Experimental Validation of External Load Effects on Micro-Contact Performance and Reliability

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Abstract - This paper presents a follow-on study previously presented at the Holm Conference. In the previous work, it was theorized that micro-switch performance and reliability was directly related to the type of external load that was connected. In particular, unintended capacitive loads may discharge at unpredictable times during switch operation and severely degrade or destroy micro-contact surfaces while properly configured loads may actually enhance performance. The severity of this potential vulnerability can be mitigated by purposely including specific circuit elements in various load configurations. This current study is to experimentally investigate and analyze this phenomenon.

I. INTRODUCTION

This work is intended to experimentally validate and expand on the concepts outlined in a previous study [1]. From that work, contact resistance modeling is the starting point [2] but the true focus is how micro-contacts interact with external loads. "Hot" versus "cold" switching was discussed [3] and will be considered here as well. The principle focus, however, is the beneficial and detrimental effects of both passive and reactive load configurations.

In this work, we'll systematically test a variety of circuit configurations. Our test methodology will be driven by the considerations outlined, while paying specific attention to the implications of "hot" versus "cold" switching. Contact temperature is critical to performance. While temperature ultimately affects the resistivity of contact materials, more importantly temperature plays a critical role in electromigration, which is a key cause of failure in micro-contacts. As electromigration can lead to drastic changes in contact geometry, this may in turn affect heating leading to a cyclical failure mode.

Finally, we test our theory that the type of load and how the load is configured can either contribute to premature failure or extend device lifetime. To accomplish this, eight separate circuit configurations will be tested, and each test repeated twice with two separate devices, through 10 million cycles of operation.

II. BACKGROUND AND METHODOLOGY

To test these theories, a test fixture was utilized which is capable of efficiently testing lifetime performance of micro-contacts using previously outlined methods and devices [4]. These micro-contacts made utilizing microelectromechanical systems (MEMs) fabrication techniques. Specifically, these were gold structures on a silicon substrate, with a Si₃N₄ insulation layer. The lower contacts were deposited with evaporated gold and upper beams made from a sputtered layer reinforced with an electroplated structure.

The test fixture is capable of measuring the µN of force applied to these micro-contacts which results from manually compressing them with an actuator capable of controlled positioning within approximately +/- 10 nm. When used in conjunction with other instrumentation, the compressive force between the contacting surfaces is directly measured along with all needed electrical measurements. This testing is conducted in an enclosure which allows us to operate in a dry, contaminant-free nitrogen environment.

The devices tested are based on the classical Holm cross-bar experiment [5]. A single 3" silicon wafer was used to fabricate approximately 40 samples, and each sample contains 16 gold-gold micro-contacts. As all of these devices are fabricated simultaneously, geometric variation between them is considered minimal.

The controls for this test stand are accessed using LabVIEW, and autonomously gather data at predetermined fixed test points during the cycling process. Data was collected by slowly closing the contact until electrical closure was achieved. The force is then ramped up to 200 µN while the contact resistance is measured. Once this initial
measurement is stabilized and the test point is completed, the precise position of contact closure is used to begin rapid “cold” switch cycling. The specific sequence follows: 1) the contact is closed, 2) current is applied through the contact, 3) current is removed, and 4) the contact is opened, then the cycle repeats. This entire cycling process occurs at a rate of up to 2,500 Hz. This allows for testing up to 10M in just a few hours.

While the micro-contacts are within an enclosure, the external load components connected to the device under test are wired externally. Eight circuits were evaluated as part of this experiment and are shown in Figure 1 below, with each of the boxes at the top of the eight circuits representing the micro-contact being tested. The ordering of the devices is such that configuration 1 is expected to result in the most damage, while 7 and 8 are expected to provide the best protection to the micro-contact.

The first configuration (1) is predicted to be the most detrimental by adding both capacitance in parallel with the micro-contact and inductance in series. Both (2) and (3) test these two detrimental configurations separately. Configuration number 4 is our baseline, with no external loading. Configurations (5) and (6) apply reactive loads in what is theorized to be beneficial RL and RC configuration, and these are combined in configuration (8). Configuration (7) is somewhat unique in that it is purely resistive, but according to our original paper might provide some level of contact protection [1].

It should be noted that the beneficial configurations contain resistors of unspecified values. For the RL and RC configurations, these are required because we are testing under DC conditions. The size of all components depend on the application in question, the internal resistance of the micro-contact itself, and how much we wish to amplify any positive or negative effects. This will be detailed more in the next section, but in general any parallel resistance needs to be large enough that the contact closing is still detectable and any series resistance needs to be small enough so that an open contact can be observed. As for the reactive components, for the purposes of this experiment we want to size these as large as possible to amplify any positive or negative effects. However, the larger the device the longer it takes to charge. So, depending on the circuit configuration, the cycle time of the test being performed, and what effect we are trying to test, we must size these components with these considerations in mind.

### III. PREDICTED RESULTS

Before discussing observed results, first consider how the various circuit configurations are expected to perform. To do this, we must consider not only the circuit configuration but also how and when voltage is applied to the contacts in conjunction with its operation (i.e. “hot” versus “cold” switching) [6]. To quickly review this concept, refer to Figure 2 below.

![Figure 1. Circuit configurations tested including 1) parallel capacitance with series inductance, 2) parallel capacitance, 3) series inductance, 4) baseline, 5) parallel RL load, 6) series RC load, 7) Resistive voltage division and 8)RLC protective loading all under DC load signal.](image)

![Figure 2. Relative timing of contact closure (solid line) with respect to applied current (dashed line) can result in cold switching (A), hot closure (B), hot opening (C), or hot switching (D).](image)

First, let's consider capacitance. If this capacitance in parallel with the switch, this effectively increases the overall capacitance of the contact. With an uncharged circuit preparing to close, no effect should be observed provided this capacitor and the switch itself are both fully discharged. Once the micro-contact is closed, it can be thought of as a resistor in parallel with the added capacitor. Depending on the frequency of the signal applied, this RC circuit will respond accordingly. But if the input is terminated soon enough for the capacitor to discharge through the closed micro-contact before separation occurs, we can expect circuit 2 in Figure 1 should have minimal effect. However, if any charge is allowed to accumulate prior to contact closure then this extra charge will result in “hot” switching as shown in Figure 2, case (B). This provides a large numbers of excess charge carriers which will rapidly discharge across the micro-contact. Unless the contact is designed to withstand this situation, excess heating will result, which contributes to accelerated electromigration and other detrimental effects.

On the other hand, what if we place a capacitor in series with a contact such as circuit 6 in Figure 1? As capacitors are inherently devices that resist instantaneous change in voltage, applying such a device through the ground path of our contact may help minimize the likelihood that undesired arcing will occur. However, since we are operating under DC conditions, we need a resistor in parallel as well, the size of which really depends on the required current capacity and overall resistance. In our case we’ll keep this resistance small, on the order of 10 ohms.
Next, let's consider inductance. When an inductor is in series with our contact, the danger lies with the contact opening rather than closing. Just as capacitors resist immediate changes in voltage, inductors resist immediate change in current. Thus, when a contact is closed and carrying current, if it is opened immediately the presence of a charged inductor, this will force current to flow in the only manner available, i.e. “hot” switching as shown in Figure 2, case (C).

What about the case where we have an inductor in parallel with our contact? Should charging occur in our opened contact, the circuit configuration allows a path for the contact to discharge without any rapid changes. In this case as well, we have added a resistor to avoid the inductor path from simply acting as a short circuit. In this case, inductance does not have a detrimental effect on contact life. However, the addition of the resistor will have resisted immediate voltage change across the contact, allowing this stored inductive energy to be transferred in part to the capacitor instead of discharging across the contact. The concept behind this operation is simply that adding a parallel resistor may alleviate residual charge in the contact prior to closing, and increasing the series resistance of the contacts ground path may similarly reduce the overall current change when our contact opens. Unlike the reactive protection configurations however, a resistive protection scheme accomplishes these effects immediately.

IV. RESULTS AND ANALYSIS

To evaluate these predictions, each circuit was built and tested to either 10 million cycles or failure, whichever came first. Each circuit configuration was tested on 2 separate devices and the highlights of these tests will be presented. First let's look at the most detrimental circuit configuration found, shown in Figure 3 below: series inductance.

The worst results were from configuration (3) shown in Figure 1, not configuration (1) which also contains the same series inductance. While configurations (1) and (2) are not shown on Figure 3, they both failed before reaching 10,000 cycles but outperformed configuration (3), which lasted less than 1,000 in both test cases. One possible explanation is that the cycle rate of the switch was much greater than the time needed for the inductor to dissipate its charge. So, after each contact closure the series inductor would ramp up in current, but once the contact opened, since inductors must maintain current, this probably resulted in current flow well after the micro-contact opened. In configuration (1), however, the addition of the capacitor will have resisted immediate voltage change across the contact, allowing this stored inductive energy to be transferred in part to the capacitor instead of discharging across the contact. Also, the baseline shown in Figure 3 illustrates the variable nature of these devices when operated without any external circuitry. This variation has been shown in previous studies to be primarily caused by electromigration induced contact damage [4]. The two spikes in contact resistance are believed to be material which has separated but did not cause the contact to fail. Typically, this condition eventually clears through continued cycling. The zero values at the higher cycle counts are related to this effect, a condition caused by the measured voltage becoming momentarily too small to detect, but with an acceptable amount of current passing through the contact.

Next, we will review what seems to be the most beneficial of the various RLC circuit configurations, series capacitance. Figure 4 below presents these results.
Figure 4, Comparison of the contact resistance of Au-Au 8μm radius micro-contacts showing the baseline device along with two repeated series RC combination (a) and (b), which lasted as long as the baseline device, but with much less Rc variation and a somewhat more consistent response through the 10M cycles tested.

In the case of adding reactive elements to protect the contact, the best results are comparable to the baseline. The other two protective configurations which use reactive components all lasted the full 10M cycles, as well, but showed greater variation in contact resistance. In this case, the data suggests that adding an inductor in parallel (configuration 8) is less beneficial than leaving it off (configuration 6).

How do these results compare to the third set of data presented, a purely resistive circuit (configuration 7). These results are shown in Figure 5 below.

Figure 5, Comparison of the contact resistance of Au-Au 8μm radius micro-contacts showing the baseline device along with both parallel and series resistances added, providing both the ability to immediately dissipate any charge during contact opening while simultaneously limiting current during a contact inadvertently opening while carrying current.

An interesting result is the two distinctive responses shown in what should be identical tests. In one case shown in Figure 5 (case a), the additional resistors seemed to reduce much of the variability, but high resistance results with a slow and steady decrease in resistance. Devices of this type typically take somewhere between 100 to 1000 cycles to ‘wear-in,' and can exhibit this sort of drop in resistance, but that is believed to be a result of the mechanics behind the contacts cycling [4]; which shouldn't be effected by an external resistance present. The second device shown (case b) shows a much more expected result: device wear-in still occurs but then the resulting closed resistance is lower and is much more stable with much less variation throughout the device lifetime.

One last point of interest involves the measurements taken for failing contacts. For each of the three detrimental configurations (1, 2 and 3), in all the devices tested it was apparent that these devices were on a path to failure during the measurement cycle itself. This is better explained in Figure 6 below.

Figure 6, Comparison of two single contact resistance measurements, both typical for devices that remained stable throughout 10M cycles or failed prematurely.

These detrimental configurations all demonstrated measurement cycles similar to the failing contact plot shown in Figure 6. This seems to indicate that these configurations consistently cause contact damage quickly, as the irregularity shown around 10-20 μN indicates eventual device failure. On the other hand, devices which last to 10M cycles almost always behaved very similar to the stable contact plot, and while the final resistance reached may have varied, any lack of smoothness of the overall curve tends to be an excellent indicator of failure yet to occur.

The way cycling of the devices and application of voltage was triggered, “hot” switching did not occur, and the switch itself exhibits a small capacitance that requires very little time to discharge. For this reason, rather large external capacitors were used relative to the contacts (approximately 200 pF), in an attempt to amplify any detrimental effects. Even so, the parallel capacitance configuration still didn’t produce as much degradation as the series inductance configuration.

With regard to circuit protection, it is difficult to fully evaluate without operating all circuits to failure. Instead, micro-contacts were visually inspected to verify material transfer or damage. To do this, a contact beam is manually separated from one of its anchors and using a probe, the beam is folded back along the edges to inspect the under-beam contact area (as shown in the bottom of Figure 7 below).
Figure 7, SEM investigation of contact surfaces after testing to 10M cycles to investigate level of induced wear by folding upper contact beam back after separating from anchor.

Unfortunately, contacts which survive to 10M cycles show very little surface damage with no difference in their visual appearance after separation (as a typical result shown in Figure 7 illustrates). In every failed device, the failure was because the contact fused shut and failed to release after the probe was removed. This kind of failure tends to not cause a lot of damage, and as shown the only indication in the image above is a small, bright dot on the beam image showing the section which fused.

V. CONCLUSIONS

Overall, most of the detrimental circuit configurations failed well before 10 million cycles. The worse performance was an inductor in series with a micro-contact. Considering our cycle rate of 2500 Hz, and the fact that our applied voltage as a duty cycle of approximately 20%, it is likely that this inductor simply didn't have time to discharge prior to contact opening. Parallel capacitance wasn’t a problem, but as mentioned previously we expect this to be more of an issue with a contact pair that is charged prior to closing.

This experiment provides experimental validation of the effects of both reactive and resistive loads and how they affect micro-contact performance. Operation through 10 million cycles was sufficient to demonstrate premature failure in detrimental circuit configurations quite easily and in fact tended to show early warning signs of failure through erratic resistance measurements during closure. Protective circuit configurations were evaluated. In most cases, the addition of these elements resulted in less contact resistance variability and in all cases, no premature micro-contact failures were observed. Overall, the theories and predictions presented in our source paper proved to be well founded.

REFERENCES