ANALYSIS OF FAILURE MODES AND MECHANISMS IN THERMALLY ACTUATED MICROMACHINED RELAYS FOR HARSH ENVIRONMENTS SPACE APPLICATIONS

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ABSTRACT

This paper reports test results on electrical characteristics, evaluation of design, failure modes and reliability of thermally actuated, commercially available micromachined relays. The selected parts have been characterized over a wide range of temperatures (from –100 °C to +180 °C) and varying load conditions (voltages from 10 V to 70 V, and currents from 5 mA to 200 mA). Mechanical integrity of the parts was evaluated by subjecting them to multiple mechanical shocks in the range from 100 G to 1000 G acceleration with up to 10,000 shocks. Operational life testing was performed at different contact voltages and current loads during 10^8 switching cycles. All components intended for space applications have to operate in vacuum conditions. To simulate space operation conditions, operational characteristics of the parts were monitored during vacuum testing. Typical failure modes associated with different test conditions are discussed in this paper.

1. INTRODUCTION

NASA has ongoing programs and missions planned for the future that require operation of planetary probes, payloads and instruments over a wide temperature range, such as below –125°C for the Martian environment to over 500°C for the Venusian atmosphere. NASA projects such as James Webb Space Telescope (JWST), Mars Exploration Rover (MER) and Mars Smart Lander (MSL) require operation at very low temperatures. Reliable cold electronics systems capable of operating at cryogenic temperatures will be needed for many future NASA space missions, including deep space probes and spacecraft for planetary surface explorations. Therefore, it is of great interest to the NASA community to evaluate performance and reliability characteristics of military/commercial temperature range devices over harsh environments and provide guidelines for testing, packaging and risk mitigation techniques in space applications.

Micromachined relays combine benefits of solid-state devices, such as low size, weight, power consumption, time response, and capability to be integrated with other microcircuits on the same wafer with desirable characteristics of conventional electromechanical relays, such as low leakage currents and high radiation hardness. MEMS switching devices do not generate spurious signals at high frequencies, have low insertion losses, high linearity, high isolation, and broad bandwidth, which is advantageous for developing RF and microwave frequency systems. These features make micromachined relays very attractive for space applications, especially for a new generation of small and nano-satellites [1].

One of the major reliability concerns in MEMS switches, especially with electrostatic actuation, is contact sticking. In this respect, thermally actuated relays have advantages over the electrostatic counterparts. The actuation mechanism in thermally activated devices creates significant mechanical forces during opening and closing, which overwhelms potential adherence forces and micro-welding of metal contacts. Besides, unlike the electrostatic microrelays, which require high driving voltages, thermally excited relays can operate at conventional voltages of 3 to 5 V.

Several types of thermal actuators have been demonstrated for optical [2, 3] and RF microswitches [4, 5], and tunable RF bandpass filters [6]. Thermal actuators have been used in a variety of applications. Relays have been reported that include a thermally actuated beam that uses a polysilicon heater on top of a SiO_2-Si-SiO_2 clamped beam [7]. For this relay, a 15 μm deflection required temperature increase of 90K. Other test results showed operation time of 5 ms, 25 μm deflection and a force of 2 gf obtained with 27V/25 mA input power. Another thermally actuated relay has been reported that uses mercury contacts to reduce the contact wear and arching effects. Contact resistance for this relay was measured to be less than 1 Ω with a maximum carry current of 20 mA [8]. Various patents have been filed that include devices using thermally actuated element to make contact with another element, and using arched micro-electromechanical beams which are actuated by providing heating from separate heating elements. The arched beams get radiatively heated to provide necessary displacement required for actuation [9]. The first commercially available thermally actuated microrelays were fabricated by Cronos Integrated Microsystems in 2000.

The purpose of this work was evaluation of the design, electrical characteristics, and reliability of thermally actuated microrelays and analysis of their validity for space applications.

2. PARTS FABRICATION, DESIGN AND OPERATION

Characterization testing was performed on a non-latching DC switch, which is manufactured using a silicon technology and a combination of three major MEMS processes: bulk micromachining, surface micromachining, and LIGA [10]. The part is designed based on a proprietary thermal actuation technology and the nickel surface micromachining technique in which high aspect ratio structures are fabricated by electroplating nickel into lithographically-defined plating stencils [11].

After sawing the wafer, the silicon dies with a size of ~ 2×2 mm are attached to the floor of a ceramic 10-pin flat package with a silver epoxy and are bonded to the package contact pads with gold wires. Figure 1 shows an overall view of the part and indicates major elements of the design: stationary and movable contacts, spring, actuator, actuator beams, and microheater. All elements, except for the microheater, have an axial symmetry and are placed above two large wells in the chip of approximately 35 μm depth each. One of the wells is formed below the microheater and actuator beams and another below the contacts, spring, and holders.

The gold plated stationary contacts are mounted on a shock absorbing spring, which also provides electrical connection to an external lead of the package, thus forming one of the two switch connectors. The movable contacts are also plated with gold and are separated from the stationary contacts with a gap of approximately 5 μm width. These contacts are attached to a thermally oxidized polysilicon joint plate, which insulates contacts from the actuator. Four holder bars support the movable contacts with the joint plate and electrically connect the contacts to an external lead, which forms another connector of the switch.

The actuator is fastened to the silicon chip with six actuator beams, which are tilted approximately 0.01 to 0.015 radian to the perpendicular of the actuator axis. The polysilicon microheater is formed under the actuator and is separated from it by a gap of approximately 2 μm of thickness. All metal elements, including contacts, springs, and actuator are made of nickel plated with gold and are separated from the bulk silicon by etching away a sacrificed copper layer. The tips of the stationary and movable contacts have matching concave/convex shapes and are plated with hard gold.

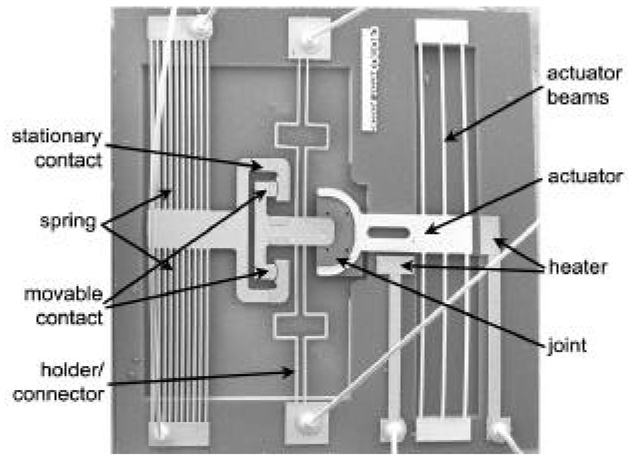


Figure 1. Major elements of the micromachined relay.

When the heater is powered up, temperature of the actuator beams increases and they elongate, creating a backward motion of the actuator that closes the contacts. When the input power supply is off, the temperature of the actuator beams drops and the movable contacts are forced to shift forward by the shrinking beams, thus opening the switch.

Using an IR thermal video system AVIO, maximum temperature of the actuator was measured at different voltages applied to the heater. Results of these experiments showed that at the rated voltage of 5 V, the maximum temperature reaches 80 ^{o}C to 100 ^{o}C, which is in agreement with the estimations.

3. ELECTRICAL CHARACTERIZATION AND TEST RESULTS

Major electrical characteristics of the microrelays, close time (τ1), release time (τ2), heating current (IH), and contact resistance (Rc), were measured at the rated voltage at the heater of 5 V. Leakage currents between the open contacts (Ilc) and between the contacts and the heater (Ilh) were measured at 100 V. All parameters were obtained using a precision semiconductor analyzer hp4156A with hp41501B pulse generator expander. Two lots of the microrelays were tested: a lot of 50 samples was procured in 2000, and another lot of 30 samples in 2001. The original specification had the following device characteristics: Rc < 400 mOhm and τ1,2 < 8 ms; however, for the second lot the requirements had been changed to Rc < 550 mOhm and τ1,2 < 15 ms.

Results of room temperature measurements are displayed in Table 1. Test data showed that the variations of the close and release times, and heating currents were within 15% to 20% limits; however, for the first lot, the variations in the contact resistance exceeded 55%. This lot had 32% samples with Rc > 1 Ohm, whereas the second lot had only one part with high Rc. The second lot had also much lesser variations in Rc and lower operation times, thus indicating some improvement in the process control. In all cases, the leakage currents between open contacts (Ilc) and between contacts and heater (Ilh) were in the picoampere range.

Table 1. Statistical data on electrical characteristics of two lots of microrelays: lot I of 50 samples, lot II of 30 samples.

Parameter:	t 1, ms		t 2, ms		IH, mA		Rc, mOhm		Ilc, A		Ilh, A	
	Lot I	Lot II	Lot I	Lot II	Lot I	Lot II	Lot I	Lot II	Lot I	Lot II	Lot I	Lot II
average	8.7	6.7	5.6	6.7	32.4	32.7	1051.0	725.2				
std. dev.	1.4	1.5	0.7	1.4	1.3	1.5	627.0	154.8				
Min	5.5	4.8	4.3	3.1	28.4	27.7	456.3	527.3	6.6E-12	1.41E-12	3.8E-11	3.51E-11
Max	11.4	11.1	7.7	10.8	35.9	34.8	2802.0	1322.5	1.2E-11	3.49E-11	1.4E-10	9.82E-11

Characteristics of several parts were measured in a temperature range from –100 °C to +180 °C. Results of these measurements are presented in Figures 2 and 3. As expected, the resistance of the heater increased with temperature, resulting in decrease of Ih from 35-36 mA to 28-29 mA over the temperature range. The contact resistance monotonically increased with temperature from 200-400 mOhm to 550-700 mOhm in the range from –20 °C to +180 °C. The resistance had a trend of reaching minimum at –20 °C to –60 °C (for different parts) and increasing at lower temperatures (< -60 °C). Switching times also manifested temperature extremes, with time-to-closure (τ_1) having minimum and time-to-release (τ_2) having maximum at approximately 70 °C.

These variations of the characteristics can be explained considering two factors affecting switching times and contact resistances with temperature. First factor, is a widening of the gap between the contacts as the environmental temperature increases. This might occur if the shift of the movable contact is not completely compensated and $\phi_o > \phi_s$. The widening of the gap will result in increasing of τ1 and decreasing of τ2 with temperature. Second is the decrease in power dissipated in the heater due to increasing its resistance. This effect will decrease the temperature of the actuator and accordingly decrease τ1 and increase τ2. The first factor, most likely controls the behavior of the parts at relatively low temperatures, whereas the second prevails at higher temperatures. Variations of the contact resistance are governed by the same factors because the size of the gap and the temperature of the actuator affect the force between the closed contacts. However, a decrease in ductility of the gold contacts at low temperatures might also affect Rc, thus further complicating its temperature dependence.

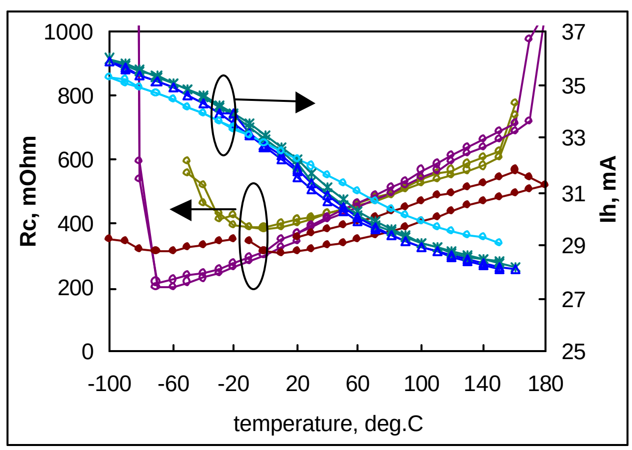


Figure 2. Temperature variations in the contact resistance and heating current at Vh = 5 V. Different marks correspond to different samples.

4. RELIABILITY EVALUATION

4.1. Mechanical testing

To evaluate mechanical robustness of the parts, five samples were subjected to mechanical shock testing in Z-direction (perpendicular to the package plane) first at 200 G, then at 400 G, and then at 1000 G. At each acceleration level, 10 shocks were performed before electrical characterization. The acceleration during the following testing was maintained at 1000 G, with the number of shocks increasing in logarithmic increments up to 10,000 shocks. Results of these tests are shown in Figure 4. No significant variations in the time-to-closure were observed in four parts during the testing; however, one part failed catastrophically (stuck open) after 1000 shocks.

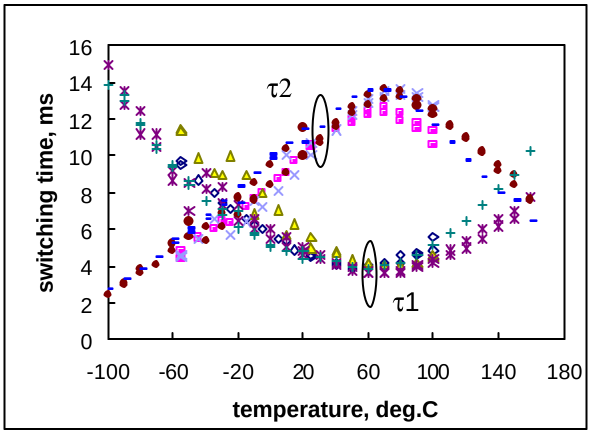


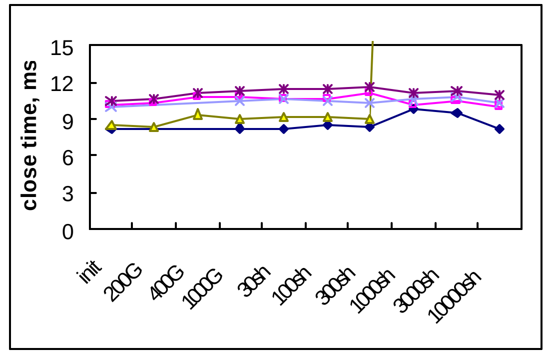
Figure 3. Temperature variations the close (τ1) and release (τ2) times at Vh = 5 V. Different marks correspond to different samples.

All parts passed testing up to 400 G, and three parts had normal characteristics after 10,000 shocks of 1000 G. Failures due to intermittent contact resistance were observed in one of the parts after ten 1000 G shocks, and two parts failed high Rc (> 1 Ohm) after 300 and 10,000 shocks of 1000 G.

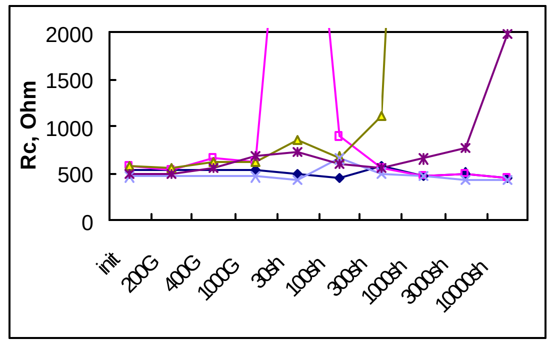
Failure analysis showed that the catastrophic failure was due to damage in both polysilicon elements of the design: the microheater and the joining plate (see Figure 4).

All parts examined before and after various stress testing had small cracks of approximately 20 µm of length in the middle area of the polysilicon joints (see Figure 5) suggesting that they were originated during manufacturing. These cracks were most likely due to mechanical stresses developed by CTE mismatch between the nickel and polysilicon elements of the tether structure.

The fact that these cracks did not cause failures of the parts and did not grow during multiple mechanical and switching life test cycles suggests that stress relief defects might be not destructive. However, designing the joint with a hole placed in the crack's location would be helpful to release the stress and further reduce risk failures.

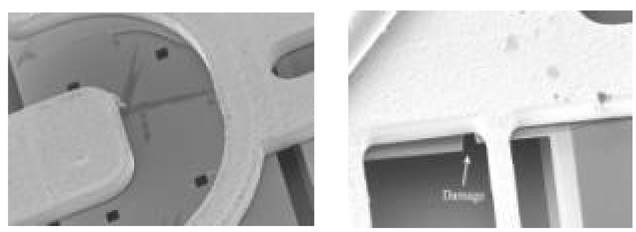


a)



b)

Figure 4. Variation of the close time (a) and contact resistance (b) during mechanical shock testing of five samples.



a) b)

Figure 4. Cracks in the joint (a) and in the heater (b) in the part failed catastrophically after 1000 mechanical shocks of 1000 G.

4.2. Operational life testing

Life testing was performed at room temperature by applying meander-like 5 V pulses with frequency of 10 Hz to the heater. Seven groups of the parts with three samples in each group were tested at different resistive load conditions as shown in Table 2. Group I was tested without voltage applied to the contacts. The parts were electrically tested after 10^3, 10^4, 10^5, 4×10^5, 10^6, 5×10^6, 10^7, 5×10^7, and 10^8 cycles.

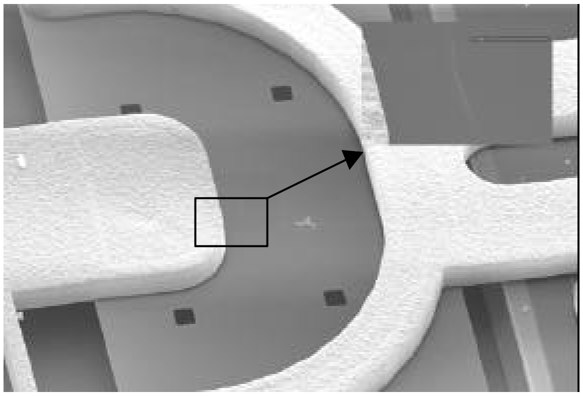


Figure 5. Typical cracks in polysilicon joints observed in all parts, which withstood mechanical and switching life testing, suggesting that this type of defects are not harmful.

Table 2. Operational life testing conditions.

Group	Switching voltage, V	Limiting resistor	Current, mA
I	No load	-	-
II	10	50 Ohm	200
III	10	100 Ohm	100
IIV	30	0.6 kOhm	50
V	30	1 kOhm	30
VI	60	6 kOhm	10
VII	60	12 kOhm	5

The switching times did not change significantly up to approximately 10^5 cycles. Then the close time increased and the release time decreased, approximately 30% to 50% by 5×10^7 cycles. It is possible that these changes were due to some plastic irreversible deformation of the spring and/or actuator beams, which resulted in an increase of the gap between the contacts. The contact resistance began increasing significantly after approximately 5×10^6 switching cycles; however, no hard failures were observed during this testing. These results agree with the data reported in [6], where no anomalies in contact resistance were observed up to 3.8×10^6 switching cycles

Figure 6 shows median number of cycles to failure obtained during life testing at different load voltages. All life test failures occurred after less than 10^6 cycles. In spite of decrease of the switching power from 1 to 2 watts at 10 V to 0.6 to 0.9 watts at 60 V during the testing, the number of cycles to failure decreased from approximately 10^6 at 10 V to only 10^4 cycles at 60 V. This indicated that the switching voltage (V) is probably the most important factor affecting the occurrence of failures during resistive load testing.

All failures during the 60 V testing and most of the 30 V failures were caused by stacked close contacts, whereas failures at lower voltages and no-load failures were mostly due to unstable, intermittent contact switching. Failure analysis showed that all life test failures were due to a local microwelding between the contacts. This, as well as analysis of normal contacts after a relatively low number of switching cycles indicates that the intimate contacts occur only at local sites near the ends of the rated contact area. Figure 7 shows metal dust (chaff) generated due to heater touching the actuator after ~ 10^8 cold switching cycles, which can be a contamination hazard.

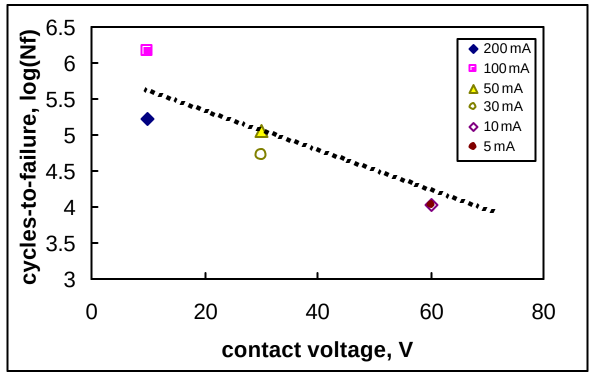


Figure 6. Median number of cycles-to-failure during life testing at different contact voltages and load currents.

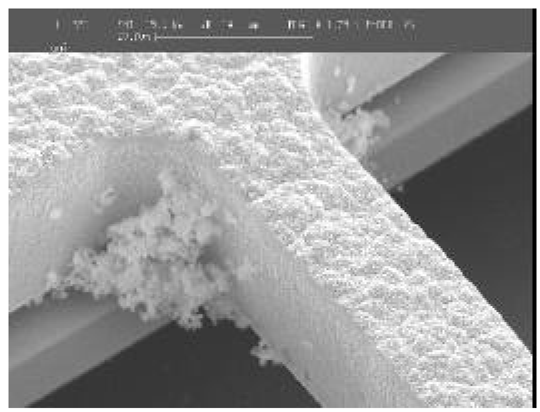


Figure 7. SEM picture of metal dust (chaff) generated due to heater touching the actuator observed after ~ 1E8 cold switching cycles.

4.3. Vacuum testing

All components intended for space applications will operate in vacuum conditions. Hermetic packages of electronic components have a certain level of seal leak, resulting in development of low-pressure conditions inside the package with time. These conditions have been demonstrated to cause failures in conventional electromagnetic relays due to arcing at relatively low voltages below 60 V [12].

To evaluate the effect of vacuum on performance of the micromachined relays, the lids in three parts were carefully punctured through and then placed in a vacuum chamber.

Two failed parts stuck open after a few switching cycles at no-load conditions in vacuum at approximately 0.1 torr. To analyze the cause of these failures, the heating currents were monitored at several heater voltages and different environment conditions. Kinetics of the heating currents measured before and after the seal puncture were virtually identical. However, when measured in vacuum anomalies in IH variations during the fast, 10-millisecond stage of the kinetics were observed starting from 4 V. The stationary currents in vacuum were approximately 20% lower then in air, suggesting a significantly higher temperature of the heater in vacuum compared to air conditions. At Vh = 5 V, the current dropped to less than 10 mA after exhibiting anomalous kinetics for a few seconds. Internal examination of the part revealed a deformed and cracked microheater (see Figure 8).

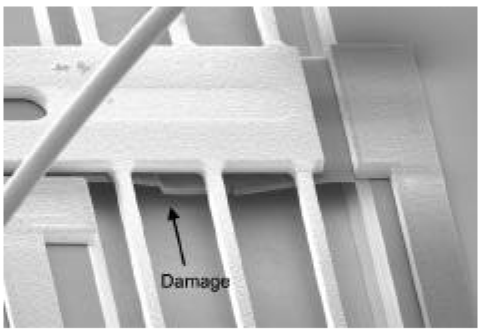


Figure 8. Deformation and cracks of the microheater in the part that failed vacuum testing.

Variations in the kinetics of the heater current and the observed damage indicate that the vacuum failures were caused by overheating of the polysilicon heaters. Under normal conditions the heat from the heater transfers mostly to the actuator by conduction and convection in the air gap between the heater and the actuator. In vacuum, the heat dissipation is reduced and the thermal resistance of the heater increases significantly, thus causing thermal runaway in the heater.

5. CONCLUSIONS

1. All parts withstood 400 G shocks and two out of five parts withstood 10,000 shocks of 1000 G, indicating potentially high mechanical robustness of the microrelays.
2. Life testing at no-load conditions showed that the thermal actuation mechanism can endure up to 10^8 cycles, however some degradation of the timing characteristics and contact resistance was observed after approximately 10^5 cycles.
3. The parts cannot be switched reliably more than 10^6 times at a contact voltage of 10 V with limiting currents of more than 100 mA. Increasing contact voltage to 60 V, reduced the number of cycles-to-failure to approximately 10^4, even at limiting currents of 5 mA to 10 mA. All failures were caused by micro-welding at the edges of the contact surfaces.
4. Vacuum testing was found to be a detrimental condition for the thermally actuated micromachined relays, designed with a gap between the heater and the actuator. The failures were due to overheating of the microheater and were caused by reduced heat dissipation and increased thermal resistance in vacuum.

7. REFERENCES

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