switch by solving the problems of tri-state switch. The push-pull switch has two-step actuation mechanism and solves all design tradeoffs between mechanical reliability and RF performance.

6. FUTURE WORK

1) Reliability experiment up to 10^{10} cycles

The mechanical reliability comparison between cantilever switch and tri-state multi-contact switch will be conducted.

2) Measurement of DC contact characteristics

In the first fabrication run of tri-state multi-contact switch, the switch has no RF signal lines. Contact resistivity versus applied voltage, the effect of contact finger/pad shapes will be examined.

3) Second design, fabrication and testing of tri-state multi-contact switch

Including RF signal lines and packagability, the modified tri-state multi-contact switch will be designed and fabricated. The RF performance and mechanical reliability with RF signals will be examined.

4) Design, fabrication and testing of push-pull switch

The push-pull switch will be designed and fabricated by using multi-layer nickel electroforming process. The basic performances such as switching actuation and mechanical reliability with DC signals will be examined. After that, the switch will be modified and the RF performance will be researched as well as the tri-state switch.

REFERENCES

- [1] J. J. Yao, "RF MEMS from a device perspective," *J. of Micromechanics and Microengineering: Structures, Devices, and Systems*, vol. 10, pp. R9-R38, 2000.
- [2] G. M. Rebeiz, "RF MEMS Theory, Design, and Technology," Wiley 2003.
- [3] G. M. Rebeiz and J. B. Muldavin, "RF MEMS switches and switch circuits," *IEEE microwave magazine*, pp. 59-71, Dec., 2001.
- [4] D. Hyman et al., "Surface-micromachined RF MEMS switches on GaAs substrates," *Int. J. of RF and Microwave CAE*, vol. 9, no. 4, pp. 348-361, 1999.
- [5] Z. J. Yao, S. Chen, S. Eshelman, D. Denniston, and C. Goldsmith, "Micromachined low-loss microwave switches," *J. of Microelectromech. Syst.*, vol. 8, no. 2, pp. 129-134, 1999.
- [6] S. Majumder, N. E. McGruer, P. M. Zavracky, G. G. Adams, R. H. Morrison, and J. Krim, "Measurement and modeling of surface micromachined, electrostatically actuated microswitches," *Tech. Digest of 1997 Int. Conf. on Solid-State Sensors and Actuators*, pp. 1145-1148, 1997.
- [7] D. Hyman et al., "GaAs-compatible surface-micromachined RF MEMS switches," *Electron. Lett.*, vol. 35, pp. 224-226, 1999.
- [8] N. E. McGruer, P. M. Zavracky, S. Majumder, R. H. Morrison, and G. G. Adams, "Electrostatically actuated microswitches; scaling properties," *Tech. Digest of Solid State Sensors and Actuators Workshop*, pp. 132-135, 1998.
- [9] H. J. De Los Santos, Y. -H. Kao, A. L. Caigoy, and E. D. Ditmars, "Microwave and mechanical considerations in the design of MEM switches for aerospace applications," *Proc. of IEEE Aerospace Conf.*, vol. 3, pp. 235-254, 1997.
- [10] J. J. Yao and M. F. Chang, "A surface micromachined miniature switch for telecommunications applications with signal frequencies from DC up to 4 GHz," *Tech. Digest of 8th Int. Conf. on Solid-State Sensors and Actuators*, pp. 384-387, 1995.
- [11] C. Wang, R. Ramadoss, S. Lee, K. C. Gupta, V. M. Bright, and Y. C. Lee, "Flexible circuit-based RF MEMS switches," *Proc. of ASME IMECE '01*, 2001.
- [12] E. A. Sovero, R. Milhailovich, D. S. Deakin, J. A. Higgins, J. J. Yao, J. F. DeNatale, and J. H. Hong, "Monolithic GaAs PHEMT MMICs integrated with high performance MEMS microrelays," *Proc. of IMOC '99 (Int. Microwave and Optoelectro. Conf.)*, 1999.
- [13] C. Goldsmith, T. -H. Lin, B. Powers, W. -R. Wu, and B. Norvell, "Micromechanical membrane switches for microwave applications," *Tech. Digest of IEEE Microwave Theory and Techniques Symp.*, pp. 91-94, 1995.
- [14] E. J. J. Kruglick and K. J. Pister, "Lateral MEMS microcontact considerations," *J. of IEEE Microelectromechanical Systems*, vol. 8, pp. 264-271, 1999.
- [15] I. Schele and B. Hillerich, "Comparison of lateral and vertical switches for application as microrelays," *J. of Micromech. Microeng.*, vol. 9, pp. 146-150, 1999.
- [16] Z. Feng, H. Zhang, W. Zhang, B. Su, K. C. Gupta, V. M. Bright, and Y. C. Lee, "MEMS-based variable capacitor for millimeter-wave applications," *Proc. of Solid-State*

- Sensor and Actuator Workshop*, pp. 255-258, 2000.
- [17] H. Hosaka, H. Kuwano, and K. Yanagisawa, "Electromagnetic microrelays: concept and fundamental characteristic," *Sensors and Actuators*, A40, pp. 41-47, 1994.
 - [18] W. P. Taylor and M. G. Allen, "Integrated magnetic microrelays: normally open, normally closed, and multi-pole devices," *Tech. Digest of Int. Conf. on Solid-State Sensors and Actuators*, pp. 1149-1152, 1997.
 - [19] M. -A. Gretillat, F. Gretillat, and N. F. de Rooji, "Micromechanical relay with electrostatic actuation and metallic contacts," *J. of Micromech. Microeng.*, vol. 9, pp. 324-331, 1999.
 - [20] H. Tilmans et al., "A fully-packaged electromagnetic microrelay," *Tech. Digest of 12th IEEE Int. Conf. on Micro Electro Mechanical Systems*, pp. 25-30, 1999.
 - [21] J. Drake, H. Jerman, B. Lutze, and M. Stuber, "An electrostatically actuated micro-relay," *Tech. Digest of 8th Int. Conf. on Solid-State Sensors and Actuators*, pp. 380-383, 1995.
 - [22] K. M. Hiltmann, B. Schmidt, H. Sandmaier, and W. Lang, "Development of micromachined switches with increased reliability," *Tech. Digest of 1997 Int. Conf. on Solid-State Sensors and Actuators*, pp. 1157-1160, 1997.
 - [23] M. Sakata, Y. Komura, T. Seki, K. Kobayashi, K. Sano, and S. Horiike, "Micromachined relay which utilizes single crystal silicon electrostatic actuator," *Tech. Digest of 12th IEEE Int. Conf. on Micro Electro Mechanical Systems*, pp. 21-24, 1999.
 - [24] J. Skimkat, "Contact materials for microrelays," *Proc. of The 11th Annual International Workshop on Micro Electro Mechanical Systems*, pp. 190-194, 1998.
 - [25] S. Majumder, N. E. McGruer, G. G. Adams, A. Zavracky, P. M. Zavracky, R. H. Morrison, and J. Krim, "Study of contacts in an electrostatically actuated microswitch," *Proc. of IEEE Electrical Contacts*, pp. 127-132, 1998.
 - [26] C. Cabuz, E. I. Cabuz, T. R. Ohnstein, J. Neus, and R. Maboudian, "Factors enhancing the reliability of touch-mode electrostatic actuators," *Sensors and Actuators*, A79, pp. 245-250, 2000.
 - [27] R. Maboudian, "Anti-stiction coating for surface micromachines," *SPIE*, vol. 3511, pp. 108-113, 1998.
 - [28] T. Miki, K. Ishikawa, H. Mamiya, and Q. Yu, "Early-stage analysis for MEMS structural optimization I: concept," *Proc. of ASME InterPACK 2005*, No. 73050, 2005.
 - [29] K. Ishikawa, T. Miki, H. Mamiya, and Q. Yu, "Early-stage analysis for MEMS structural optimization II: its application to microrelay reliability," *Proc. of ASME InterPACK 2005*, No. 73049, 2005.
 - [30] A. Cowen, B. Dudley, E. Hill, M. Walters, R. Wood, S. Johnson, H. Wynands, and B. Hardy, *MetalMUMPs Design Handbook Rev. 1.0*, MEMSCAP, 2002.
 - [31] A. Kobayashi, S. Takano, and T. Kubono, "Measuring equipment and measurements of adhesion force between gold electrical contacts," *IEEE Trans. on Components., Packaging and Manufacturing Tech.*, A 21, no.1, pp. 46-53, 1998.
 - [32] Z. -K. Chen and K. Sawa, "Effect of arc behavior on material transfer: A review," *IEEE Trans. on Components., Packaging and Manufacturing Tech.*, A 21, no.2, pp. 310-322, 1998.

- [33] J. Oberhammer, "Novel RF MEMS switch and packaging concepts," Ph.D. dissertation, Royal Institute of Technology, Sweden, 2004.
- [34] *CoventorWare User Handbook*, Coventor Inc., 2005.