Abstract - This paper presents an experimental investigation of micro-contact performance (i.e. contact resistance) and reliability (i.e. successful cycles) evaluated under time-varying, low frequency, low amplitude, alternating current (AC) test conditions. Previous research efforts have focused on either direct current (DC) or high frequency, radio frequency (RF) test conditions. This work attempts to bridge the gap in prior work by generating knowledge related to frequency, phase, and amplitude effects on micron-sized electrical contacts. Contact support structures, micromachined with gold on gold micro-contacts, were actuated using an externally applied contact load of approximately 200 µN and tested in dry, nitrogen ambient environments to minimize pre-test contact surface contamination. Contact resistances measured were comparable to those obtained using a DC. However, reliability is drastically reduced with AC signals between 100 to 100 kHz. Device failure typically occurred prior to 10k cycles on devices proven to last beyond 100M cycles or more under DC conditions. Phase of the AC appeared to have some influence on the manner of failure, as did AC signals that persisted through contact opening. In all cases examined, noticeable physical damage in the form of material migration was observed using a scanning electron microscope.

I. INTRODUCTION

The study of micro-contacts has generally been focused on areas which are likely to provide the greatest benefit. When these devices were first developed, understanding their behavior relied on applying models for macroscopic devices and refining their application to these micro structures. While, in general, many of the fundamental laws work well, the nature of devices on this scale has led to the need for accommodations being made, the behavior of thin-films being a prime example. To refine these models, testing is typically accomplished using direct currents and voltages, as this is a simpler, more straightforward method and removes any time dependent issues that may arise.

Interest in using micro-switch devices for RF applications has accelerated study in this particular area, but this doesn’t address if there are any peculiarities in using micro-contacts with even the most basic alternating current or voltage circuits.

To explore this further, this initial study will focus on conducting tests for the performance and lifetime of micro-contacts under low frequency alternating current (AC) conditions. Given our current understanding of direct current (DC) operation and what we’ve observed along the way in order to gain this understanding, there are many potential aspects worth investigation.

Similar micro-contact studies have been performed using a test stand designed to accomplish this task under DC conditions [1]. This study will make use of that test stand with modifications to accommodate the new test conditions. Similarly, a micro-contact device suitable for use with this test stand will be employed.

II. BACKGROUND

While there are several potential topics we could address regarding AC performance of these devices, we will limit our observations to those likely to produce results given our contact design. To that end, we will start with some tests to address two topics.

A. Impacts of AC operation on performance and reliability

Based on previous studies, it is apparent that the polarity of a DC load applied to a micro-contact can be critical to its long-term performance [1]. Electromigration has proven to be a primary failure mechanism in these kinds of devices [2] and can be accelerated under the right conditions. This failure mechanism is caused by joule heating, but the resulting changes in contact geometry can lead to further increases in contact resistance, which then contributes to such heating, resulting in a cyclic failure mechanism [3].

In the macro world, AC is thought to have gained acceptance because it provides a means of power with much greater efficiency over long distances when compared to transmitting DC, thereby producing less heat. However, AC operation occurs slowly enough and can be thought of as DC operation with alternating load biasing. Previous studies have suggested that micro-contact performance can vary depending upon which side of the contact is positively or negatively charged [4]. Considering these points together suggests that low frequency AC signals may in fact be damaging to these...
kinds of devices.

B. Spectrum analysis in response to AC

Switches constructed using micro-contacts are typically thought of as either an opened or closed circuit. In a closed state, their contact resistances have been modeled as a function of contact force [4]. In an open state however, this capacitive element tends to be ignored when dealing with DC loads. Previous works in RF applications have been based on the observation that the scale of devices like this are likely to produce capacitances compatible with RF frequencies and therefore should be of little concern with low frequency signals. But as a contact closes, these parallel plates will come closer together, changing this capacitance. Therefore, it may be a stretch to assume only high frequency AC signals would be affected by using these micron-size devices.

Consider also that testing these sorts of devices have proven that damage during operation can change contact geometry significantly. Under the right conditions, could this change in geometry also change the effective capacitance mentioned above?

III. METHODOLOGY AND EXPECTED RESULTS

To test the concepts introduced above, let’s consider each individually and address peculiarities which may result from conducting these particular tests, how to address these issues, and what we expect to see for results.

A. Impacts of AC operation on performance and reliability

While testing performance and lifetime of micro-contacts while operated under AC conditions may seem straightforward, there are some limitations imposed which must be addressed. One such issue is illustrated by Figure 1 below which shows the signal used to actuate the contact with the signal sent across the contact after closure.

![Figure 1, Monitoring of automated contact actuation signal with load applied to closed contact.](image)

Contact resistance will still be measured intermittently using a DC signal, but actuation cycles will occur with AC signals. To automate the process of measuring contact resistance while performing large numbers of cycles, high frequency cycling is necessary. Under DC conditions, existing hardware allows us to cycle the contact at a frequency of approximately 2.5 kHz. A sine wave of this frequency (such as the contact actuation signal shown in Figure 1 labeled ‘Contact Actuation’) can be performed in such a way that a DC pulse with a 20% duty cycle phased correctly will result in only cold switching of the device. However, if we wish to instead apply an AC signal as shown and we still intend to only cold cycle switch, a single cycle burst at this frequency must be completed during this 20% duty cycle (as shown in Figure 1, ‘Applied Load’). If the contact is cycled at 2 kHz, then the minimum frequency which can be burst must be at least 10 kHz. If the applied AC load is at a lower frequency, then this will result in one of two cases.

One possibility is if we burst one full cycle to ensure the signal looks like a true AC pulse. Then, this AC signal will continue even after the contact is opened and we have “hot” switched the device. The extreme case of this would be when the burst lasts longer than one full cycle of the contact switching, which would mean our contact cycling simply clips portions of a continuous AC load.

The second possibility is that we ensure that we only “cold” switch the device and attempt to cut off the signal before one full cycle has occurred. This may result in a variety of conditions depending on how much of the signal was seen and what phase it was when it started, but realistically will still produce some degree of “hot” switching.

If our burst signal is in the range of kilohertz, this doesn't pose an issue because we can't physically switch the contact fast enough. However, if we wish to test at lower frequencies and ensure that we are only “cold” switching our devices, then this will require considerable test time. For example, if we wish to test the effects of operating with a 10 Hz load, we must limit our contact cycle frequency to 2 Hz. So to reach 10 million cycles, this would require approximately 57 days of testing as opposed to approximately 2 hours at 2.5 kHz cycle rate. For this reason, for some of the lower frequencies evaluated we will be limiting the number of cycles in some cases, and in others extending our bursts even though this will result in partially hot switching the devices under test.

B. Frequency response to AC

To better understand what sort of results we expect to see in this area (and therefore what we should be testing for), let's examine how the contacts being tested are physically constructed. Consider Figure 2 below which shows a sketch of the micro-contacts in question. The upper contact beam's lower surface contains a hemispherical bump, approximately 8 µm in radius, but only protrudes roughly 100-200 nm. The lower contact surface is a thin-film of gold, and the nominal separation of the beam and this film is approximately 2 µm.
Typically with micro-contacts, the contact resistance has traditionally been the key parameter of interest, and most models for these devices focus on this aspect of their performance. Considering their physical structure however, one could also model them as a capacitor prior to their closure (or more accurately two capacitors in parallel – one from the 8 µm radius bump and a second from the rest of the common area between the two contacts). With DC circuits this observation is often trivial, but not necessarily with AC loads.

This introduces the possibility that the micro-contact need not fully close in order to conduct an AC signal. While typically devices relatively the same size as ours will only pass much higher frequencies in this manner, the range of capacitance and contact resistance values results in a wide range of observable RC values. If the contact resistance were to become very large after the micro-contact is closed, we would then have a resistor in parallel with the remaining micro-contact surfaces, forming an RC circuit.

IV. RESULTS AND ANALYSIS

Next we will present the results of the tests performed. Note that for each test, a separate device was used but all devices were fabricated from the same 3" silicon wafer during the same fabrication run.

A. Impacts of AC operation on performance and reliability

Previous testing efforts on these devices utilize a 1 V DC pulse across the contacts during the closed portion of it cycling. After the designated number of cycles, the resistance of the contact is measured as a function of contact force up to 200 µN. For AC testing, the same basic approach will be used. The DC pulse which was the load previously will instead be used as the burst trigger for our desired AC signal. First, let's look at the results when we maintain cold cycling conditions and apply various signals between 100 Hz and 100 kHz, as shown in Figure 3 below.

As shown in this figure, the resistance initially appears to be similar in the four devices tested. In all but one case, however, the device failed prior to the targeted 10M cycles of operation. For all the devices which failed in this experiment, the contacts failed to open after the number of cycles indicated (i.e. became permanently closed). In the one case which reached this number of cycles, large variations in contact resistance were observed.

For these tests, the applied load shown in Figure 1 was used. This means that after each contact closure, only a single cycle of the applied load was applied. Next, we consider the effects of reversing the applied load (i.e. phase shift the applied load by 180 degrees). Given our best case from the first test appeared to be at 10 kHz, we'll compare that data with another device tested using an inverted 10 kHz load shown in Figure 4 below.

While both of these devices lasted to 10M cycles, both showed large variations in contact resistance typically associated with damaged contacts which will be investigated visually below.

Third, let's consider the effects of intentionally extending
the AC load past the cold-switching period and opening the contact at different phases of the AC signal. Figure 5 below shows the results of this test.

Figure 5, Comparison of contact resistance of 1,000 Hz, 800 Hz and 600 Hz loads applied to 8 µm contact radius Au-Au micro-contact cycled at 200Hz.

In this case, we started with the results from three new devices, each cycled at 200 Hz of switching frequency. The AC load applied however was one full-cycle pulse of 1,000 Hz, 800 Hz and 600 Hz loading. For the 1,000 Hz pulse, this would result in “cold” switching, but for the two lower frequency pulses, these result in opening of the contact while the pulse is still active. For both of the lower frequencies, the micro-contacts failed well before the target of 10M cycles, with the 600 Hz failing at just under 60,000 cycles and the 800 Hz device almost a full order of magnitude less at around 7,000 cycles.

As similar results were observed by switching the polarity in the DC case [1], this supports the theory that an AC signal still has the possibility of causing deterioration through electromigration. As was mentioned previously and reiterated here, contact failure occurred while the contacts were closed not during transition. Thus, damage and ultimately failure occurred through material attempting to migrate across the contact. To illustrate this, we’ll examine surface images of failed contacts and compare them to a typical DC contact operated to 10M cycles of actuation, shown in Figure 6 below.

To expose the underside of the beams, these contacts were physically folded back using probes. As we can see in the 100 kHz case, the contact pattern is very symmetric and several pits have occurred on both sides, with the material dislodged being relocated around the area. Note that the circle on the pad side is not aligned with the bump on the upper beam (again, shown in both the 100 kHz and 10 kHz cases). This circle is an alignment mark that was used during device fabrication. Alignment error in this case has shifted the point of contact but as they were all fabricated together, this shift is common to all devices tested. When compared to the DC contact which endured a full 10M cycles and was still operation, virtually no damage occurred. These devices have been shown to last orders of magnitude longer under DC conditions, and typically this design fails due to eventual surface contamination which after only a few hours of operation hasn’t had time to occur.

Figure 6, Exposed upper beams (left) and lower pads (right) from device exposed to 100 kHz and 10 kHz AC loads, compared to identical device tested with DC to 10M cycles of operation.

B. Frequency response to AC

To evaluate areas of interest mentioned previously, test devices and various contact loads were exposed to a range of load frequencies, and the output response was measured using a spectrum analyzer over frequencies ranging from 10 to 100 kHz. The six resulting spectrums are shown in Figure 7 below.

For this test, six input frequencies were applied and for each, the frequency response was measured. While for each of the 6 applied frequencies (10 kHz, 15.8 kHz, 25.1 kHz, 39.8 kHz, 63.1 kHz and 100 kHz), the correct single-frequency response is predominant in each response. There are significant peaks which appear at around 42 kHz, 60 kHz and 90 kHz as shown. These do not appear to shift as a function of frequency but do vary slightly in magnitude. These peaks do not appear if the signal is applied directly to the spectrum analyzer. In other words, if we leave the experimental setup entirely intact, but only remove the closed contact, the two responses obtained are shown in Figure 8 below, ruling out any other part of the test as a source of these three peaks.
V. CONCLUSIONS

This experiment provides the results of how several identical Au-Au micro-contacts respond to a variety of AC conditions. Under cold-switching conditions, most devices failed through permanent closure prior to reaching 10,000 cycles, with the lowest life observed with the 100 Hz device that lasted only 600 cycles. Inverting the applied AC signal produced a slightly different response; both inverted and non-inverted devices lasted to 10M cycles, but both were extremely erratic during their performance lifetime. This erratic behavior is likely additional manifestations of the eventual cause of failure, and thus may be a possible early indication sign of this kind of failure. The phase effects resulting from extending this AC load past the opening of the device resulted in early device failure, all of which was visually verified through SEM imagery, indicating material transfer as the only apparent damage. Finally, the frequency response of these devices were tested between 10 kHz and 100 kHz, and while each frequency passed through the devices quite well, specific frequencies within this range also appeared at all frequencies tested, possibly caused by a modulation within the device itself, or demonstrating a sensitivity in the connections to the device capable of picking up these frequencies from an outside source.

REFERENCES


