Electrical Characterization of MEMS Microgrippers in Circuits

REU Final Report
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1. Abstract

Integrating MEMS devices with electronic textiles (E-Textiles) and fabrics requires an understanding of how these devices interact with circuit components in different operating conditions. In this paper, we characterize the electronic properties of MEMS “grippers” in contact with conductive wire. We discuss general guidelines for optimizing the design of said “grippers” and potential MEMS-based circuits. We then demonstrate how these grippers can act as non-rigid circuit components that effectively transfer power to devices such as LEDs. Analysis shows that our “grippers” are suitable conductors (<150 Ω) under standard operating temperatures (25°-100° C) with potential for use as sensors for current overflow or temperature. Methods such as parylene deposition and silver epoxy “glue” to stabilize MEMS performance for robust applications are also discussed and briefly explored.

2. Introduction

A major challenge in the field of e-textiles is the integration of traditionally rigid circuits with flexible substrates and materials. MEMS microgrippers printed onto a silicon (or other) substrate then released onto a fabric mesh, offer a potential solution to this challenge. MEMS grippers are useful for adhering MEMS to any type of fabric, and as we demonstrate in this research, conductive materials such as copper wires. This work focused purely on wire-gripper interactions to demonstrate that MEMS microgrippers are efficient, conductive circuit components that can be used to fabricate a detachable MEMS device onto a free fabric mesh. However, we were unable to fully release a MEMS device structure onto such a mesh during this project due to time constraints.

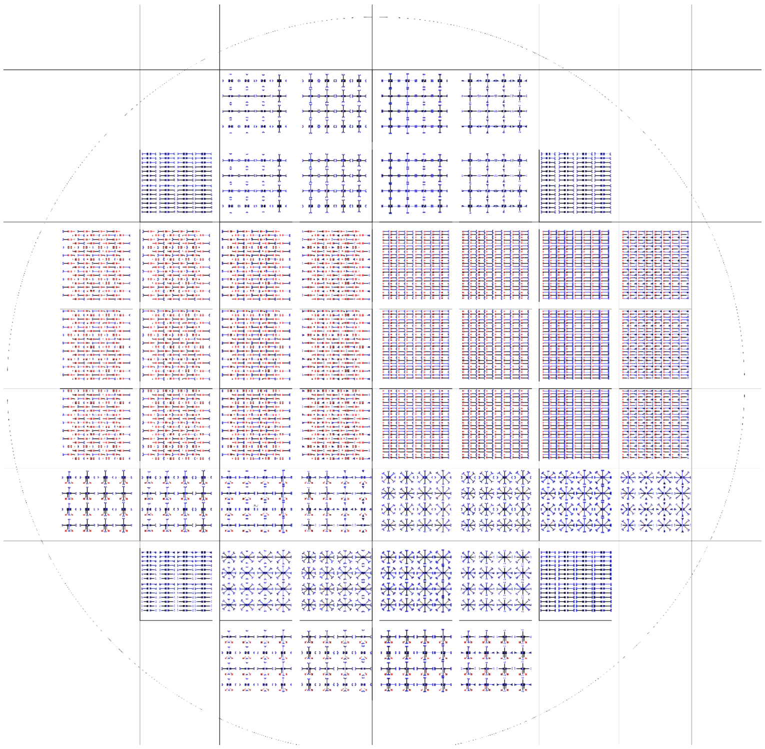
This project can be separated into two main components: Wire-Gripper interactions and load-bearing (LEDs) experiments. For the first, we demonstrated that MEMS microgrippers are influenced by current and temperature. Experiments showed that microgrippers generally tended to see smaller changes in Resistance per Current change as temperatures increased, and were relatively stable within the 25°-100° C operating range. Additionally, we demonstrated that post ~140° C, our microgripper designs began to have arbitrarily high resistances - Signaling they no longer contacted the wire. Further discussion of methods to minimize wire-gripper connections and suggestions to optimize designs are found within. For the second part MEMS microgrippers were demonstrated to be viable circuit components with high conductivity. We showed that LEDs could be powered individually or in parallel in our circuit, implying that more complex circuits are possible with microgrippers acting as wires (small resistors). Further experimentation with parylene coating and silver epoxy solder showed that these circuits could see vastly improved stability with similar performance in flexible fabric meshes. Overall, our microgrippers can be generalized as flexible wires with ~50 Ω of resistance.

3. Methods

Credit to Danming Wei, who developed the photolithography process

3a. Photolithography

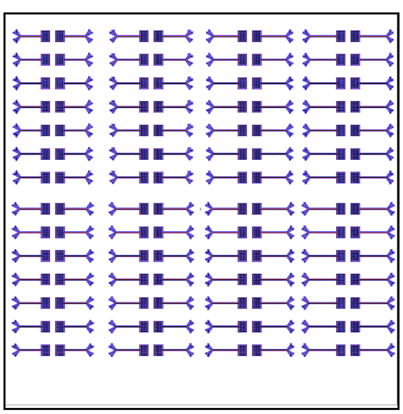
To fabricate our devices, we started with a Silicon wafer of ~500 nm SiO_2. Using Filmetrics this was determined to be ~557.4 nm in thickness, within acceptable tolerances. We then spun Photoresist 1813 onto the wafer and used the Suss Mask Aligner to expose the wafer for 12 seconds in “Hard” contact mode with our first mask design.



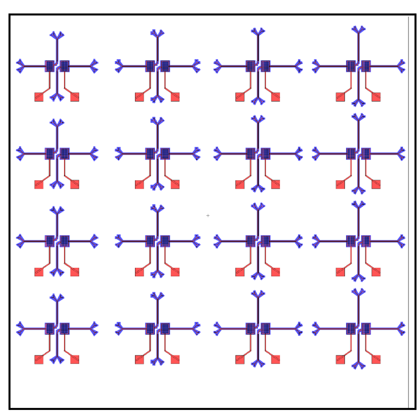
Mask Design 1:

- Four gripper test structures
- Single-Grippers
- Double-Grippers
- Quad-Grippers
- Contact pads
- Mesh-Grippers (8 legs)

This mask was designed specifically for the SUN LED used in our experiments.



For Double-Gripper LED

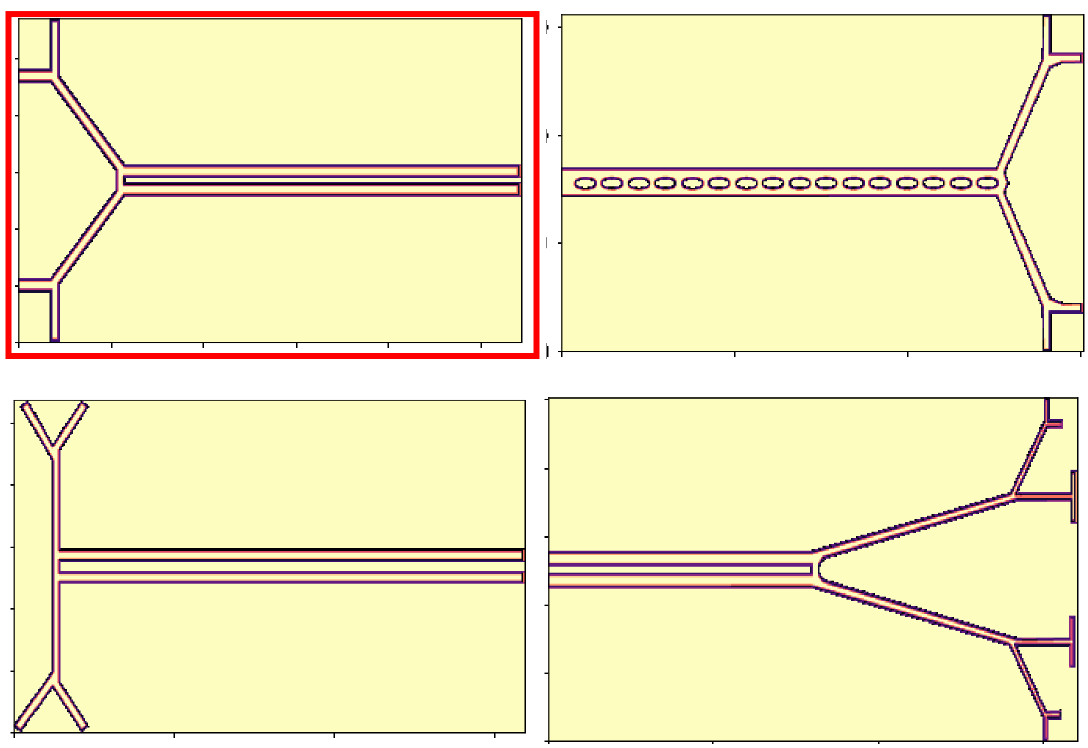


For Quad-Gripper LED w/ Contact Pads

Without further development, we then used the YES Image reversal oven to reverse the PR pattern. After this, the “Flood-E” mode was used to expose the entire wafer without a photomask for twice the amount of time as the previous step, or 24 seconds. The exposed PR was then developed with MF-319 for ~1 minute, rinsed, and dried.

The next step was sputtering Au/Ti on the wafer with PVD75. We spent ~2 minutes for Ti sputtering and 5 mins for Au (Power: 300W, 5mTorr, Ar gas) to create a patterned layer ~470nm thick. After removing the wafer from the PVD75 we then began the lift-off process with Acetone. After ~1 hour of an acetone bath, we transferred the entire setup into a sonicate bath for ~6 hours in total, with 1 break in between to leave the wafer in a still acetone bath overnight. We saw difficulty in precisely lifting off all of the small holes in the leg designs below, but overall had a great lift-off of all components.

Leg Designs:



Leg length shown: 600 microns.

Leg lengths varied from 650-825 microns in 25 microns increments.

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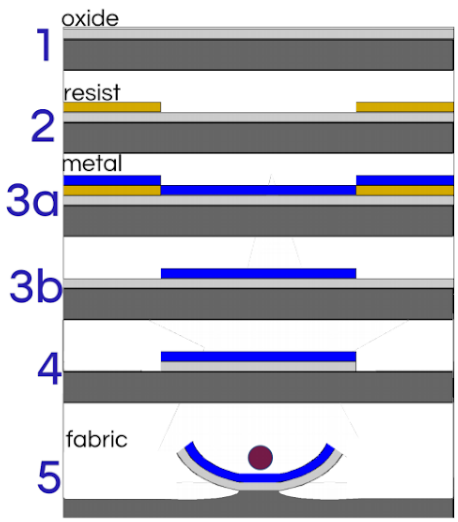
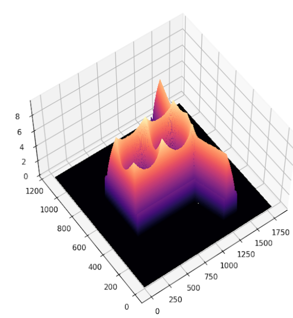
*Of all leg designs shown, the design bordered in red had the easiest manufacturing process and best performance in wire-gripper contacts. For grippers along this line we recommend pursuing this sort of design instead of the others.

We then began the second photolithography with the 2nd mask, spinning PR 1813 and exposing with the Suss Mask Aligner at Hard contact for 12 seconds. At this stage proper alignment of the mask was needed, and the anchors used in previous photomask designs proved to be sufficient. We then developed the PR with MF-319 for ~1 minute, and cleaned/dried the wafer. At this stage all patterns were present, and there was a layer of PR just around the edges of each design in Mask 1 to act as ‘holes’ for future etching to focus on. We then used the March RIE to remove the SiO2 layer, leaving the lower substrate open.

At this stage, a final layer of PR 1813 was spun onto the wafer to act as a protective barrier, and the wafer was sent for dicing into individual chips. Individual chips could then be rinsed, dried, and put into the Xactix etcher for the release process.



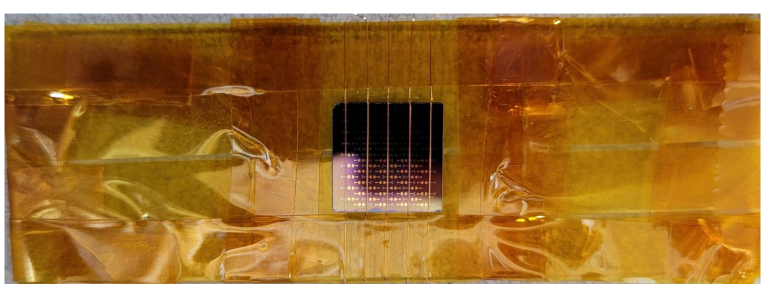
← Visual representation of the entire process



Representation of Etching process

3b. Manufacturing

Having now our individual chips, we aligned copper wires onto them in order to simulate a conductive fabric mesh. Bare copper wires were manually placed and taped onto a glass slide containing the chips as shown below, with specific alignments varying depending on the chip design. As a general design rule, it was good to leave a small (but visible) space between the contact pad and the copper wire to maximize the odds of a successful release.



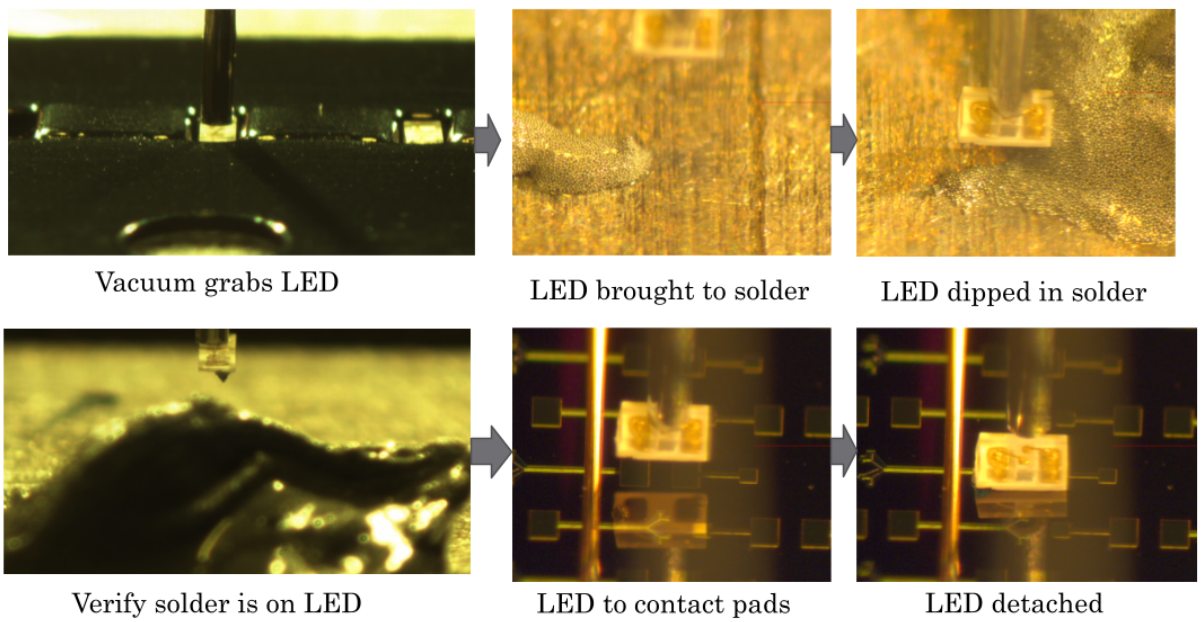
Example of a proper sample.

Post-manufacturing

After successfully laying this wire structure in place, the entire glass slide was taken for the final Xenon release. In general, structures of this type took ~10-15 cycles of Xenon etching at 30 seconds / cycle in order to fully release. Individual chips without such structures took ~7-10 cycles of Xenon etching at 30 seconds to fully release. It is important to avoid overetching (>30 cycles), as the Au/Ti bilayer itself could be eaten away by overexposure to gas.

For experiments involving the usage of LEDs, an additional step was required prior to Xenon etching - the placement of individual LEDs. Two methods were used to do this.

First, we used the NEXUS system at the University of Louisville in order to precisely place individual LEDs with silver epoxy solder onto their contact pads. An outline of the process can be seen below.



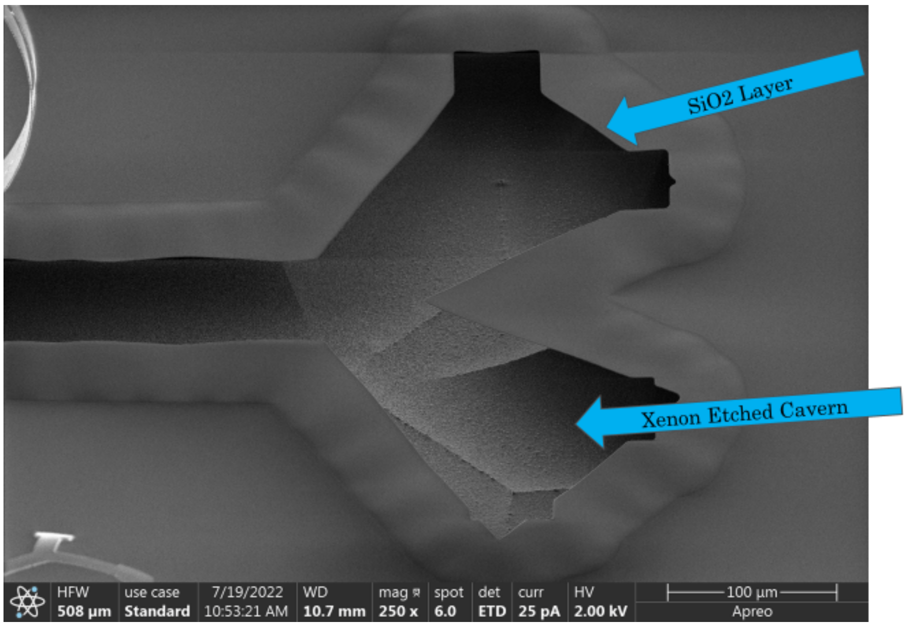
This process allowed for near-exact placement of individual LEDs and generated clean samples. However, due to time constraints our general data was collected using a manual approach. After collecting an amount of silver epoxy solder onto a glass slide, a cutting knife was used to drop a spot of solder onto a no-device region on the silicon chip. Then, individual drops of solder were transferred onto the contact pads, after which LEDs were placed using a handheld vacuum pen. Minor adjustments to placement and orientation were possible by pushing the LED with the knife, and we saw (in general) successful placement of LEDs using this method.

3c. Finished Products

This work's experimental results can be categorized into three parts:

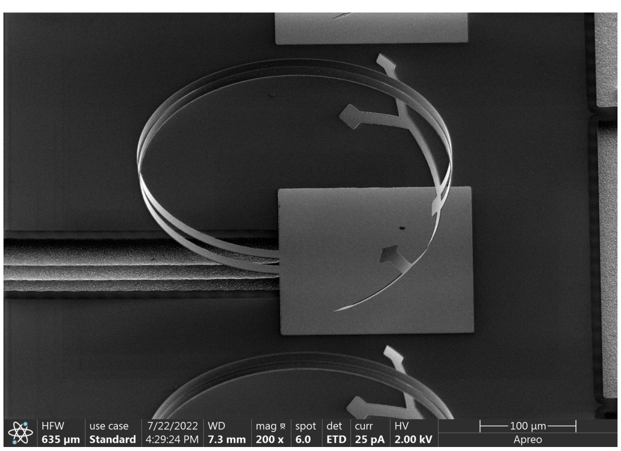
- Free-released cantilevers
- Wire-released cantilevers
- Wire-released cantilevers with LEDs

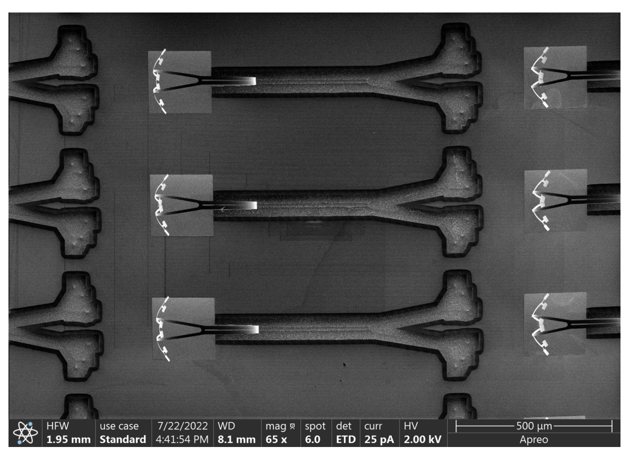
Below are SEM images of each experimental part. The first image, of the etch hole left by the Xenon gas, illustrates how these microgrippers were released. Removal of the silicon substrate underneath the Au/Ti layer left the bilayer strain free to release into it's optimal state.



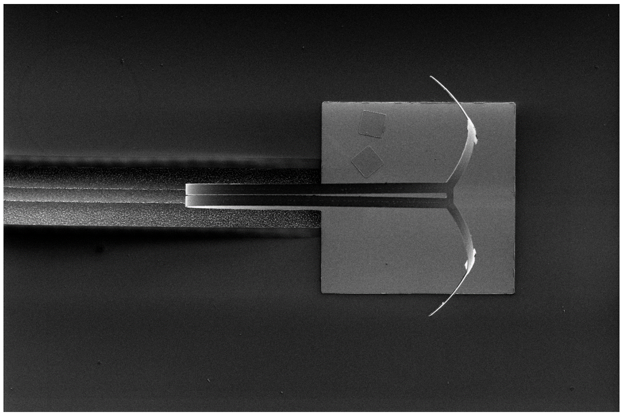
As shown, we see even etching of the silicon substrate with slight lines left on the areas furthest away from the microgripper edges.

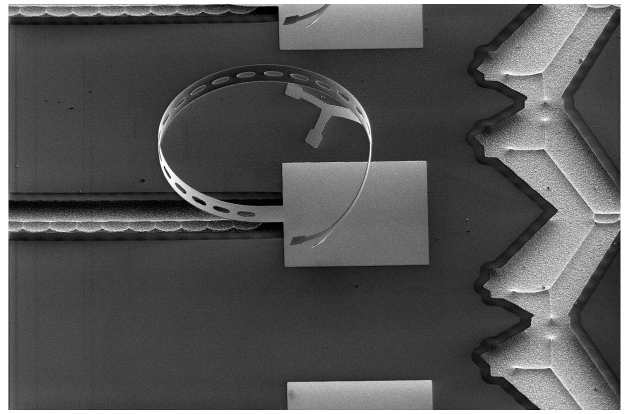
Free-Released Cantilevers:





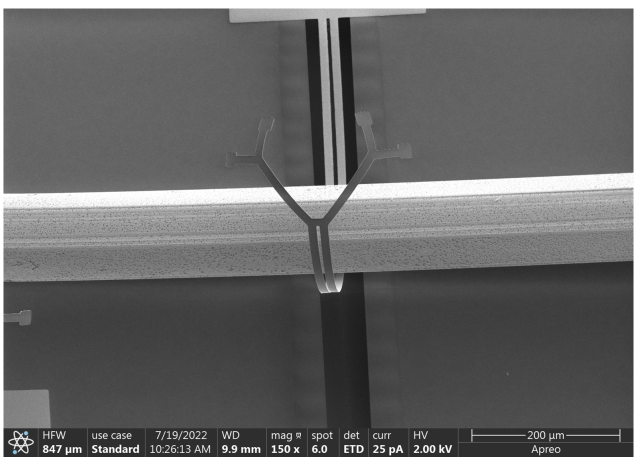
Left: Rectangular design free-released, Right: "Tree" design free-released

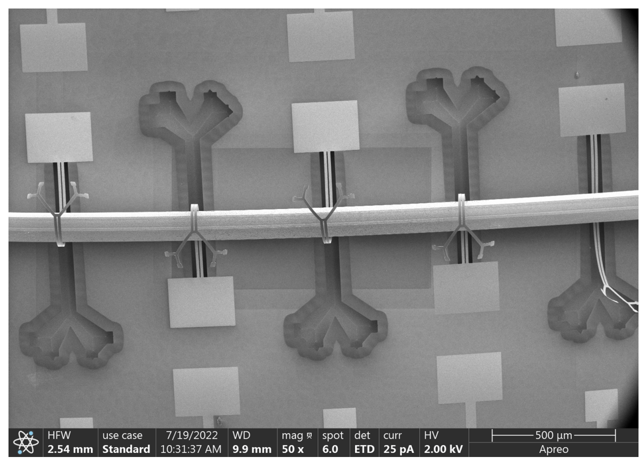


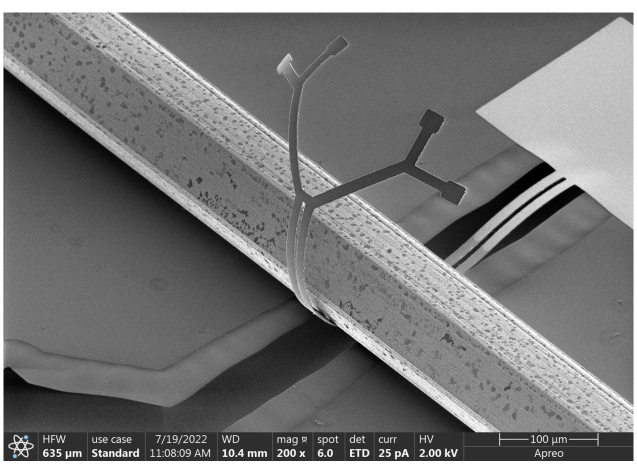


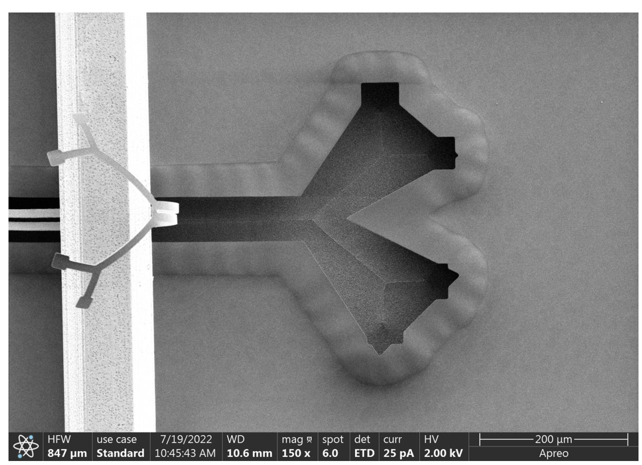
Left: Leg design used in experiments,   Right: Leg design with holes

Wire-Released Cantilevers:

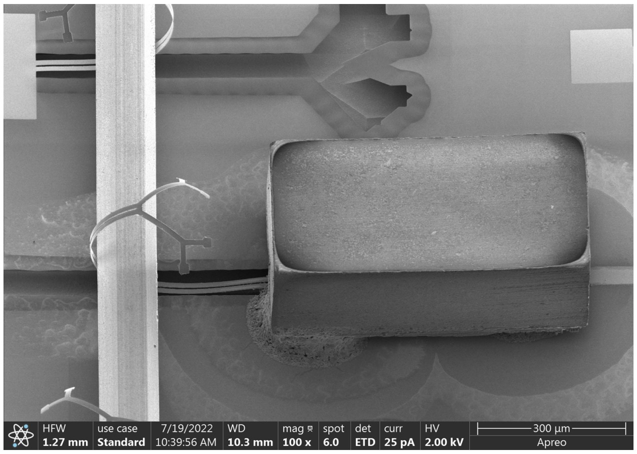


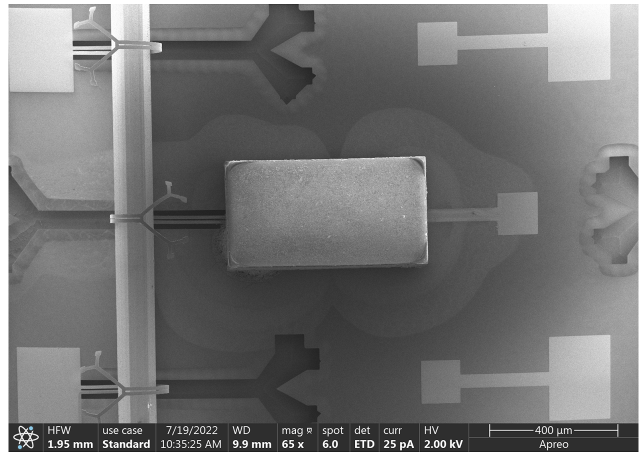


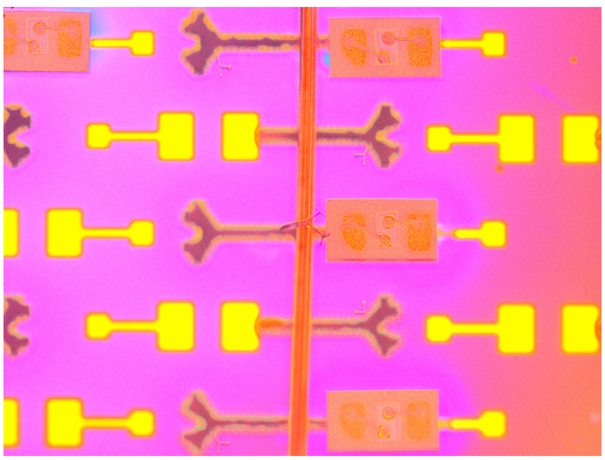


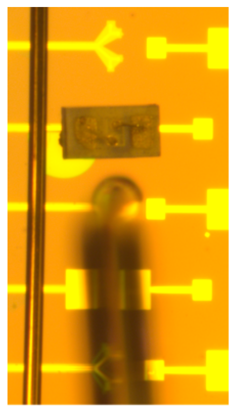


LED-Released Cantilevers (Single Grip):

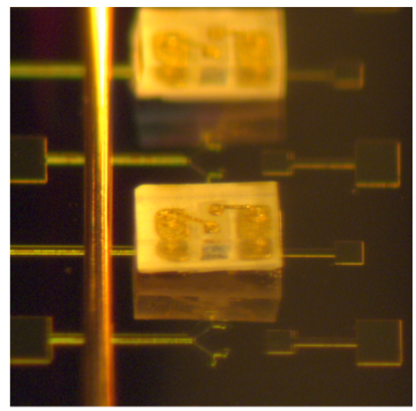




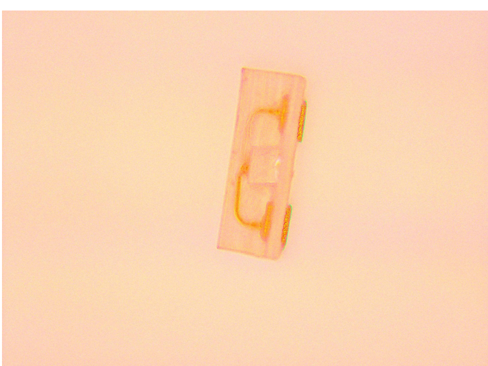




Top View

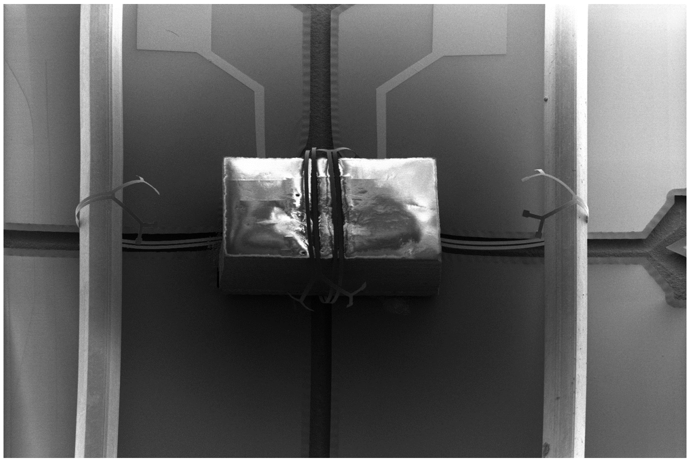


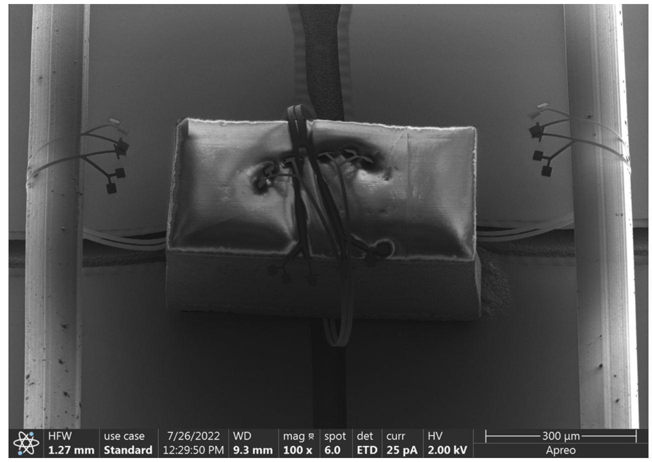
Side View



← Image of SUN LED (Sideways)

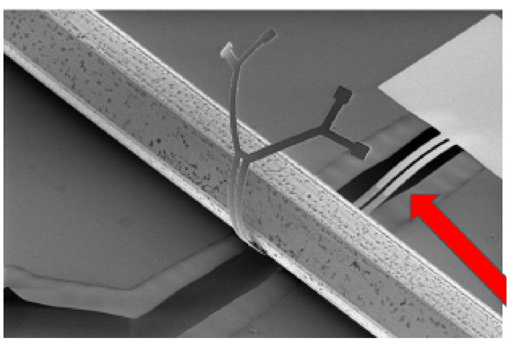
LED-Released Cantilevers (Double Grip):



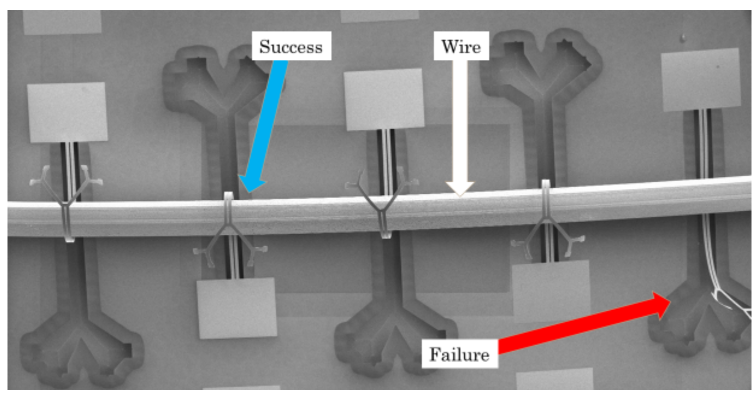


3d. Remarks

In general, we saw good connections to the wire across all designs. However, the best results (approximately) were seen with the outlined gripper design (henceforth referred to as Gripper design 1) with criterion being the contact area between the gripper legs and the copper wire.

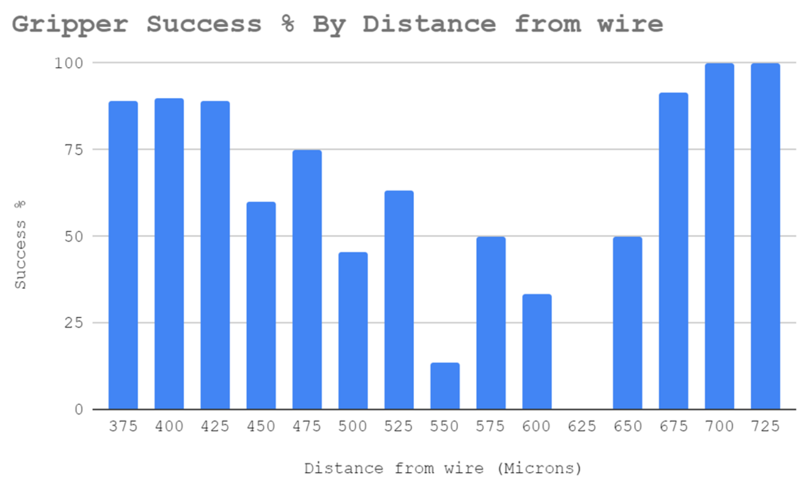


Release onto wire



Gripper-wire connections could succeed or fail for a variety of reasons, with the most common being improper alignment of the copper wire onto the wafer due to manual processes. For grippers with optimal wire placement, failed connections still occurred but with a lower frequency. These errors were due to a variety of reasons, with the most apparent being defects on the metal patterns due to tweezer impacts or deformations.

Regarding the rate of success, a visual inspection of gripper-wafer connections as a whole revealed an interesting result - The distance between the wire and the contact pad of the gripper influenced connection success rate.



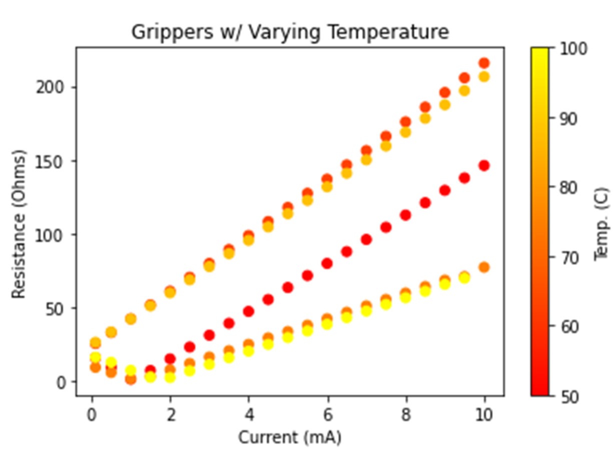
Indeed we observed that the optimal distance from pad to wire was below 425 µm or above 675 µm.

This conformed with a previous papers results that saw a similar phenomenon between gripper connection success and distance from the center of the gripper structure.

This phenomenon is likely due to the nature of how these gripper structures curl. "Interruption" of the curling process by the copper wire at specific regions of the gripper legs likely increased the probability of biaxial twisting or simply failed releases, which lead to the sharp drop in successful connections we see above.

4. Electrically Characterizing MEMS Grippers

To electrically characterize our grippers, a simple four-wire probe setup was used. Two probes were used to pass a steady current through the system, while two probes were used to measure the voltage and resistance drop across the system. Overall the voltage measurements were more accurate than the resistance measurements, due to the nature of the Multimeter and it's resistance measurements. However with proper setup the resistance measurements were stable.



Here we can see the relationship between Resistance and Current as we increased the temperature from 50° C -> 100° C.

We see a clear decrease in the slope as temperatures increased, implying that higher temperatures diminished the effect of large currents on the resistance of the gripper. By extension this means that higher temperatures diminished the effect of large currents on the curvature change of the grippers, as the resistance of these bilayer structures relative to the copper wire are determined largely by the contact area between the two. We also see that the “0” resistance point changes depending on the temperature of the grippers. This tells us that the minimal resistance point of these grippers is determined by both the current and temperature, similar to what we expected in previous papers.

Another interesting phenomenon was observed during this experiment:

Gripper #	Before Ω	After Ω
1-1	770	8.353
1-2	14.27	14.07
1-3	466.7	15.63
1-4	10.2	9.76
1-5	17.8k	13.28

“Juicing” grippers with large currents (~20 mA) and returning to normal currents (~0.1-5 mA) stabilized performance

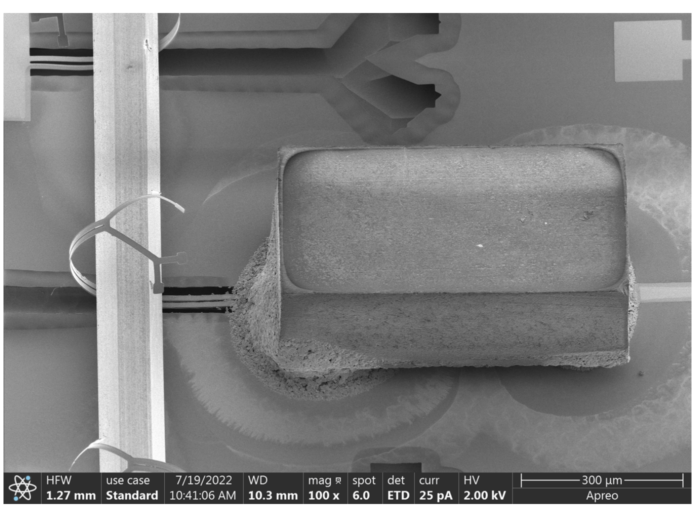
Large gripper resistances post-manufacturing could be greatly reduced by simply pumping a large current (20 mA) through the grippers and returning the current to it’s original state.

We believe that this phenomenon was due to the change in current causing a sharp, instant change in the curvature of the gripper. After reducing the current to reasonable levels, this forced the gripper to reform a contact with the copper wire in an optimal-contact state, thus reducing the resistance to expected levels.

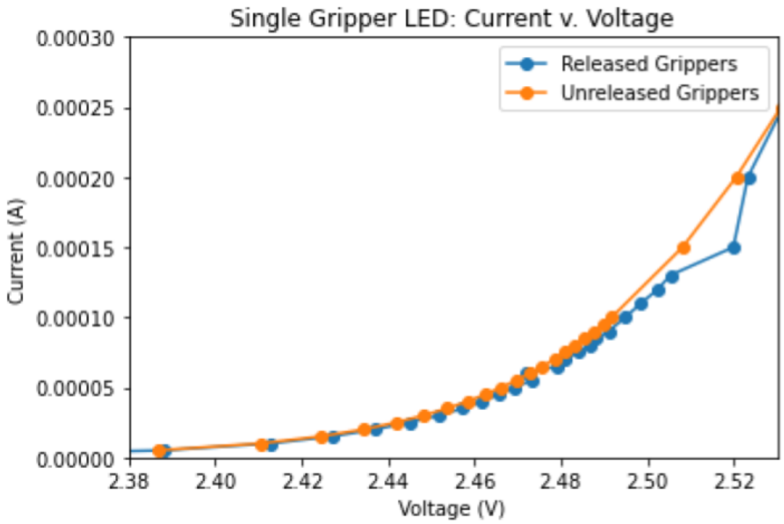
For future usage of these gripper structures we advise that a similar method of “pumping” current through grippers before usage as wires is done, as this would greatly decrease variance in gripper resistance and allow for more reliable circuit designs.

5. Usage of MEMS Microgrippers for Circuits

Microgrippers proved to be remarkably similar to conventional wires when used in circuits. When put into a single-gripper circuit system to power a blue LED, we demonstrated that there was only a slight impact in circuit performance when the grippers were curled onto a wire as compared to when the grippers were flat on the surface of the silicon wafer.

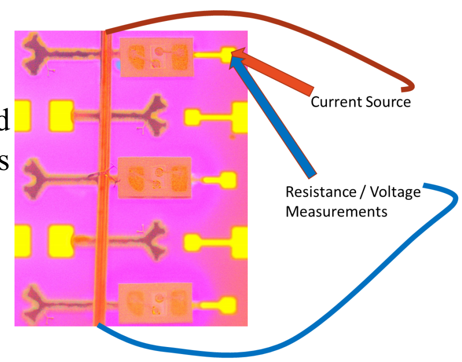


← Single-gripper LED system. Two probes were attached on the wire to the left, and two probes were connected to the contact pad on the right (not visible).



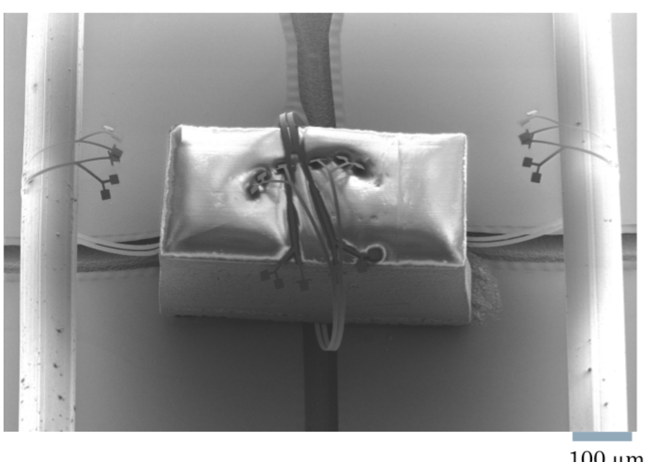
As shown, the difference between released and unreleased gripper performance was almost minimal - With slight differences in resistance measurements for our gripper designs.

A diagram of our setup can be seen below.

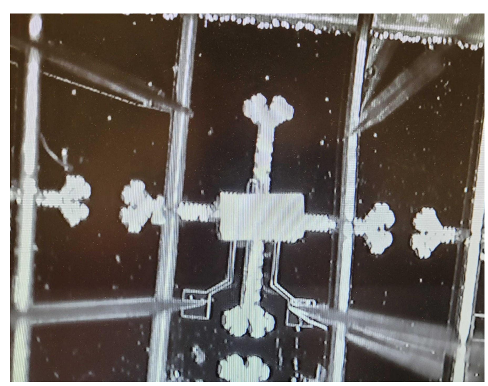


Overall this shows that our grippers are relatively good conductive wires, and have little difference in performance as compared to basic wire connections

Further testing with dual-microgrippers in circuits showed that complete powering of LEDs were possible through microgrippers which demonstrated similar results.

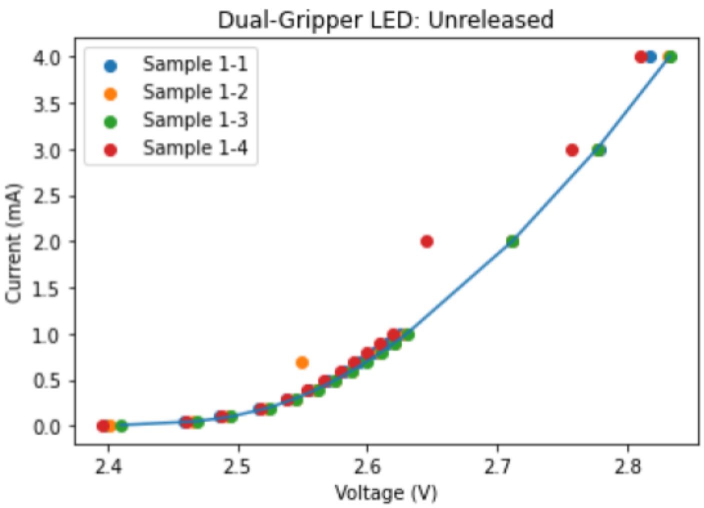


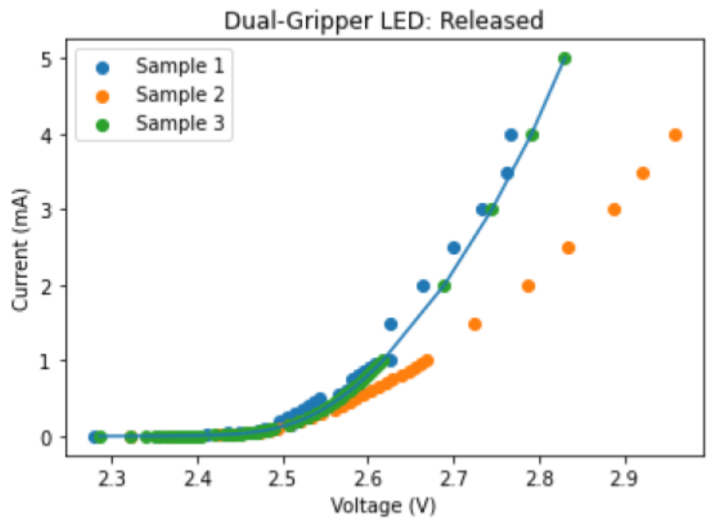
Fully released double-grip for LED



Four-probe setup

We saw that having dual-gripper powered LEDs saw a bit more variance across sample LEDS, but overall showed the same relationship: Effective powering of a circuit. Experimentation showed that LEDs could be lit individually, or multiple in parallel depending on circuit design. This implies that LEDs can be considered to be simple resistors when released.





6. Final Remarks

Overall we saw that MEMS microgrippers could be used as effective circuit components of resistance ~15 Ohms at optimal states. We demonstrated through LED-wire-gripper systems that circuits of arbitrary complexity could be made using these grippers. We also provided guidelines for the design and implementation of these grippers, with a note for future work to focus strongly on experimentation with new designs and refinement of existing models. Implementation of parylene and silver epoxy solder to stabilize the performance of this system showed great promise, with minimal effects on the curves of the Current (mA) v. Voltage (V) graphs of the circuit systems, and the usage of parylene reducing errors to near-zero. Future works should focus on the optimization of the release process, improving yield rate per chip, and exploring methods to efficiently release the entire MEMs circuit structure from the substrate onto a free-floating fiber.

This final report serves as a draft for a future publication, which will be titled similarly with additional content regarding in-depth discussion about specific methods, advisement for future work, and more data currently being refined.