Failure Analysis of Radio Frequency (RF) Microelectromechanical Systems (MEMS)

Jeremy A. Walraven, Edward I. Cole Jr., Lynn R. Sloan*, Susan Hietala, Chris P. Tigges, and Christopher W. Dyck**

Sandia National Laboratories, P.O. Box 5800, MS 1081, Albuquerque, NM 87185-1081, USA
email: jawalra@sandia.gov

*Agilent Technologies, 7600 Jefferson Street, #92, Albuquerque, NM 87109
**Emcore Optical Devices, 10420 Research Road SE, Albuquerque, NM 87123

ABSTRACT

MEMS are rapidly emerging as critical components in the telecommunications industry. This enabling technology is currently being implemented in a variety of product and engineering applications. MEMS are currently being used as optical switches [1] to reroute light, tunable filters [2], and mechanical resonators [3].

Radio frequency (RF) MEMS must be compatible with current Gallium Arsenide (GaAs) microwave integrated circuit (MMIC) processing technologies for maximum integration levels. The RF MEMS switch discussed in this paper was fabricated using various layers of polyimide, silicon oxynitride (SiON), gold, and aluminum monolithically fabricated on a GaAs substrate. Fig. 1 shows a metal contacting series switch. This switch consists of gold signal lines (transmission lines), and contact metallization. SiON was deposited to form the fixed-fixed beam, and aluminum was deposited to form the top actuation electrode.

To ensure product performance and reliability, RF MEMS switches are tested at both the wafer and package levels. Various processing irregularities may pass the visual inspection but fail electrical testing. This paper will focus on the failure mechanisms found in the first generation of RF MEMS developed at Sandia National Laboratories. Various tools and techniques such as scanning electron microscopy (SEM), resistive contrast imaging (RCI) [4], focused ion beam (FIB), and thermally-induced voltage alteration (TIVA) [5] have been employed to diagnose the failure mechanisms. The analysis performed using these tools and techniques led to corrective actions implemented in the next generation of RF MEMS metal contacting series switches.

Key Words: RF MEMS, Metal Contacting Series Switch, Failure Analysis, Focused Ion Beam (FIB), Scanning Electron Microscopy (SEM), Resistive Contrast Imaging (RCI), Thermally-Induced Voltage Alteration (TIVA)

INTRODUCTION

RF MEMS are becoming recognized as an excellent alternative to existing RF switching technologies. Although the field is relatively new, results have shown that performance enhancements and manufacturing costs reductions are characteristics of this technology [7]. In many cases, RF MEMS components can outperform an equivalent solid-state circuit. These MEMS switches make the system (or subsystem) lighter and less power consuming. MEMS technology addresses these and other

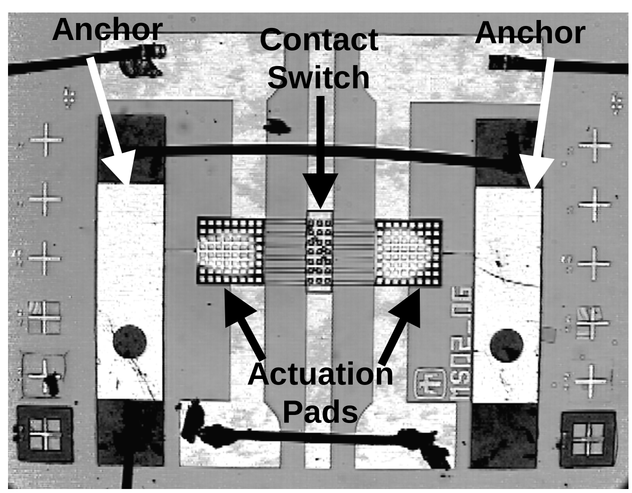

Fig. 1. Top view optical image of an RF MEMS metal series contact switch developed at Sandia National Laboratories.

critical issues such as insertion loss that currently exist in solid-state switching technology.

Metal contacting series switches also offer distinct advantages to their shunt switch counterparts. Shunt switches (switches that transfer high frequency signals through a thin dielectric material, to the signal line) eliminate metallurgical issues by contacting a thin dielectric material but have limited bandwidth. Metal contacting switches offer capabilities of transferring both AC and DC signals through the switch to the signal line. The thin dielectric material present in shunt switches prevents transfer of DC signals.

To produce low cost, reliable MEMS switches these devices must be batch fabricated. Irregularities can occur during fabrication that limits yield, functionality, and reliability by structural or electrical degradation. This paper will describe the failure mechanisms found in the first generation of RF switches.

FABRICATION

RF MEMS switches were fabricated using a surface micromachining technique with various polymer, metal, and insulator films. These devices were fabricated on three-inch GaAs wafers. GaAs was selected as the base substrate over silicon primarily due to its integration and compatibility with current MMIC process technology.

The devices are fabricated as follows: Polyimide was deposited and patterned on the surface of the GaAs substrate. Silicon oxynitride and photoresist were deposited and patterned over the polyimide. A reactive ion etch (RIE) was used to remove regions of the SiON and polyimide to the substrate. Gold was deposited via electron beam evaporation to form the signal and ground lines (100μm wide and 2μm thick). The remaining gold was removed using a lift-off process. A third layer of polyimide was deposited and cured. Photoresist was deposited and patterned over the polyimide. Gold was then deposited to form the contact region. After lift off, SiON was deposited to form the fixed-fixed component. Photoresist is deposited and patterned to allow deposition of Au or Al on top of the SiON to form the top electrode. 0.25μm of Al deposited over selected regions of the surface forms the top electrodes [7]. The polyimide acts as the sacrificial material, containing the fixed-fixed beam until ready for release. A dry release process (RIE barrel etch) was used to free the structural components and is preferred over a wet chemical process to avoid stiction and adhesion related failures during the release process. This process yields an RF MEMS structure with a 3μm gap spacing when the switch is in its off state, and a 400μm^2 contact area when in the on state. The cross section diagram illustrated in Fig. 2 shows the SiON fixed-fixed beam along with the contact metallization, actuation pads, signal lines, and anchors.

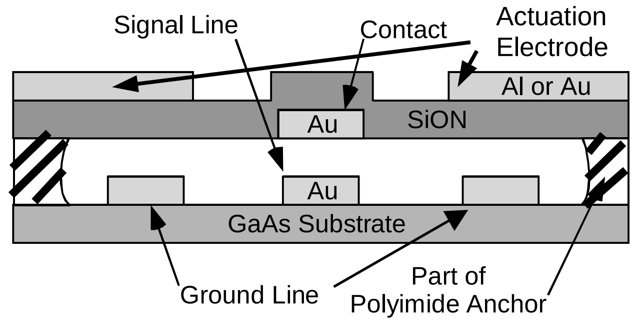

Fig. 2. Cross section diagram of a metal series contact switch revealing the contact and signal line metallization and the top and bottom electrodes.

The metal contacting series switch operates by applying a bias to the actuation electrodes that pulls down the beam via electrostatic attraction. This causes the central portion of the device to contact the signal line putting the RF switches in the “down” or pass-through state. This pass-through state allows the RF signal to transfer through the contact switch to other components in the system. When the switch is suspended or in the “up” state, the signal line is isolated (open) or in the “blocking” state, preventing the RF signal from passing to the next portion of the circuit. Such switches have been employed for RF/microwave systems and subsystems for signal routing, impedance matching, and amplifier gain adjustments [7].

EXPERIMENTAL

Several RF contact switches were tested for functionality. A 12 V square wave actuation signal was supplied to the actuation pads, allowing the switch to move into the pass position. One volt DC was supplied to the signal line. A functional device passed the 1 V DC signal through the switch into the other signal line. The current passing through the signal line and contact was limited to 13 μA using a series resistor in the test setup. The square wave actuation signal was increased in 1 V increments until device failure. A functional failure was defined as the inability of a device to pass a 1 V DC signal from the signal line through the switch to the other signal line. Many of the devices failed between 28 and 32 V square wave actuation signals. Devices that failed initial testing were not evaluated, but brought directly to failure analysis.

These devices were packaged in 24-pin dual-in-line packages (DIP). This package allowed easy access to the device for structural characterization, electrical testing, as well as failure analysis.

FAILURE ANALYSIS

OPENS

Failure analysis of the RF MEMS metal contacting series switches has revealed two failure mechanisms. The first failure mechanism was a structural defect along the beam regions leading to an open circuit preventing the device from actuating. The second failure mechanism was an incomplete etch step that induced particle contamination and bridged between two components of the device leading to an electrical short. Resistive Contrast Imaging (RCI) was employed to diagnose the first failure mechanism and localize the failure site. RCI generates a relative resistance map between two test

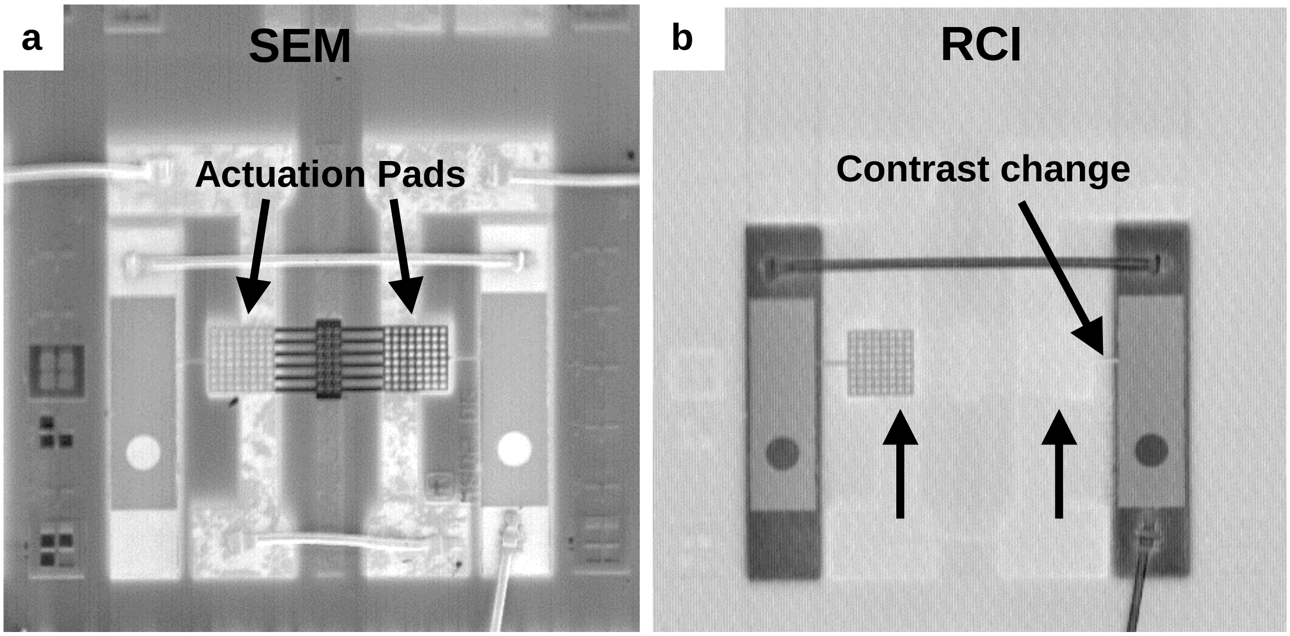

Fig. 3. a) SEM image of an unbiased metal contact switch shows non-uniform contrast between the actuation pads. **b)** RCI image of a unbiased device reveals the left actuation pad has electrical continuity to the anchor is observed, while the right actuation pad is not electrically connected to the anchor.

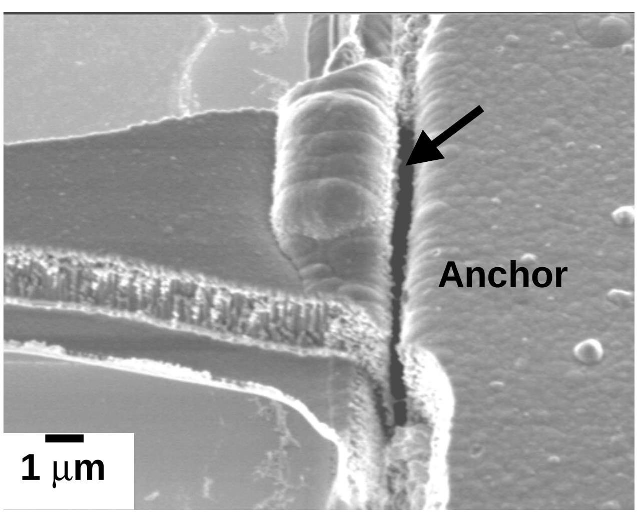

Fig. 4. SEM image revealing an open between the anchor and the mechanical flexure arm of the device (black arrow).

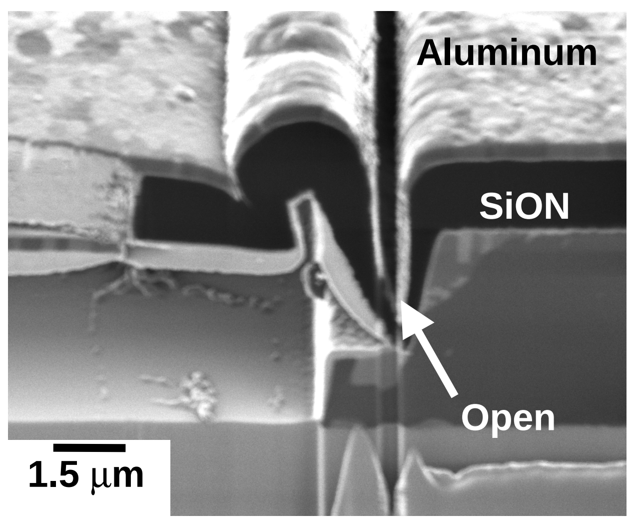

Fig. 5. FIB cross sectional analysis along the fulcrum of the support arm/anchor revealed no aluminum in the open region (white arrow).

points of an IC or MEMS. If a resistance change occurs along a conductor linked to the test points, (such as an open conductor); the RCI image will display an abrupt contrast change at the open site [8]. As illustrated in Fig. 3a and b, the SEM and RCI images (respectively) show a failed switch with the two actuation pads at different potentials.

Closer analysis of the suspected failure site revealed from the RCI analysis (Fig. 3b) showed a “break” on the top level metal along the fulcrum of the actuation pad where it is connected to the anchor. This region represents the flexible component that allows the actuation pads and contact switch to move. Fig. 4 is a SEM image revealing a deep track (black arrow) along the fulcrum of the mechanical arm/anchor of the RF switch. This deep trench is formed during an etch step in the SiON. As shown in Fig. 5, cross sectional analysis along the fulcrum of the mechanical arm using the FIB revealed preferential thinning of the top metal layer. The aluminum deposited on the surface of the SiON either did not completely fill the trench or partially filled it during deposition. This led to premature failure due to breakdown of the thin metal region or an open/non-functional as-fabricated device.

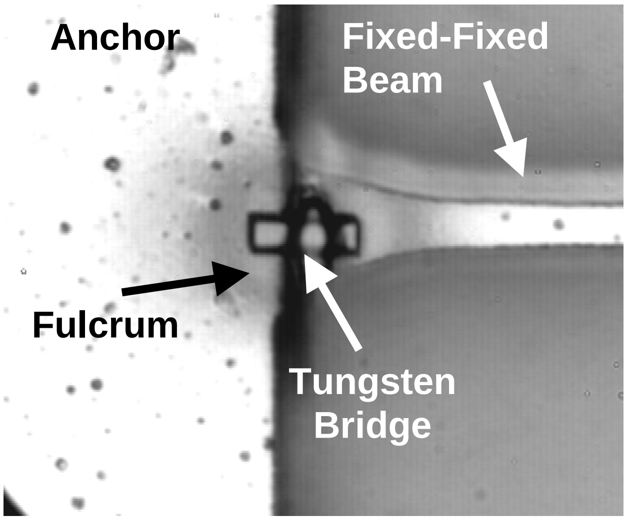

Fig. 6. Cantilever/fulcrum region with tungsten deposited over the open region (white arrow).

A 30 V stress test induced failure by damaging the thin layer of Al resulted in an open circuit. To verify the failure mechanism, the FIB was used to deposit tungsten along the surface of the fulcrum (Fig. 6), bridging the over-etched gap illustrated in Figs. 4 and 5. Tungsten was deposited using tungsten hexacarbonyl gas bled into the chamber through a nozzle above the device. The ion beam was rastered over the area of interest, disassociating the tungsten from the molecule releasing the carbon and depositing tungsten along the rastered surface. This step was performed to bridge the open region, determine if this is the root cause of failure and as a post process fix to restore electrical continuity to the device. Post FIB modification testing resulted in a functional switch,

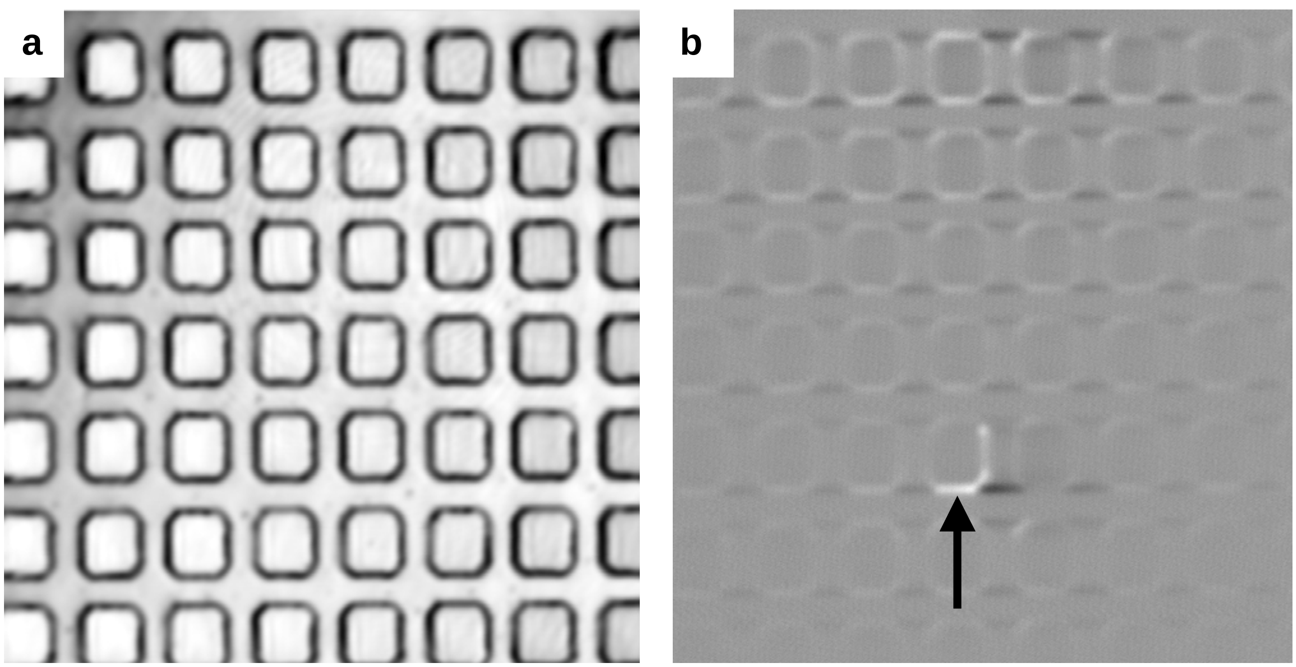

Fig. 7. a) Reflected light image of an actuation pad. **b)** TIVA image of the same actuation pad (same field of view) showing a path to ground along an etch release hole.

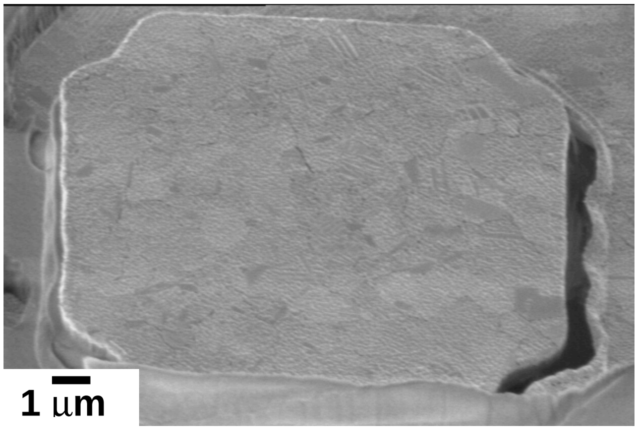

Fig. 8. SEM image revealing an incompletely released aluminum piece in an etch release hole.

indicating the open was the only failure site on this device.

SHORTS

In cases where a device failed due to electrical shorting, Thermally-Induced Voltage Alteration (TIVA) was employed to locate the failure site. This technique utilizes a scanning optical microscope equipped with a laser to heat the region of interest. The MEMS is held at constant current while monitoring the change in voltage as the laser scans the device. As the laser rasters over the device, the resistance of the shorted region will change [9]. The change in supplied power with the change in resistance is mapped [9]. A TIVA image mapped in conjunction with a reflected light image revealed the failure site.

As shown in Fig. 7, the TIVA image shows a spot along the edge of an etch release hole region of the actuation pad. This region coincides with the location of the short along the edge of the etch release hole in the actuation pad (designated by the black arrow in Fig. 7). Further examination of this region using a SEM is shown in Fig. 8. The top level metal (Al) had not been completely lifted off during processing. Closer inspection of the contact and actuation pads showed small pieces of metal not fully etched or released from the structure. However, the metal piece corresponding to the TIVA image was the only region that was electrically shorted. These small Al pieces bridged the actuation pad to the electrode, shorting the device and making it inoperable.

CONCLUSIONS

As shown in the first generation of RF switches, various batch fabrication related issues need to be addressed prior to manufacturing. The failure analysis results led to corrective actions in both design and processing and enabled the successful development of the next generation of RF MEMS contact switches. Particle contamination resulting from the lift-off etch can electrically short or obstruct mechanical motion of a device. By modifying the lift-off process as well as the SiON etch, the open circuit and metal particle contamination failures were significantly reduced, improving functionality and device reliability.

FUTURE WORK

Further process and design modifications to increase the switching speed and reduce inadvertent electrical shorts and opens are currently underway. These and other corrective actions will be implemented in the next generation of RF metal contact series switches.

Other failure mechanisms common to metal contact switches include arcing, welding, stiction, corrosion, oxidation, fretting, etc [10]. The issues involving contact metallurgy of the signal lines and contact material must be addressed to improve the overall performance and reliability of these switches. Shunt switches (capacitive coupling switches that use a thin layer of dielectric material and an air gap between two metallic contact surfaces) can be used to switch RF signals and avoid metallurgical contact issues. However, these switches only work for AC RF signals and are incapable of passing DC signals through the dielectric material. Metal contact switches are better suited for low frequency applications (including DC) as well as high frequency applications.

ACKNOWLEDGEMENTS

The authors would like to thank the Sandia Compound Semiconductor Research Laboratory staff for their processing and development efforts and Alex Pimentel for his FIB work. The authors would also like to thank Dan Barton, Charles Hembree, and Richard Anderson for reviewing this paper. Sandia National Laboratories is a multiprogram laboratory operated by the Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000. For further information about MEMS technology at Sandia, please visit our website at: http:\\www.mems.sandia.gov.

REFERENCES

[1] 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, 8th Int. Conf. On Solid-State Sensors and Actuators*, 1995, pp. 1165-1168.

[2] L. E. Larson, R. H. Hacket, M. A. Melendes, and R. F. Lohr, "Micromachined microwave actuator (MIMAC) technology – a new tuning approach for microwave integrated circuits," *Tech. Digest, IEEE Microwave and Millimeter-Wave Monolithic Circuits*, 1991, pp. 27-30.

[3] L. Lin, C. T-C. Nguyen, R. T. Howe, and A. P. Pisano, "Microelectromechanical electronic filters," *Proc. IEEE, 10th Ann. Int. Workshop on Micro Electro Mechanical Systems*, 1992, pp. 25-30.

[4] C. A. Smith, and E. I. Cole Jr., "Resistive Contrast Imaging: A New SEM Mode for Failure Analysis," *IEEE Transactions on Electron Devices*, Ed. 33, No. 2, 1986, pp. 282-286.

[5] J. A. Walraven, E. I. Cole Jr., and P. Tangyunyong, "Failure Analysis of MEMS Using Thermally-Induced Voltage Alteration," Proceedings from the 26th ISTFA, 2000, pp. 489-496.

[6] J. J. Yao, "RF MEMS from a device perspective," J. Micromech. Microeng 10, 2000 pp. R9-R38.

[7] J. J. Yao and M. F. Chang, "A surface micromachined miniature switch for telecommunication applications with signal frequencies from DC up to 4GHz," Transducers, June 1995, pp. 384-387.

[8] E. I. Cole Jr., and J. M. Soden, "Scanning Electron Microscopy Techniques for IC Failure Analysis," **Microelectronics Failure Analysis Desk Reference**, 3rd ed., 1995, pp. 163-175.

[9] E. I. Cole Jr., P. Tangyunyong, D. A. Benson, D. L. Barton, "TIVA and SEI developments for enhanced front and backside interconnection failure analysis," ESREF Proceedings, 1999, pp. 991-996.

[10] E. J. J. Kruglick, "Microrelay design, performance, and systems," Ph.D. Thesis, Berkeley Sensor and Actuator Center, 1998.