# Powering Wire-Mesh Circuits through MEMS Fiber-Grippers

Nathan Song[1], Danming Wei[2], and Cindy K. Harnett[3]
[1] Department of Physics, University of California Berkeley, United States
[2,3] Department of Electrical and Computer Engineering, University of Louisville, United States

***Abstract*— Packaging electronic devices within electronic textiles and fibrous substrates requires an understanding of how fibers interact with circuit components in different operating conditions. In this paper, we use microeletromechanical (MEMS) devices to put devices in electrical contact with fine wires. We characterize the electronic properties of MEMS-to-wire contacts and discuss general guidelines for optimizing the design of these 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 (under 150 Ohms) under standard operating temperatures (25-100 deg. C) with potential for use as sensors for current overflow or temperature. Methods such as parylene deposition and silver epoxy to stabilize MEMS performance are briefly discussed and explored.**

***Keywords—MEMS, E-Textiles, Fabrication***

## I. Introduction

Fiber-gripping out of plane microelectromechanical structures (MEMS) show promise for integrating novel circuit designs with flexible, porous substrates such as fabrics. Researchers have previously investigated strain-engineered MEMS as microspring contacts for wafer-level packaging [1,2,3,4], and more recently, have integrated springy MEMS onto fibers to improve electromechanical contacts within electronic textiles [5]. Our previous research has shown that MEMS grippers are capable of current-driven reversible geometric transformations [6] and can latch onto fibers in commercially produced fabrics [7,8,9]. In this work we demonstrate that MEMS grippers act as variable resistance components and characterize gripper-wire behavior in response to varying currents and temperatures.

Considering the potential environmental conditions for fabric-based electronics [4,5,8], we demonstrated that MEMS-based circuits can operate when stabilized with silver epoxy droplets and/or parylene coating. Initial results show such measures can increase circuit stability. Some early flaws noticed in grippers were sensitivity to temperature, unpredictable latching, and weak van der Waals forces on the gripper-wire contact. Temperature sensitivity was minimized with parylene coating and has potential for sensor applications [10]. Non-uniform initial latching contacts were resolved with an initial overload of the circuit (Section III). Weak gripper-wire contact strength requires further physical testing to understand the influence of wire diameter, surface conditions, and gripper composition.

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## II. Design & Methods

To characterize wire-gripper interactions, we laid copper wire over gripper-carrying 1 $cm^2$ silicon wafers. Grippers were then released onto the wires with $XeF_2$ etching. Further details on gripper fabrication procedure and design can be found in prior publications [6,11].

### A. Design and Fabrication

Our work focused on free-released grippers, wire-released grippers, and wire-released grippers powering LEDs (Fig. 1). Different gripper designs were tested, but our characterization results focused on one design (Fig. 1 middle, right) that maximized contact area. A bright field and dark field mask were used to deposit our desired metal pattern and expose desired regions to $XeF_2$ silicon etchant, respectively. Gripper lengths were set from 650 to 825 microns, with 25-micron increments.

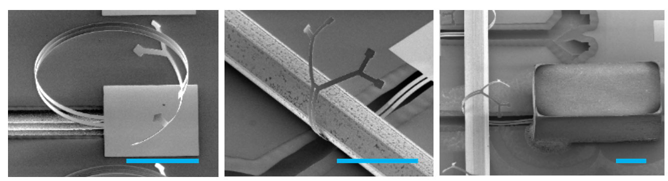

*Figure 1. Blue line in images represents 200 microns. Left-to-right. Electron micrographs of free-released grippers, grippers released onto copper wire, wire-gripper connected to SUN LED.*

For grippers released onto wires, copper wires ~120 µm thick were laid parallel by hand or the NEXUS system [12] across grippers prior to release (Fig. 2). It was important to ensure the wires were parallel and that they lay flat against the chip. Wires were secured to a glass slide with nonconductive tape (>200 C°).

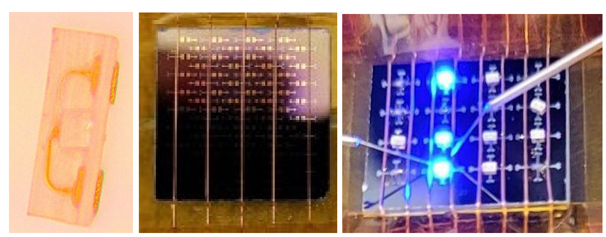

*Figure 2. Left-to-Right. SUN LED with contact pads visible, Gripper-wire setup on a glass slide, LEDs powered by grippers.*

Anchor points were an important feature of our gripper designs. These wider regions, visible as square ends on grippers in Fig. 1 and Fig. 3, ensured the gripper stayed on the substrate while thinner portions were released. Imaging the rough but evenly shaped 'caverns' left by the $XeF_2$ gas (Fig. 3) reveals a smooth detachment process dependent on feature radius. For future designs, this suggests that release order is controllable [8,11]. Anchors should remain relatively small for metals such as titanium that are vulnerable to $XeF_2$ however, as prolonged exposure to the vapor can etch them.

### *B. Stabilizing Device Performance*

A four-probe setup was used throughout experiments (Fig. 2). Two probes passed a steady current through the system, while two probes performed measurements. Small vibrations and changes in current/temperature were noted to have significant effects on gripper resistance, likely due to changes in the contact area between the gripper and wire [6]. Upon initial release, grippers were measured to have resistances between 30 Ω – 4M Ω, with large variance in same-sample repeated measurements. To minimize these fluctuations, we found that initial ramping of gripper-wire systems to 20 mA completely removed vibrational effects on gripper resistance for subsequent currents < 4 mA. A table of these improvements is below (Table 1).

**Table 1** Gripper resistance (Ω) for five samples before/after exposure to 20 mA

| | Before | Variance | After | Variance |
|---|---|---|---|---|
| | 770 | 50 | 8.35 | 0.2 |
| | 14.27 | 0.3 | 14.07 | 0.1 |
| | 466.7 | 0.2 | 15.63 | 0.1 |
| | 10.2 | 0.1 | 9.76 | 0.2 |
| | 17800 | 200 | 13.28 | 0.05 |
| **Averages** | 3812 | 266 | **12.22** | **0.41** |

We see drastic improvement in gripper conductivity post-exposure. This was likely due to the change in current causing a sharp, sudden change in the curvature of the gripper [6]. After reducing the current, the gripper reclasped onto the copper wire in a stable state. A reduction in resistance and variance followed. Another possibility could be vaporization of residual polymers from the $XeF_2$ process, which is known to produce a Teflon-like film in the presence of water vapor. This exposure was done prior to all experiments.

### *F. Guidelines for Yield Optimization*

While assembling our devices, we observed a geometry-dependent failure rate for gripper-wire connections. The main causes for failure were poorly aligned wires, manufacturing defects on the grippers, or twisting during the release process (Fig. 3). To maximize wafer yield it is recommended to design grippers without tight-packed, distinct features like holes [8].

A critical factor was the distance between gripper end and the copper wire. Tracking the rate of successful gripper releases, we found that the optimal distance from gripper end to wire was below 475 µm or above 675 µm (Fig. 4). This result was like a previous observation [8] where gripper clasping success saw two peaks outside an inner region of failures. Though further analysis of our bimetal gripper is needed, the poor mid-range clasping was likely due to the wire interrupting the grippers' curling behavior at a critical point [13,14]. The distance from the gripper pad to the wire did not have an apparent effect on clasp success.

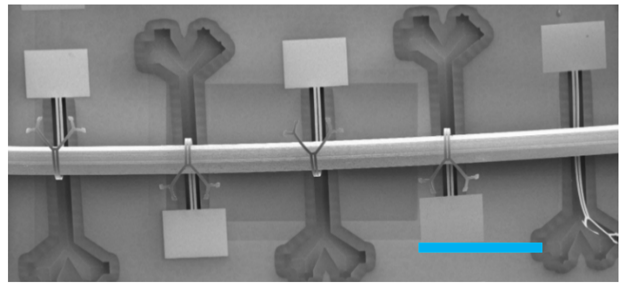

*Figure 3. Blue line represents 600 microns. Left: Row of gripper-wire clasps. First four from the left are successfully released, the last failed due to twisting. Contact pads visible as large rectangles.*

Fig. 3 shows that gas etching occurred in the open regions of the dark field mask with darker regions indicating shadows from oxide left overhanging by the isotropic etch. Reference [11] gives further detail on release sequencing and controlling the radius of curvature of released strained bimorph structures. Here, the radius of curvature is larger than the wire, giving the gripper a horizontal line for electrical contact where it is constrained by the wire. To speed the release process it is useful to do preliminary etching pre-alignment, as the wire reduces physical access to the etching region.

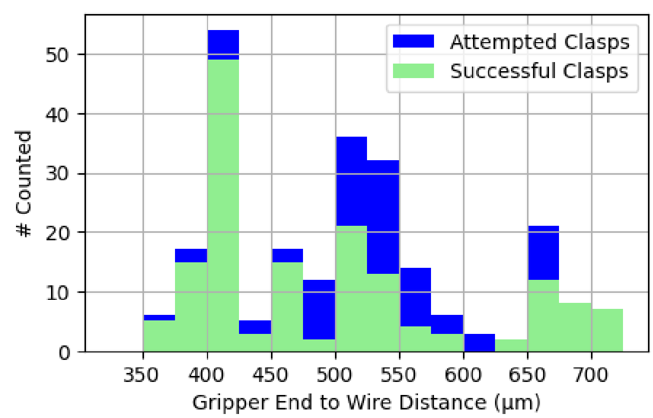


*Figure 4. Bar graph of gripper clasps onto wire. Blue shows number of attempted clasps, green shows number of successes. Distances were collected into 25 µm bins.*

## III. RESULTS

### *A. Electrical Characterization of Grippers*

Experiments were conducted on six samples, of which one is provided below. The grippers exhibit current-dependent resistance with a variant relationship to temperature. In general, increasing the temperature increases the resistance of the 40-80 °C range, with resistance staying between 50-200 Ω (Fig. 5). Resistance variance remained low in this region with linear relationships between current and resistance. Though sample-to-sample performance varied, linear fits for the 40-80 °C range were grouped closely together; Temperatures in this range had little effect on gripper performance.

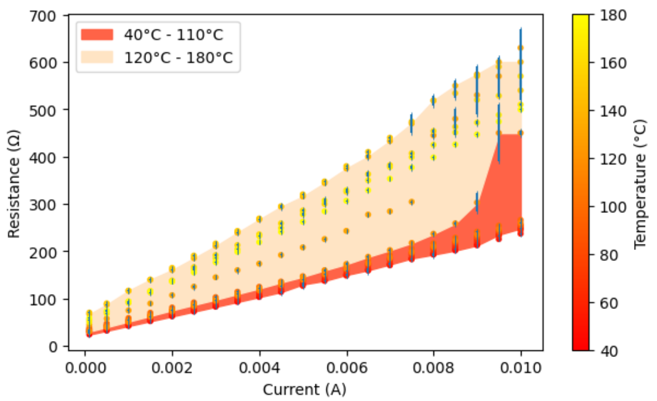


*Figure 5. Resistance v. Current measurements for wire-gripper system. Data points plotted with lighter colors as higher temperatures. Note higher variance bars at higher temperatures.*

At higher temperatures, we saw higher variance in gripper resistance. Though resistance – current measurements retained a linear relationship, large currents saw significant (>10%) variance in gripper resistance. We did not find sufficient evidence for any relationship between temperature and the gripper sensitivity to current, apart from average sensitivity staying below ~17 Ω/mA. Individual gripper data also showed that resistance can *decrease* with increases in current. This supported the idea that gripper resistance is dependent on wire contact area – Changes to the curvature (positioning) of the wire impact the resistances [6]. Considering the variety of contacts [8] a gripper can make with wire surfaces this is not unusual.

### B. Powering LED Circuits

Grippers were like conventional wires when used in circuits (Barring variable resistance as a function of temperature, current, and contact area). Grippers were used in single and double-gripper circuits. Single-gripper circuits had probes powering one terminal of the LED through a contact plate and a wire connected to the other terminal by a released gripper. Gripper contact can be seen in Fig. 1 (right), with silver epoxy solder shown as sedimentary deposits near the base of the rectangular block (LED). The presence of grippers had minimal effects on the performance of LEDs at room temperatures (Fig. 6, left), shown by the small deviation between the unreleased and released circuit measurements. This relationship was consistent across four samples.

Brief exploration was done with silver epoxy deposition and parylene coating to stabilize circuit performance (Fig. 6, right). the grippers – However, this is highly dependent on gripper contact with the wire and the presence of mid-experiment vibrations. We saw stable performance across all samples in Droplets of silver epoxy were placed onto gripper-wire connections and solidified in an oven. After measurements, parylene coating was added to these samples. Due to high failure rates only two LED samples were functional post-procedure, with only one being stable. This preliminary sample was very stable. Nearly zero fluctuations were observed in Voltage measurements, and produced voltage was reduced by ~0.1 V at 4 mA.

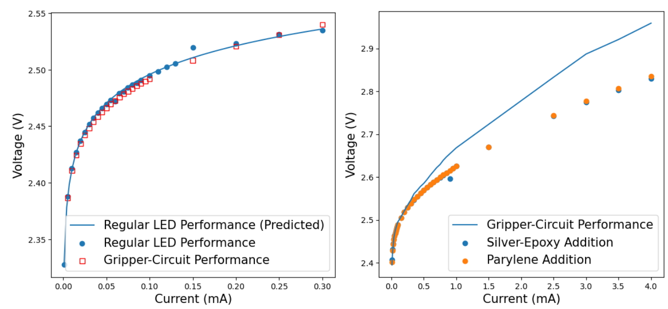


*Figure 6. Left: Voltage-Current measurements for circuit on chip vs. circuit with grippers released. Right: Effects of stabilization methods (Silver Epoxy, Parylene) on gripper-based circuits.*

Further exploration of stabilization methods for gripper-based circuits is necessary. This sample data suggests that silver epoxy deposition forces the gripper to stay in a constant configuration with the wire, with parylene coating providing further shielding from outside elements. As such, resistance errors from variable contact areas are largely removed.

## IV. Conclusions

We have shown that MEMS biactuating grippers can be treated as flexible, conductive wires with resistances (post-treatment) of 5~200 Ω. The curvature of these grippers and their effective resistance can be directly set through currents or indirectly through temperatures. The grippers explored have shown potential for usage in flexible circuits, with conductivity being maintained when silver epoxy solder or parylene coating was applied to enhance stability. We have also demonstrated that gripper resistances can be normalized to ~15 Ω by introducing a large initial current of 20 mA before returning to standard operating currents.

Present results show that fully-integrated circuits on fabric meshes are theoretically possible. The next step is to detach the load (Sun LED, or other) from the wafer, possibly through initial manufacturing on a glass-based substrate or gas-etching.

## V. Acknowledgments


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