

Experimental validation of external load effects for micro-contacts under low frequency, low amplitude, alternating current (AC) test conditions

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Abstract— This paper presents experimental results of micro-contacts subjected to low-frequency, low-amplitude alternating current (AC) loads with external circuit loading effects. Previous experiments have demonstrated micro-contacts that typically perform well under DC conditions consistently fail prematurely under low frequency alternating current loads. This increased failure was observed as a decrease in device lifetime (1,000 cycles or less), and more variability in contact resistance during operation. Under DC loading conditions, it has been demonstrated that device lifetime can be affected by the load applied to the micro-contact, extending life or promoting premature failure depending on the type of load applied. This kind of lifetime testing involves cycling the contact and applying a DC load at a cycle rate up to 2.5 kHz. Due to AC conditions, test methodology required we slow this test cycling down if we wish to ensure cold switch testing was accomplished. This control of test conditions along with applying external protective loading is critical in evaluating test results, specifically in identifying root causes of failure. These failures traditionally have been attributed to hot switching, but data presented indicates that devices which were subjected only to AC cold-switch conditions show still shows signs of degradation. To evaluate how influential loading is under AC conditions, the load effects on these devices was studied by utilizing a designed experiment which evaluated various load configurations, reactive and passive component sizing, frequency of the voltage applied, and the cycle rate of switch operation. Of the 15 devices tested, 13 successfully reached the 10 million cycle mark and were still functional at that point. However, contact resistance near the end of all but one test began to steadily climb and often was accompanied by swings in variability. This change typically occurred at approximately 100,000 cycles of operation, and in all cases observed, the increase in contact resistance was permanent. The data indicates that this type of protection can increase lifetime in these devices, but at a cost of increased contact resistance when compared to the micro-contacts initial contact resistance.

Keywords—Micro-switches, Micro-contacts, Reliability testing, Microelectromechanical Systems

I. INTRODUCTION

Application of microswitches to RF applications is continuing to be an area of active research, addressing several of the outstanding issues with their use [1][2][3][4]. Most of the more recent works center on addressing specific application issues and how to alter device designed to address these concerns. One such area of concern still under investigation is general performance and reliability of micro-

additional complication of an AC load makes this kind of failure even more complex. To break down this task of understanding the failure mechanics under these conditions, focusing first on lower frequency responses may help in understanding the fundamentals behind these failures in higher frequency applications.

Previous work has indicated that under low-frequency, low amplitude AC conditions, device failure typically occurred between 1000 and 100,000 cycles [5]. Device failure is predominantly due to shorted contacts, and this is usually attributable to material transfer caused by electromigration. Similar tests under DC conditions have shown improved performance when external loads, both in parallel and in series are added. This experiment will investigate the effects of applying these external loads to devices tested under low frequency, low amplitude AC conditions and observe the responses.

II. TEST Setup

A. Test Stand

The test stand used in this experiment is shown in Figure 1. The enclosure maintained a nitrogen environment while the piezo-controlled force sensor assembly provided the actuation of the micro-contacts to the desired contact force. This assembly was used not only to measure the contact resistance but also to cycle the device up to 2.5 kHz, which simulated the cycling encountered during lifetime wear. During this cycling, an electrical load was applied which more accurately represented usage during the devices life. That load was supplied from a function generator that was synchronized to the mechanical movement of the contact.

During the initial study of unloaded low-frequency, low-amplitude AC loads, timing of the load signal was discussed in detail [5]. In the experiments presented here, all loading was strictly cold-switched: no potential was present during contact closure, and all current was reduced to 0 Amps prior to contact opening. Because of the time required for a full cycle at low frequencies, the testing time was reduced sufficiently so that only a single cycle of AC was applied during each cycle of simulated use.

B. Micro-contact Design

The devices used in these experiments were identical to those used for the baseline study. Figure 2 shows an illustration of the design of these micro-contacts. Each beam is electroplated gold, roughly 150 μm in length, 75 μm wide and 6 μm thick, with a 1 μm gap between the beam and lower contact. The lower contact is a thin film of evaporated gold, 280 nm thick with a 50nm titanium adhesion layer. This was

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contacting surfaces in RF applications. Failure mechanisms are a complex phenomenon under DC conditions; adding the

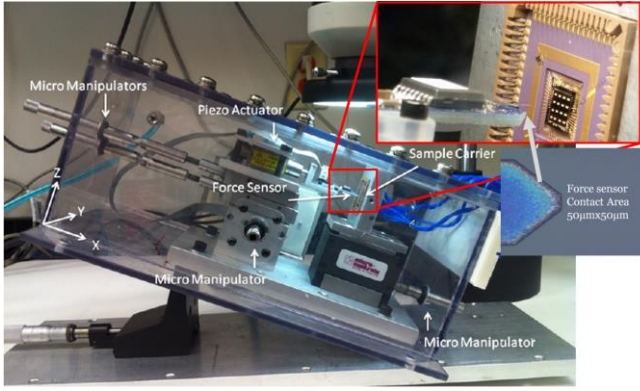


Figure 1 Test enclosure with externally actuated force sensor assembly. Test reticle of 16 devices is shown in inset.

deposited on a layer of silicon nitride on the surface of a silicon substrate. The bottom of the beam was fabricated to contain a hemispherical contact bump with a radius of 8 μm .

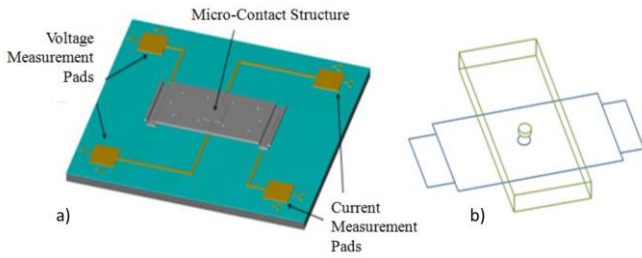


Figure 2 Physical structure of micro-contacts [8]. The left illustration (a) shows the four contact points required for testing while the right illustration (b), a more detailed view of the overhead beam with contact bump on the underside in relation to the lower thin film which serves as the bottom contact.

C. Prior Performance of unloaded AC tests

The baseline data for these experiments are shown in Figure 3 [5]. These results contained no external loading, and these tests were conducted using only cold-switch conditions. Three devices were tested, each at a different frequency, and all failed well before the 10 million cycle goal. The device tested with a 10 kHz load experienced failure after 2.3 million cycles. The two devices which were tested with 1 kHz and 100 kHz both failed before 1,000 cycles as shown. For all three tests, the AC load was comprised of a single cycle applied during the fully closed period of the micro-contact mechanical actuation cycle. In the case of the 1 kHz load, the overall cycle time at which the contact itself was cycled was limited to 200 Hz, which maintained cold-switched conditions. For the 10 kHz load the testing time was increased to 1 kHz, and for the 100 kHz load the cycle time was the full 2.5 kHz. These conditions were repeated for all experimental data presented here, but with the addition of externally loaded circuit components.

III. RESULTS

Testing was conducted with four loading configurations, similar to those from previous works with external circuit configurations with DC electrical loads [6], and the four selected were those which proved beneficial under DC conditions. The first of these tests was with a purely passive load, comprised of a 5 M Ω resistor in parallel with the contact, and a 1 Ω resistor in series. The plotted values of contact resistance shown in Figure 4 below do not include the external series resistance. The parallel 5 M Ω resistor must be included

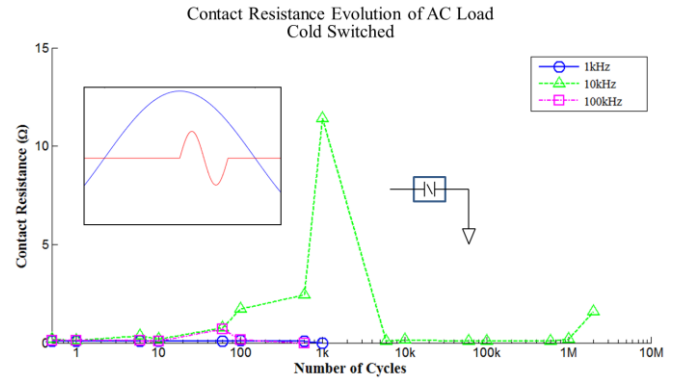


Figure 3 Results from low-frequency, low-amplitude AC loading at 1 kHz, 10 kHz and 100 kHz with unloaded contact. For the 10 kHz test, device failed due to shorting at ~ 2.3 million cycles, the 1 kHz and 100 kHz tests resulted in the same failure mechanism prior to reaching 1,000 cycles [5].

in the measurement with this test methodology, but its effects on the measurement were considered negligible. As can be seen from this first set of data, all three devices lasted for 10 million cycles of operation at which time testing was arbitrarily terminated. In all three cases, similar contact resistances were observed, and in each case remained remarkably stable. Of particular interest was the slight increasing trend in all three cases, but in one case (the 1 kHz device) this resistance dropping back down to normal levels. This resistance correction was similar to the response shown in DC testing, where irregularities in contact resistance tended to show stabilization with these sort of passive loads applied [6].

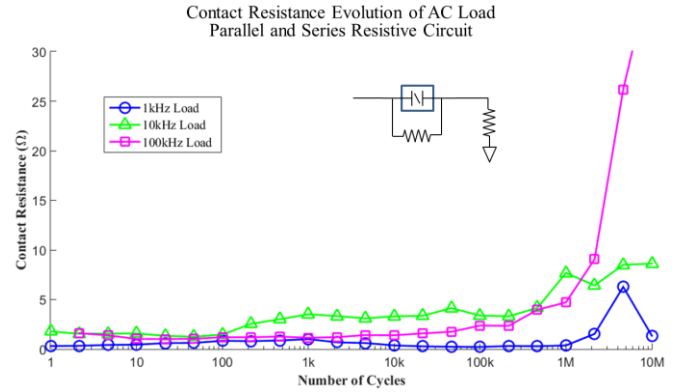


Figure 4 Test results for three load frequencies, each with parallel and series resistances added. The parallel resistance was 5 M Ω s while the series resistor was held to 1 Ω . Testing was comprised of a single test cycle under cold-switched conditions, limiting the test cycle rate (200 Hz actuation rate for the 1 kHz load, 1 kHz actuation for the 10 kHz load, and 2.5 kHz

Next we will consider the second loading configuration tested, as shown in Figure 5. The same resistances were used as in the previous test, but in addition the parallel resistance had a series inductance added (0.1 μH) and the series resistance was placed in parallel with an additional capacitor (0.6 pF). All other test conditions remained the same the previous test. When comparing these results to the last test, it is important to note the scale on the plot. While the variability was more erratic than the previous test, this variance was less than 2 Ω s throughout the duration of these tests. This circuit configuration also resulted in one failed device, which occurred during the 1 kHz AC load test. This failure occurred after ~ 4.9 million cycles, at which point, the contact failed to open (i.e. was shorted closed). This set of data also includes the most stable result observed from all tests conducted. This occurred with the 10 kHz test, which settled after just a few

cycles of operation and remained at roughly $0.25\ \Omega$, even up to 10 million cycles.

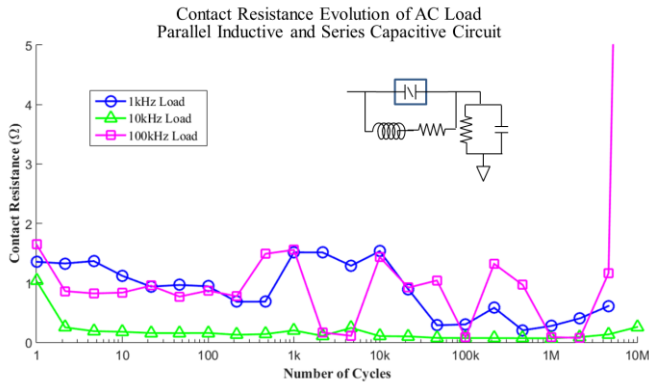


Figure 5 Test results for three load frequencies, each with parallel RL and series RC added. The parallel resistance was $5\ \text{M}\Omega$ s with $0.1\ \mu\text{H}$ inductance while the series resistor was held to $1\ \Omega$ with a $0.6\ \text{pF}$ capacitance. Testing was comprised of a single test cycle under cold-switched conditions, limiting the test cycle rate (200 Hz actuation rate for the 1 kHz load, 1 kHz actuation for the 10 kHz load, and 2.5 kHz actuation for the 100 kHz load).

The third circuit configuration considered is identical to that of the previous test, but without the capacitance as shown in Figure 6. Every other aspect of this test is otherwise the same as before. Note here we see the second of the two failed devices, which similarly was with the 1 kHz load, and in this case resulted in device failure after ~ 0.8 million cycles. The two contacts which did last to 10 million cycles showed the same high increase in resistance near the end of the test, and as with the purely resistive case (Figure 4), the 10 kHz test showed the high increase in resistance, while the 10 kHz showed the same remarkable stability as it did in Figure 5.

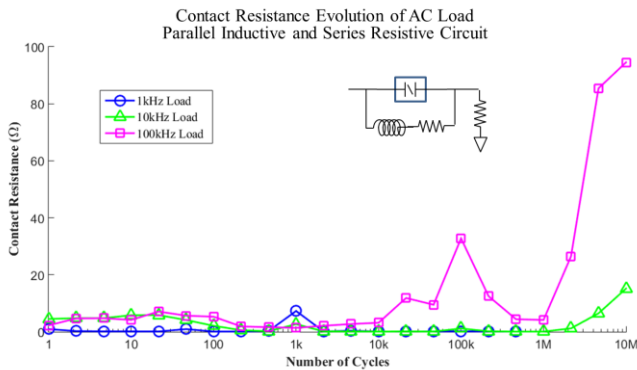


Figure 6 Test results for three load frequencies, each with parallel RL and series resistance added. The parallel resistance was $5\ \text{M}\Omega$ s with $0.1\ \mu\text{H}$ inductance while the series resistor was held to $1\ \Omega$. Testing was comprised of a single test cycle under cold-switched conditions, limiting the test cycle rate (200 Hz actuation rate for the 1 kHz load, 1 kHz actuation for the 10 kHz load, and 2.5 kHz actuation for the 100 kHz load).

The next test results were from the last of the four circuit configurations investigated. Instead of removing the capacitance from the test shown in Figure 5, the inductance was removed. So in this case, we still had a $5\ \text{M}\Omega$ resistor in parallel with the contact with no inductor, and a $1\ \Omega$ resistor and $0.6\ \text{pF}$ capacitor parallel combination in series with the micro-contact as shown with the data on Figure 7. In this test, all three frequencies showed similar results to each other, but different than any previous test. Note again the scale, resistance increases that were relatively large, and until 100,000 cycles resistance values that were climbing steadily. Around that point however, all three devices showed very large increases in contact resistance, and in all three cases

there was some level of recovery, but nowhere near back to fully-recovered, stable values. All three devices did however last the full 10 million cycles and while their contact resistances were fairly large, were still operational at end of each test.

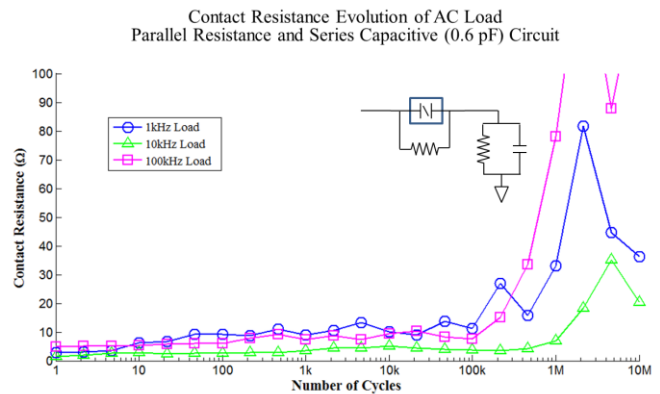


Figure 7 Test results for three load frequencies, each with parallel resistance and series RC added. The parallel resistance was $5\ \text{M}\Omega$ s, while the series resistor was held to $1\ \Omega$ with a $0.6\ \text{pF}$ capacitance. Testing was comprised of a single test cycle under cold-switched conditions, limiting the test cycle rate (200 Hz actuation rate for the 1 kHz load, 1 kHz actuation for the 10 kHz load, and 2.5 kHz actuation for the 100 kHz load).

The fifth and final set of data we'll discuss is an identical circuit configuration as the previous test, but the capacitance was tripled (so instead of $0.6\ \text{pF}$, a capacitance of $1.8\ \text{pF}$ was used). The results of these tests are shown in Figure 8. The starting resistance of the 10 kHz device tested was $\sim 28\ \Omega$ s and showed some erratic behavior throughout, but the other two devices tested showed a very similar overall result as to the previous tests. Contact resistance increased and showed more variability past the 100,000 cycle mark, but the micro-contacts continued to function.

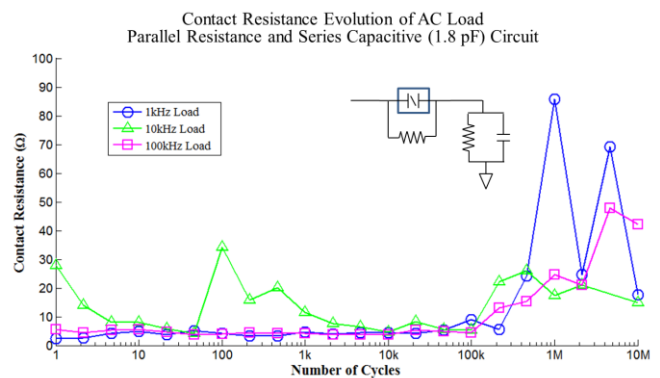


Figure 8 Test results for three load frequencies, each with parallel resistance and series RC added. The parallel resistance was $5\ \text{M}\Omega$ s, while the series resistor was held to $1\ \Omega$ with a $1.8\ \text{pF}$ capacitance. Testing was comprised of a single test cycle under cold-switched conditions, limiting the test cycle rate (200 Hz actuation rate for the 1 kHz load, 1 kHz actuation for the 10 kHz load, and 2.5 kHz actuation for the 100 kHz load).

When considered as a whole, there are a lot of interesting observations to be made from this series of tests. To summarize:

- Two of the 15 devices failed prior to 10 million cycles. Both failed due to a shorted contact, both were test involving a 1 kHz load at 200 Hz cycling frequency, and both were with the only two circuits that utilized parallel inductance and resistance circuitry.

- For all of the five sets of data, the 10 kHz data showed overall the least amount of variability, with the exception of the last set of data.
- For all sets of data, the 100 kHz test resulted in the highest ending contact resistance, while the 10 kHz and 1 kHz data sets showed comparable results to each other in each case.
- Repeatedly, sharp increases in contact resistance were observed which later decreased without device failure. In most cases however, the ‘recovered’ contact resistance was higher than before this event occurred.

IV. CONCLUSIONS

From these results, several conclusions can be drawn. It is clear that the external loading can be used to extend the life of a micro-contact, assuming some level of variability in contact resistance is tolerable. Previous work from which our baseline data was obtained demonstrated 100% failure in all devices prior to reaching 10 million cycles [5]. In this study, those tests were repeated but with the addition of various forms of circuit protection. Of the 15 devices tested, 13 of those devices reached 10 million cycles and were still operable.

Also, it can be observed that while this form of protection clearly extends lifetime, contact resistance is still being affected. Consider the data presented on the 10 kHz test signal applied with both parallel inductance and series capacitance from Figure 5. Of the 15 tests conducted, this was the only device which showed stable, predictable contact performance through 10 million cycles with apparently little change at any point during the test. All other devices that lasted to 10 million cycles showed a point at which contact resistance began to steadily climb, and did not show any indication of recovery. In most cases, this increase was then accompanied by fluctuations in variability and large spikes in contact resistance. As with DC devices which demonstrated these fluctuations, these macro-contacts also managed to operate under these conditions [6].

The final conclusion that will be drawn is that low-frequency, low-amplitude AC loads are able to damage contacts even under cold-switched conditions. Extreme care was taken in these experiments to ensure this cold-switching condition was kept, and in all but one case decrease in performance was still observed. If these kinds of loads are required and the observed variance in contact resistance can be tolerated, the structural breakdown that occurs can be mitigated by applying these principles to the surrounding

circuit elements, and the data collected here indicates the use of this technique is justified to enhance reliability.

V. REFERENCES

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