BI-DIRECTIONAL MICRO RELAYS WITH LIQUID-METAL WETTED CONTACTS

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INTRODUCTION

Micro relays and switches are promising micro products that have attracted numerous research efforts from both industry and academia for applications in RF systems, telecommunications, automotive, and other fields. MEMS relays are smaller and potentially cheaper than the conventional electromechanical relays because they can be batch fabricated using microfabrication techniques. Relays with metal-to-metal contacts are still preferred over solid-state relays (SSR) because they have higher breakdown voltage, low on-state resistance, higher off-state resistance, good isolation and good linearity.

There have been many previous works on micro relays. These relays can be grouped according to their actuation mechanisms; the most common types are electrostatic, electrothermal, and electromagnetic. Electrostatic actuation \([1,2]\) provides fast response time and consumes little energy, but the main drawback is small actuation force. To compensate for the small force, these actuators require high voltage, which is not compatible with standard IC chips, and might cause cross talk between the actuation electrode and the signal lines. Small gap distance between electrodes can increase the actuation force, but could lead to capacitive coupling and low breakdown voltage. Furthermore, the low actuation force leads to relatively high contact resistance.

Electrothermally actuated relay can exert higher force, but are generally slow, power hungry and typically require high current inputs \([3,4,5]\). High actuation and restoration force allow for low contact resistance and reliable separation. Unlike electrostatic actuators, continuous power consumption is required to keep the contact in the closed position.

Electromagnetic actuators, on the other hand, have high force and high displacement, but the fabrication process tends to be more complicated \([6,7]\). They may require the use of thick conducting layer(s) for coils, and high permeability materials for cores, which are not commonly used in MEMS. Electromagnetic actuators tend to be power hungry, just like thermal actuators, to keep contacts closed. Both electrothermal and electromagnetic actuated relays try to make use of bi-stable designs such that power is only consumed during the switching operation; and no power is consumed in either the bi-stable on or off positions \([5,8]\). This paper present micro relays powered by bi-directional electrothermal electromagnetic actuators with liquid-metal wetted contacts. These relays combine the best characteristics of high force thermal actuators, bi-stable design, and low contact resistance.

DESIGN

The bi-directional actuator used in the relay have been described in details previously \([9]\). The actuation beams have lengths of 950 to1200\(\mu\)m, width of 10\(\mu\)m, and thickness of 20\(\mu\)m. These actuators can achieve displacement over 40\(\mu\)m and exert force greater than 3mN in both directions. All relay actuators are built on top of a 25\(\mu\)m deep thermal isolation trench and the gap between the contact surfaces range from 20-50\(\mu\)m. The Bi-directional actuator allows for implementation of single pole double throw (SPDT) relay configuration as shown in Fig. 1. SPDT relay has a common terminal, a normally closed terminal, and a normally open terminal. Using the bi-directional actuator, one current path can be normally kept closed and the other opened. When the actuator is moved to the opposite direction, the normally closed terminal is opened, and the normally open terminal is closed.

![Figure 1. Bi-directional actuators make a) relays that can function as a single pole double throw (SPDT) configuration with normally opened, normally closed, and two common terminals b) bi-stable design that requires energy only during switching.](image-url)
FABRICATION

These relays are fabricated with the MetalMUMPs process, with some optional post processing steps. The MetalMUMPs process has a total of 8 thin film layers patterned by 6 masks, where the main structural layer is a 20µm-thick electroplated nickel. The metallic structures can be mechanically connected and electrically isolated using silicon nitride bridges such that a moving electrical contact can be attached to a bi-directional actuator while remaining electrically isolated from both the fixed contacts and the actuator. A simplified cross section of the micro relay is shown in Fig. 2. The detail process flow can be found in the MetalMUMPs design handbook.

![Figure 2](Image 178x474 to 286x576)

Figure 2. (a) The cross sectional view showing the contact area of the micro relay. (b) SEM microphoto of a fabricated contact with a nitride bridge.

The MetalMUMPs process is designed for lateral contact relays. Low contact resistance is achieved by electroplating the structural top and sidewall with a gold overcoat approximately 2µm thick. However, this gold overcoat can be very rough as shown in the SEM microphoto in Fig. 3 such that the actual contact area of metal-to-metal contacts could be small and the contact resistance could be big. Previous literature claims that a clean gold-to-gold contact with 0.7Ω contact resistance, has a actual contact area 0.125µm in radius.

The contact resistance could be decreased by coating the contacts with a liquid-metal. For example, mercury has been used in both macroscale and microscale relays. Macroscale mercury displacement relays can switch hundreds of amps with contact resistance as low as 1mΩ. Mercury is very conductive (96mΩ-cm) and has a low melting temperature of -38°C. However, mercury is also highly toxic. The liquid-metal used in this experiment is a non-toxic gallium alloy with a -20°C melting temperature. The liquid-metal is evaporated onto the MetalMUMPs die using a thermal evaporator. The shadowing effect of evaporation causes the top surface deposition to be thicker than the sidewall surface and Figure 3 shows the SEM microphotos of the liquid-metal wetted contacts. The shadowing effect could be minimized by putting the targeted die at an angle from the evaporation source, and rotating the dies several time during the evaporation process. Although most of the liquid-metal still end up at the top surface, there is enough on the sidewall to produce measureable difference.

![Figure 3](Image 307x616 to 422x738)

Figure 3. (left) The gold overcoat on the top and side walls of the contact area is 2µm thick and very rough as fabricated. (right) After the liquid-metal deposition, the top surface has more liquid-metal than the sidewalls due to the directional evaporation process.

EXPERIMENTAL SETUP AND RESULTS

The relays are tested under a normal laboratory environment without packaging and most of the relay actuators are built with six actuation beams. Testing of trenched and non-trenched actuators have shown actuators built on top of a 25µm-deep thermal isolation trench are about 3 times more energy efficient. The typical operation voltage and current of the relays are between 0.25V-0.5V and 0.5A-0.8A. Short-term reliability tests are conducted using a function generator and a high current amplifier capable of outputting 25V and 5A up to 2kHz to repeatly switch the relays.

Contact resistance is measured using a multimeter via two probe tips to measure the resistance form one fixed contact, to the moving contact, and to the other fixed contact. The probe tips are then moved to the same pad to measure the parasitic resistance form the probe tips and wires in the testing setup. The difference between the two measurements is treated as the actual contact resistance, which include the bulk resistance of the moving and fixed contacts, and two interface between the moving and fixed contacts as illustrated in Fig. 2(b). The bulk resistivity of 20µm nickel and 0.5µm gold composite structure is approximately 0.003Ω/µm, hence the two surface contacts are the major contributors to the contact resistance.

The MetalMUMPs process introduced a tensile residual strain such that the apex of the sine-shaped bistable beams were several microns lower than the as-drawn design. Residual strain greater than 650µε would exceed the 30% safety factor designed into the beam curvature as-drawn and puts the beams into the non-bistable region. For example, an as-drawn design has an apex height of 25µm, but was measured at 16µm (908µε) after the fabrication process. The relay can still operate bi-stably by heating the bistable beams using resistive heating to cause thermal expansion and increase the curvature. This proves the bi-stable mechanism can work but the residual strain issue must be adressed using either designs that compensate for the residual strain, or better plating process to minimize the built-in residual strain.

The measured breakdown voltage of the relays is >200V while the theoretical breakdown voltage of a
metal-air-metal contact is >360V for a gap larger than 5\(\mu\)m\textsuperscript{[13]}\). The measured off-state resistance exceeds the multimeter limit of 100M\(\Omega\). The measured contact resistance of the gold-to-gold contact as fabricated is typically 0.3\(\Omega\)-0.4\(\Omega\). The gold surface of the dies looks brown instead of gold color probably due to the contamination problem in the manufacturing process. It is believed that this brown color is not caused by the surface roughness of the gold because once the top surface is scratched with a probe tip, clean metallic gold can be observed. Furthermore, the brown color coating can be removed using Piranha, but the nickel structural layer will be damaged. It is hypothesized that photoresist may have dissolved during the plating process and was deposited on the metal structures. As a result, some of the contacts have resistance as high as several ohms. After cycling the contacts open-close several times to several dozen times, the contact resistance can usually go down to 0.3\(\Omega\)-0.4\(\Omega\).

These relays are capable of switching a large amount of power without the liquid-metal contacts. Experimentally, as much as 120V and 0.5A was hot switched across a 250\(\Omega\) resistor, and up to 50V and 1A was hot switched across a 50\(\Omega\) resistor. However, during the high power hot switching process, contacts of these relays quickly deteriorated. Once the contacts fail, they often fail catastrophically and the contact resistance jumps up to several megaohms. Figure 4 shows the optical and SEM photo of a failed contact. It appears the gold coating is gone, and the actual contact surface could be oxidized nickel.

![Figure 4. Damaged relay contacts after high power hot switching: (left) optical photo (right) SEM photo.](image)

Long term hot-switching experiments are challenging. Once voltages and currents are hot switched across the relay contacts, the contacts stop conducting after several hundreds to several thousands cycles. The exact failure mechanism is unkown, but airborne contamination is the likely culprit. The relays are tested under normal atmospheric conditions where contaminants like soot, dust, and other air pollutants such as sulfides, hydrocarbons, eventually coated the contact surface. It is possible that contact arcing and heat generated at the contact eventually cause the surface contaminant to coat the actual contact areas. One relay has hot switched up to 10V and 200mA for over 1000 cycles before failure.

The bi-directional actuators are very reliable; some have been tested over 1-million cycles without failure. Furthermore, the bi-directional relays with spring loaded contacts presented in this paper have also been cycled for more than 100,000 repetitions (flexures fully compressed) without failure under cold-switching condition; and there was no sign of wear or deformation at the contact surfaces. Typically, the relay failed when the moving contact and the stationary contact were no longer co-planar. Ambient temperature has an effect on the amplitude of actuator displacement. When the temperature drops, more power must be supplied to achieve the same amount of displacement. When the ambient becomes hotter, excessive force exerted at the contact can cause the contacts to slide on top of each other. This problem can be solved making the structural layer thicker, and by controlling operating temperature using good packaging methods.

The micro relays can cold switch a much larger amount of power; as much as 4A and 200V (800W) can be passed without contact welding. However, heat generated at the contact under high current level cans actuate the thermal actuators. For example, it takes less than 0.5W to close the relay contacts, but 4A of current dissipated through 0.3\(\Omega\) contact resistance can generate 4.8W of power. Even though the contacts won’t weld, the thermal stress caused damage to the actuators. One way to reduce this thermal stress problem is to use spring loaded design for the moving contact as shown in Figure 5. The spring can act as thermal insulation between the contacts and the actuator, and it can absorb some of the thermal stress caused by contact heating. It was suggested that a clean gold-to-gold contact need roughly 100\(\mu\)N of force to achieve a contact resistance of 0.1\(\Omega\)\textsuperscript{[11]}. Therefore, the flexure is designed with a spring constant of 100\(\mu\)N/\(\mu\)m and a gap of 6\(\mu\)m to assure the spring flexure can maintain the necessary force on the contact.

![Figure 5. Spring loaded design for the moving contact: (a) SEM photo of spring in the uncompressed state, (b) optical photo of spring flexure fully compressed. The spring constant is 100\(\mu\)N/\(\mu\)m, and the gap between the flexure is 6\(\mu\)m.](image)

In order to further reduce the contact resistance, the concept of liquid-metal was applied. Figure 6 shows the current vs. contact resistance of a liquid-metal contact. Since the contact resistance is very low, accurate measurement is difficult. Any resistance in the measurement system such as connection wires, heating of the resistors, and probe contacts will introduce errors. The figure shows best effort to eliminate those error by substracting the parasitic resistance measured from the same contact pad as described in the previous section. It was observed that when the passing current increases, the contact resistance decreases probably due to local heating that causes the relaxing of surface tension of liquid-metal and more contact areas are established to reduce the
resistance. In a different liquid-metal contact relay, a contact resistance as low as 0.015Ω has been measured using a multimeter. Table I compares the important characteristics of the liquid-metal contacts vs. gold-to-gold contacts presented in this work.

![Figure 6. Current vs. contact resistance of a liquid metal coated contact.](image)

**Table I. Typical contact characteristics**

<table>
<thead>
<tr>
<th>Contact Type</th>
<th>gold (Ω)</th>
<th>Liq.-metal (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>On resistance</td>
<td>0.3~0.4</td>
<td>0.015~0.1</td>
</tr>
<tr>
<td>Off resistance</td>
<td>&gt;100M</td>
<td>&gt;100M</td>
</tr>
<tr>
<td>Max current carried (A)</td>
<td>4~5A</td>
<td>4~5A</td>
</tr>
</tbody>
</table>

Experimentsally, liquid-metal coated contacts can pass very large current and it is important to have the contact resistance as small as possible. For example, a 3A current passing through a 0.02Ω contact would only dissipate 18mWatt. However, the probe tips used to test the relays could get hot at 3A because of its own contact resistance can be much larger than the liquid-metal contact. The force required to obtain low liquid-metal contact resistance is smaller than the gold-to-gold contact. However, excessive coating of liquid-metal could cause shortage of the contact. Figure 7 shows that even when the contacts are physically separated, large droplets of liquid-metal as the result of excessive liquid-metal coating can bridge the air gap and electrically short the contact.

![Figure 7. Excessive coating of liquid metal can cause electrical short of contacts: (a) an optical photo of contacts in open position and big droplets of liquid-metal can be observed; (b) close up view of liquid-metal bridging the contact even the relay is in open position.](image)

It should be noted that the bi-directional actuators have no problem separating the liquid-metal contacts. The separation force of the bi-directional actuator is comparable to the actuation force, both in the neighborhood of several millinewtons. It is noted that previous research on electrostatically actuated relays with mercury droplet contacts suffered from contact separation problems[14].

**CONCLUSION**

We have demonstrated micro relays with gold-to-gold and liquid-metal contacts that have many characteristics close to an ideal switch. These include very low on-state resistance, very high off-state resistance, high breakdown voltage, and good current carrying capacity. The voltage requirement to actuate these relays are very low. Although the energy consumption to actuate these relays is high, the operational energy consumption can be significantly reduced using a bi-stable mechanical design. Future research would also include process improvement for liquid-metal coating and reliability testing of the liquid-metal coated contacts.

**REFERENCES**