BISTABLE MEMS RELAYS AND CONTACT CHARACTERIZATION

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ABSTRACT

A bistable switching relay structure for DC signals has been developed which provides a self-holding double gold contact with as low as 2.4Ω measured contact resistance, 80mA current carrying ability, 7-12V actuation, and air gap isolation when open. The bistable frame structure can be used to design the holding force of the contact with minimal impact on actuator requirements. The frame also allows control over the necessary force and displacement of actuation almost independent of relay requirements. A lateral contact geometry was designed to allow fabrication of the relays in the MCNC MUMPs dual polysilicon foundry process with no assembly. The contact design was characterized using a polysilicon vernier structure to develop force/current/conductance curves and reliability information. The characterization data has been used to develop design information for micro-contacts.

INTRODUCTION

MEMS relays have numerous potential applications. The North American relay market alone is US\$1.4 billion, and the recent explosive market share of surface mount relays (from 1.2% in 1993 to 19.6% in 1997) demonstrates the value of miniaturization[1]. Additionally, new applications become available as it becomes feasible to integrate large numbers of relays onto smaller substrates. Some of our target applications are voltage generation in the hundreds of volts and similarly high voltage driver switching which cannot be realized reasonably with solid-state devices due to limited breakdown voltages. The low parasitic feedthrough can also be taken advantage of in certain high fidelity applications such as RF and sensor switching.

For our target applications the most important performance requirements are low drive voltages, truly "micro" size so that large scale integration is possible, and zero assembly. Impressive previous work has been done using electrostatic[2][3][5][6], magnetic[4], fluid flow[7], and thermal actuation[8] but none meet all three of our requirements. For large scale analog integration it is also important that a relay be bistable such as [9] to minimize power dissipation during non-transition periods.

Here we present a bistable MEMS frame which allows a relay to be realized which is bistable and can be actuated by a range of methods. Appropriate electrodes have been developed and tested, and the importance of force and current levels have been measured to define a functional design space for designing microrelays. The device has been fabricated in the commercial foundry MUMPs process [10] using a design which does not require assembly.

THE BISTABLE RELAY FRAME

The principle of the bistable frame is shown schematically in figure 1. The frame is fabricated in the open position. The rotary beams ride on fixed pin joints which allow them to rotate in a circular path. This circular path deflects parallel support springs inward as the structure transitions from one stable state to the other (figure 1b). In figure 1c the bistable action has been stopped as the crossbar runs into the electrodes. The remaining spring force from the bistable action holds the con-

Figure 1. Bistable action in the relay frame holds the device in an open or closed state without actuation. Inset SEM shows a bistable frame with pin & joint interface for use with a thermal stepper motor.

tact shut. By changing the position of the electrodes the contact closure force can be changed.

Electrode placement controls the proportion of the spring force which is applied as contact force. The magnitude of the spring force can be controlled separately by design of the lateral flexing beams. Once the frame has been designed to set the contact force a particular moment around the fixed pin becomes necessary to actuate the bistable relay. The design of the rotating beam provides leverage between the actuator and the required moment, increasing design flexibility by allowing force/distance trade-offs. The minimum moment arm is currently set by fabrication requirements and play in the pin joints to about $4\mu\text{m}$. Some improvement is possible.

Many designs were tried for the sliding pin joint. The most reliable we found is a circle of second poly over a toroid of first poly with a circle of contact from second poly to first poly within, but not touching, the geometry of the first poly. The overetch does not reach the substrate and the results is a strong and reliable sliding pin made with only two polysilicon layers.

Figure 2. Electrode and crossbar cross-sections. The crossbar (top polysilicon on the left) moves to the right during relay actuation, the first poly underneath it is a forming piece and is left behind. SEMs shows that some gold is deposited on the face of the crossbar where it will hit the gold face of the electrodes.

Figure 4. Micrographs showing the bistable frame used to put the crossbar across the electrodes to form a bistable relay. Positions in between these are not stable and snap to one of these. The photo on the left corresponds to figure 1a and the photo on the right corresponds to figure 1c.

CONTACT GEOMETRY

The process has two structural polysilicon layers and we want to allow a lateral relay contact design using final metallization (gold in the MUMPs process). Several lateral contact geometries were designed and a successful one is shown in figure 2. The crossbar (shown in figure 2b) provides contact by sliding into and

Figure 3. Several different contact shapes using the cross section of figure 2. A and B have contact perpendicular to the applied force. C and D have contact at an angle to the applied force. A is the structure from the SEMs of figure 2. B has convolutions to reshape the gold. C has flexible angled contact arms on the crossbar. D is rigid, and has the best reliability and lowest contact resistance.

bridging across two electrodes (figure 2c). The SEMs show an arrangement in which the contact and crossbar meet perpendicular to the forces being applied, this is equivalent to figure 3 a and b. Structures using the cross-section from figure 2 and the geometry shown in figure 3d had the lowest contact resistance and best reliability. The device shown in figure 3d exhibited a contact resistance below 9Ω when cycled over 80 times with a 5V open circuit, $400\mu\text{A}$ load and forces near $500\mu\text{N}$. Fatigue testing of this sort has been limited by the inevitable eventual mistakes made at a manual probe station. Automatic test structures and SEM investigation of reliability are planned.

A direct thermally actuated [11] relay (non-bistable) using the structure in figure 3a achieved 2.4Ω contact resistance (for a total relay resistance of 4.8Ω) and 80mA current maximum when actuated at 7-12V. Cyclic testing was limited by a design flaw in the thermal actuators which required running them beyond elasticity to achieve contact.

A functional device with both frame and contact is shown in figure 4. These structures were also fabricated with vernier springs to measure the force required to actuate the bistable frame and

achieve contact. On structures without stiction problems the snapthrough using geometries shown in figure 4 required less than 7μN (on a throw of 100μm) and achieved electrical contact consistent with the results in figure 6 when held by the force from the bistable frame. Thermal stepper motors have been demonstrated with arbitrary throw and greater force (50-100μN) than this[11]. One interesting point is that this force is best applied in a circle tangent to the rotating path of the actuating arm, leading us to a ball-in-slot actuating design to couple the motors and bistable frames. The ball in slot interface was designed by simulation in the Working Model software package[12].

CONTACT MATERIAL ISSUES

The primary consideration for microrelay contact design is contact area. Higher contact area corresponds to lower constriction resistance and lower contact temperature (with correspondingly longer contact lifetime and higher current levels). True contact area and quality at this scale is determined primarily by the hardness of the contact material and its resistance to forming surface layers, not by the apparent surface areas brought into contact. Thus the ideal contact material should be both soft and relatively corrosion resistant. Gold, the available metal in the foundry MUMPs process, fits these design criteria quite well.

A second consideration is the adherence force in the relay. The adherence force must be overcome to separate the electrodes and crossbar once contact has been made and depends greatly on the mode of operation. As the two contact surfaces come close the first interactions take place at asperities which project above the average surface of the contacts. Initial contact is elastic in nature and has fundamentally derivable electromechanical behavior. As the temperatures increase (softening the material) and the force increases the surface asperities begin to yield and deform progressively and contact becomes "weak" plastic behavior. Weak plastic behavior is more complicated than elastic and is typically characterized by empirical models[13]. As temperature and current densities continue to increase the contact material begins to liquefy and deform destructively and nonrepeatably. This is sometimes referred to as "strong" plastic deformation and is bad for reliability if the contact layers are microscopic, as here. We do not consider strong plastic deformation to be a viable operating regime for micro relays and have attempted to avoid it.

The elastic behavior adherence forces measured in [15] and elsewhere are different for different materials. There are significant differences between hard and soft metals.

The weak plastic behavior adherence force derived in [13] is approximately 40% of the closure force if the separation motion is perpendicular to the surface. This number is independent of contact material because it stems from clean metal-metal adhesion in areas where plastic deformation has broken away any surface film. The plastically deformed contact area is inversely related to the material hardness and the tensile strength to pull the contact area apart again is proportional to the hardness [14] so, to first order, the material hardness properties cancel if we assume plastic deformation is reached. It has been noted that harder materials such as rhodium show less adherence than gold at comparable force levels [15]. We are not interested in constant force contact design here, but rather comparable contact performance. Rhodium, a typical "hard" contact material, exhibits a higher resistance in the tests where it exhibits low adherence, and theory predicts that it will exhibit similar adherence once it deforms enough to match the lower resistance of gold contacts. Interestingly, the 40% adher-

Figure 5. Crossbar on polysilicon vernier to allow measurement of force during I-V contact characterization. Deflection of vernier is converted to force through linear beam theory.

ence estimate means that for comparable performance with softer and harder metals the harder metal will have a higher adherence force because it takes more force to reach plastic deformation and low contact resistance. This implies that if large actuation forces are available, such as in macro relays, the hard and soft metal issue must be entirely reconsidered. One of the primary considerations in force limited design, then, is what regime of operation we wish to use in the contact: plastic or elastic deformation. If we run in plastic deformation, the design favors soft metals. Optimal design thus requires extensive contact characterization.

We expect designs such as the one in figure 3d with contact surfaces oblique to the applied force to exhibit lower adherence forces due to the occurrence of shear rather than tensile separation. We have no quantitative estimate for this yet.

CONTACT CHARACTERIZATION

To characterize the contacts shown in figure 2 we designed structures supporting a crossbar on a vernier support with a predictable spring constant as in [16] (figure 5). The structure was pushed into contact using probes and the force was measured by measuring the displacement of the vernier springs on a video screen. The resolution of the system is 0.1μN after magnification, measurement, and calculation. Great care must be taken not to let stiction interfere with the measurements -- the vernier is only accurate when all the roving is deflecting together in a coordinated fashion and the crossbar is sliding freely.

In order to characterize the mechanical mechanisms occurring at various current levels, I-V characteristics were taken at multiple forces and the data was fit to the established relation

$$G \propto aF^b. \quad (\text{EQ } 1)$$

Figure 6. Conductance versus force and current. Current is a factor because of temperature. Equicurrent lines represent model fits to equation 1. Data was not fitted for a group of four points where the data at the lowest force had bad values.

Where G is the conductance, a is an offset, and b is the exponential relation between force and conductance. As surface asperities are forced against each other and electrical contact is made it can be calculated from basic principles that the conduction area goes as force to the $1/3$ power during elastic behavior[17]. This means that we expect b to remain at $1/3$ during the entire elastic regime. The exponent b has been approximated [13] as 0.5 during weak plastic deformation and unity during strong plastic deformation. Current, Conductance, and Force data is shown in figure 6. We expect the equicurrent fits to show different values of b as the gold contact asperities soften with temperature.

The resulting values of b from these fits are shown in figure 7. The expected elastic region (region I, $b = 1/3$) is clearly visible. At a certain current (and associated temperature) the value of b begins to increase again, signalling a transition into weak plastic

Figure 7. Plot of the fitting constant b for lines in figure 6. Expected values are drawn in. Uncertainties for the value of b are 0.015. The data here shows experimental confirmation of the predicted behavior.

Figure 8. 3 successive traces of contact resistance versus current show the practical effects of the trends in figure 7 on contact performance. The similarity of the 3 traces show that the contact is not being degraded at these current levels.

yielding (region II). As the current continues to increase the value of b begins to change more slowly and the statistical accuracy of the models degrade. The initial rise to $1/3$ in figure 7 contains statistically very significant models but is not well understood. Previous work has indicated that at extremely small deformation levels the elastic behavior of gold increases by a factor of 10 and approaches the ideal crystalline strength[18]. It is possible that region 0 represents transition from this much higher modulus to bulk behavior, but this is still speculation. Currents beyond those shown here caused nonrepeatable degradation in contact behavior for this particular contact geometry and were therefore excluded from this test so that all data could be verified on the same structures. All I-V data sets were taken 100 times and any that did not prove consistent within our error bounds were discarded as unstable. Very good vibration isolation was required. Lifetime tests at different currents are underway.

Since the current carrying capability of a contact run in plastic deformation is significantly higher than during elastic deformation we want to design relays that run in the safe region of small scale plastic deformation (region II). Given our previous discussion of contact and adhesion force this design preference reinforces our decision to use the softest appropriate material.

IMPLICATIONS FOR DESIGN

The R-I curve in figure 8 shows 3 traces of data from the contacts being characterized. This data is from the same structure as produced the data in figure 6, but none of these traces were used to generate figure 6 or the models. The regions marked correspond to those in figure 7. The poorly understood initial rise to elastic behavior has been labelled as "region 0". This resistance to current relation shows that there are many regimes of operation which work in a repeatable fashion. If we design relays which operate in region II, the weak plastic deformation region, in a given application we can maximize performance and reliability while also optimizing materials for low force.

During data collection for figure 6 no current was applied to the relay during mechanical switching. The results show the regions of operation and predict behavior, but will not necessarily predict absolute resistances when switching under load.

CONCLUSIONS

We have designed a bistable frame for actuating a relay which provides a repeatable closure force, lever interface to actuators, and no force input requirement to hold the relay in place. Relays have been designed, fabricated and tested using this frame. The lateral contact design has been fabricated and tested to further explore design variables, and acceptable regions of operation have been established. The test data also provides insight into the behavior of microcontacts and allows for some materials considerations. Additional characterization will be needed for higher frequency performance.

Further research will explore the possibilities of single step actuation and further explore the physics of relays to advance design. The bistable relays presented here typically have a higher resistance than is desirable for our target applications but new contact shapes have demonstrated higher reliability and lower resistances.

Layout and additional information can be found online at www-bsac.eecs.berkeley.edu.

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