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Redesigning Micro-Electromechanical Systems for Additive Manufacturing

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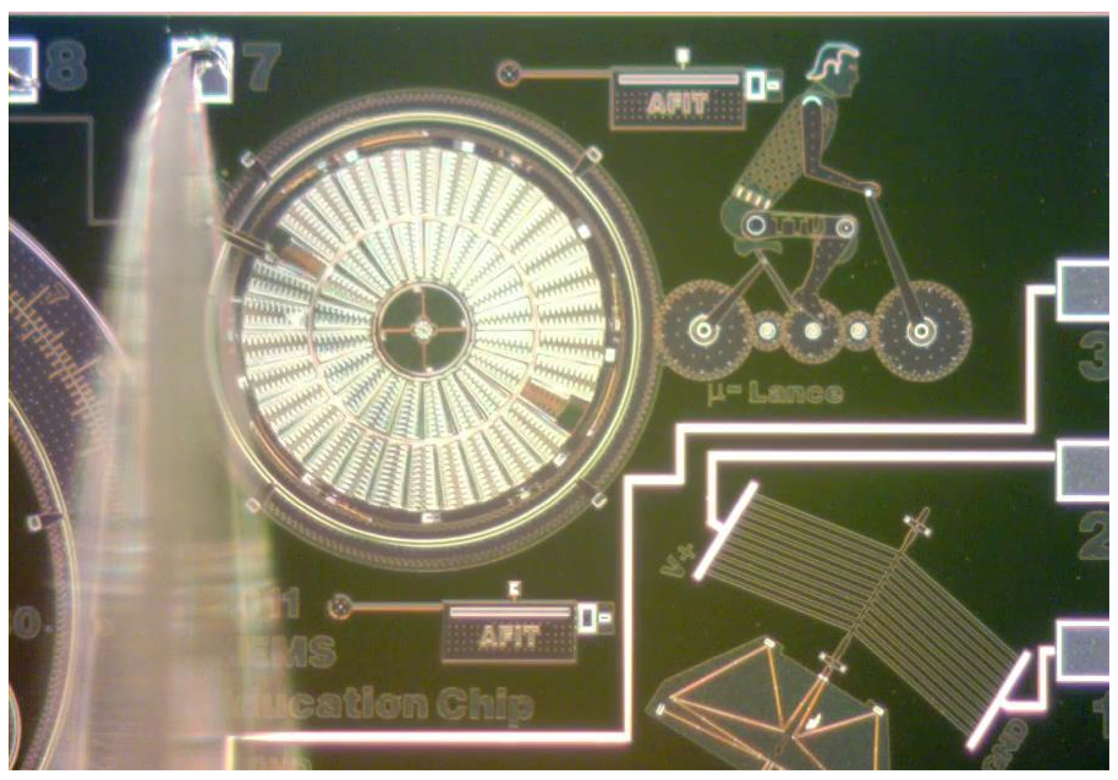
Problem

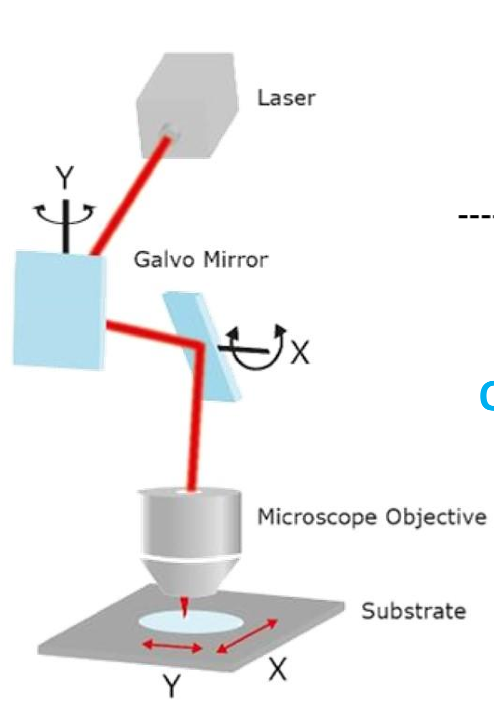
Micro-electromechanical systems (MEMS) are devices that sense and actuate at the microscale. Typically, MEMS devices are fabricated using multi-step, clean-room techniques which are time consuming in both design and fabrication and thus cost prohibitive for prototyping or small-scale production. Recently, simple MEMS actuators have been fabricated in a single-step approach using micro-scale 3D printing techniques such as multi-photon lithography [1]. Subsequent thin-film metal deposition produced dynamic MEMS that move through applied electrical power. In our work, we aim to adapt tried-and-true MEMS devices such as chevron actuators—traditionally fabricated using, for example, the SUMMiT V process developed at Sandia National Labs—to be compatible with additive manufacturing, and ultimately develop complex multicomponent systems and functions.

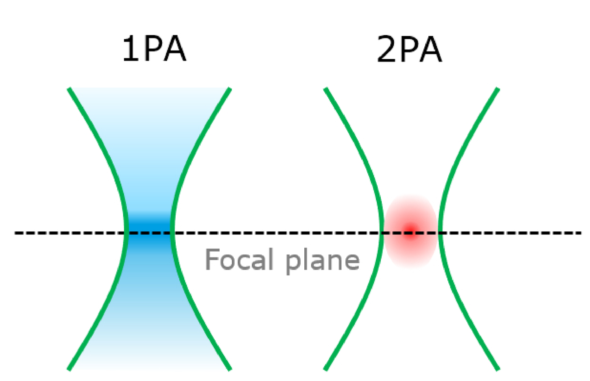
MEMS produced with SUMMiT V process (Tim Dallas)



Overarching question: Can MEMS be fabricated via 3D printing?

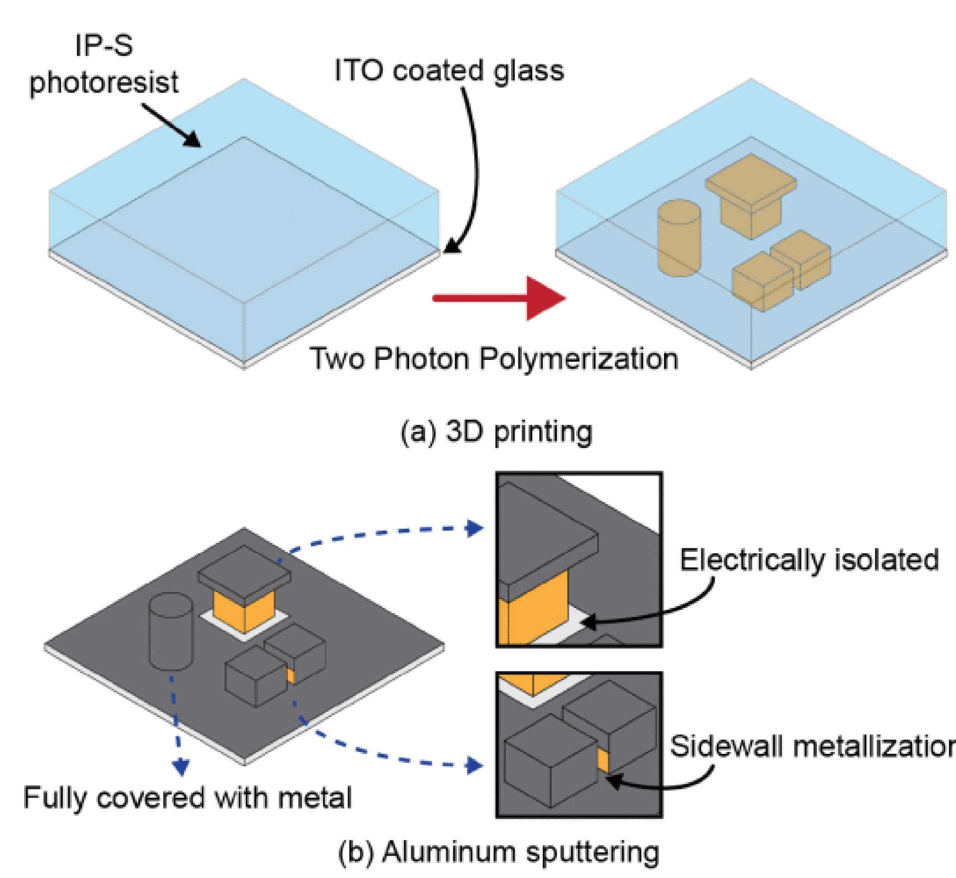
Approach





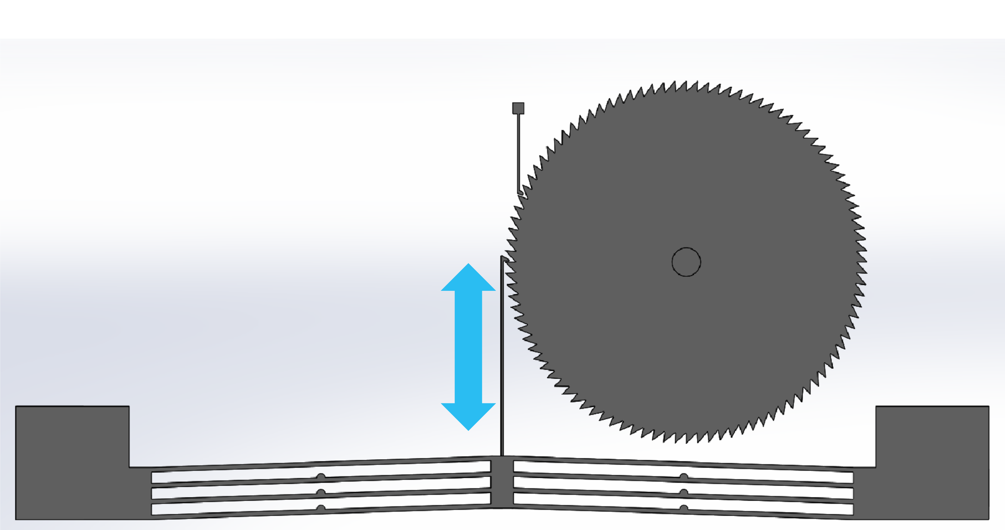
One-photon absorption vs two-photon absorption

Schematic of galvo scan printing



Fabrication process [1]

Multi-photon lithography is a submicron additive manufacturing process using two-photon polymerization (to fabricate free-form, 3D structures. For builds that exceed the printing field of the focusing objective, multiple fields of view are stitched together. The MEMS structure we studied was a rotational drive assembly consisting of a chevron actuator and gear. The chevron actuator uses electrothermal actuation to move vertically and spin the gear.



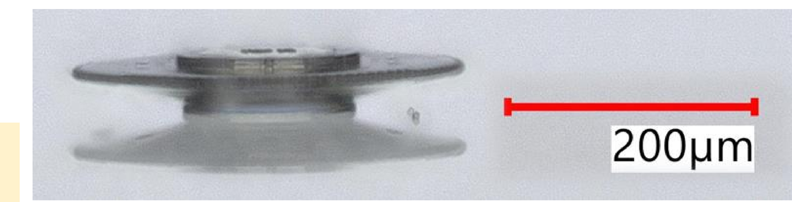
Actuation direction of chevron

After printing, the samples were developed in a PGMEA bath for 10-20 minutes to remove excess photoresist, then rinsed in an IPA bath for 5-10 minutes to remove excess PGMEA, then dried in air at ambient temperature. Finally, the samples were coated with 70 to 100 nm of aluminum via sputtering to increase conductivity of the device. Electrical current is run through the aluminum coating, which heats the entire structure via resistive heating. The entire chevron actuator is electrically isolated from the substrate via intentional shadowing during the aluminum sputtering. The cured photoresist then expands as it heats, and the design of the chevron arms forces vertical displacement at the center, where a long actuation arm connects to the teeth of the gear.

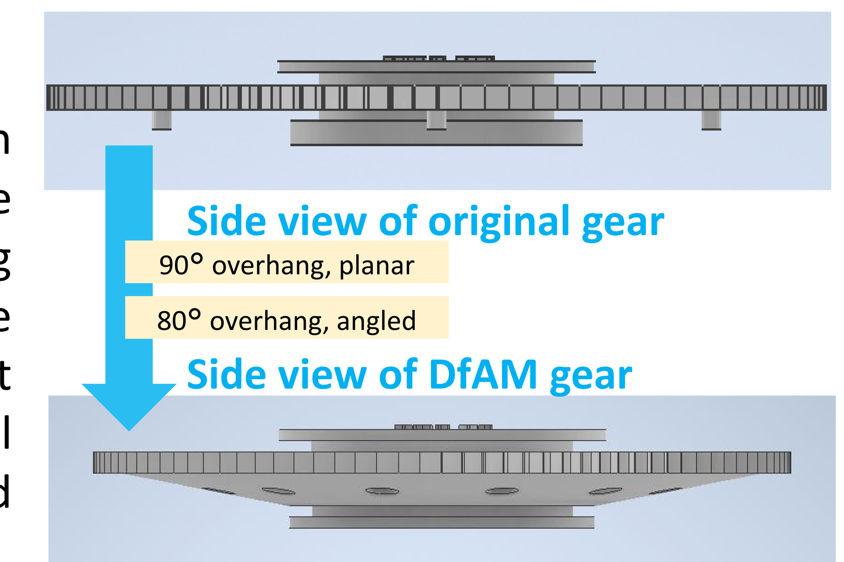
[1] *J Microelectromech Syst* 29, no. 4 (2020): 544-552.).

Results

Improved Stability During Printing

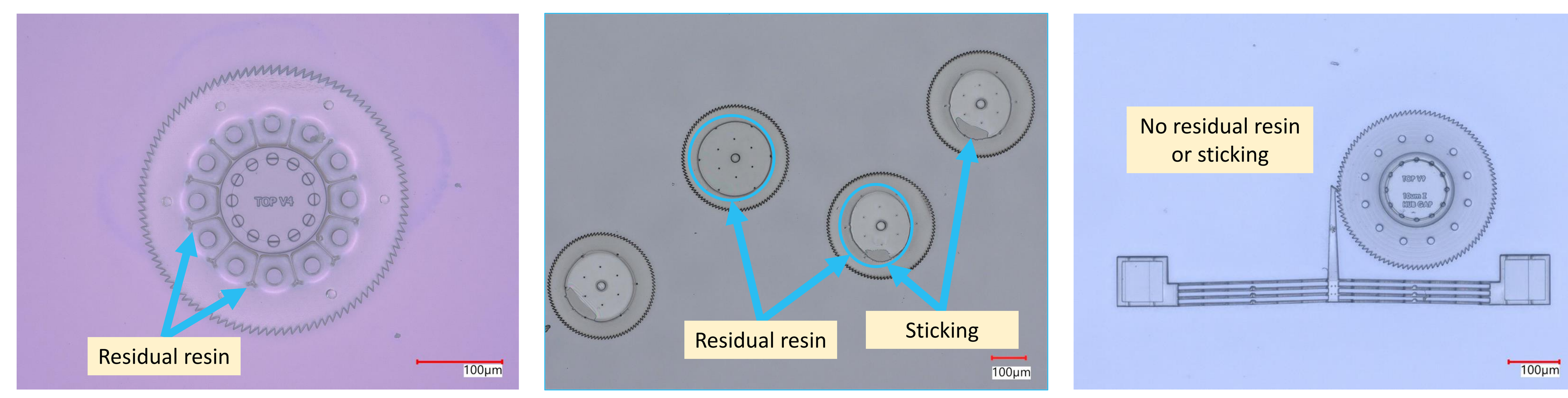


Angled gear (80° overhang) stable during printing



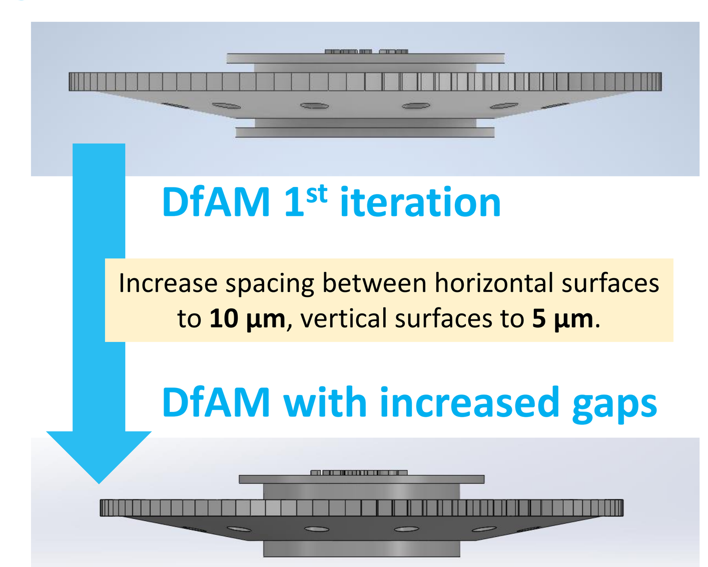
Usually, MEMS devices are highly planar with long, unsupported spans at an overhang of 90°. At the scale tested, 90° overhangs cause stability issues during printing. We found that overhangs of ≤80° provide enough stability to subsequent layers to print successfully, since each new layer only has a small unsupported section at the edge. This edit was included in our gear redesign.

Solved Residual Photoresist Issues

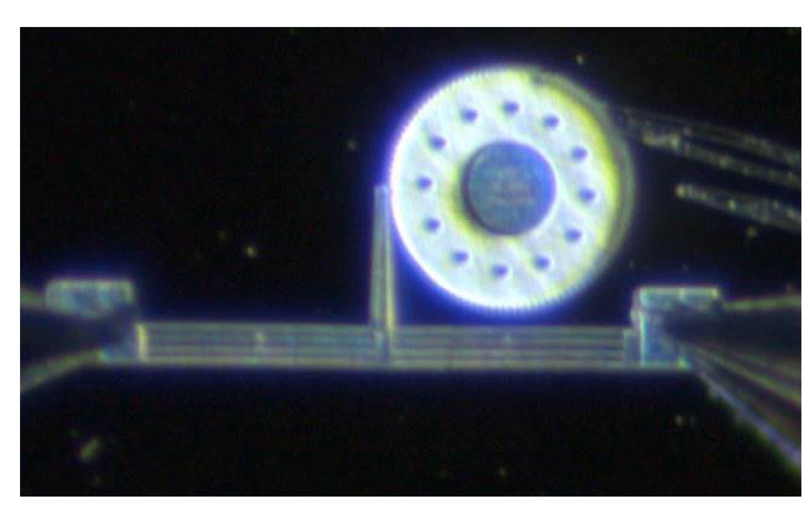


Clear improvement of residual resist removal as design iterations increased

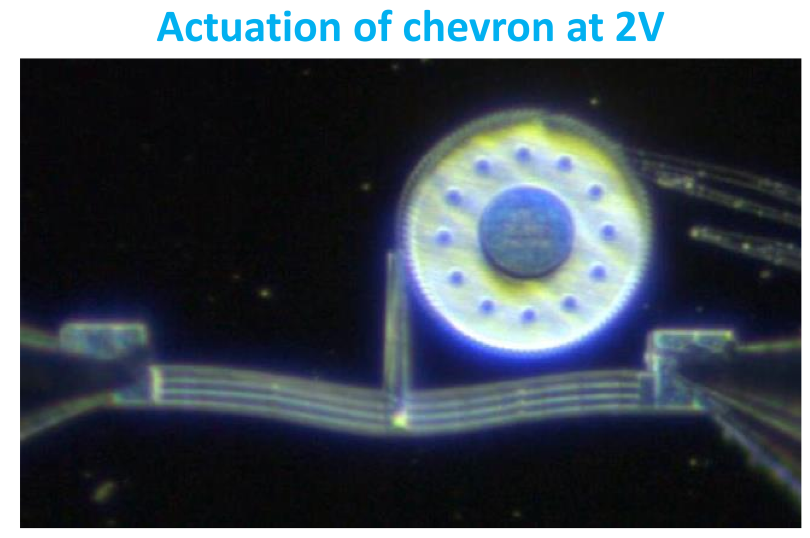
Another problem with translating traditional MEMS designs into 2PP is that residual photoresist is difficult to dissolve between the substrate and the printed gear, as well as between the moving parts of the gear. We found that adding extra drain holes, 15 µm in diameter, through the gear solved this issue. The drainage holes allowed enough of the developer to reach and dissolve the residual photoresist in an appropriate amount of time.



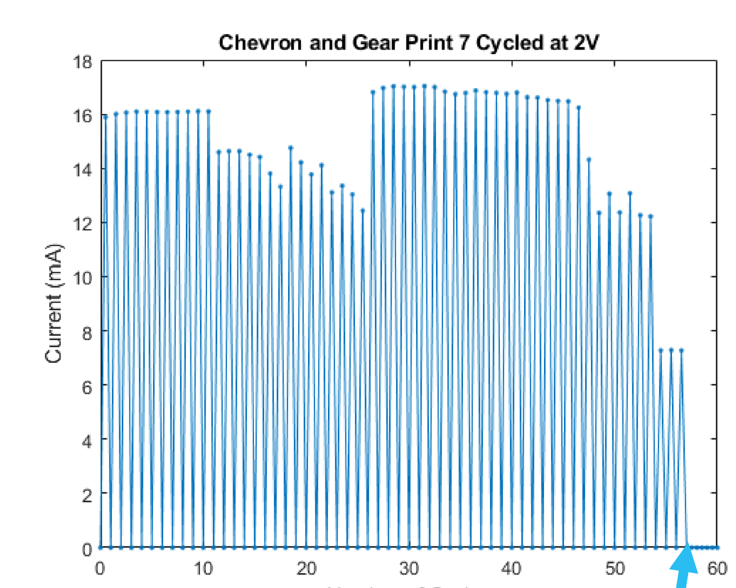
Successful Actuation of Gear

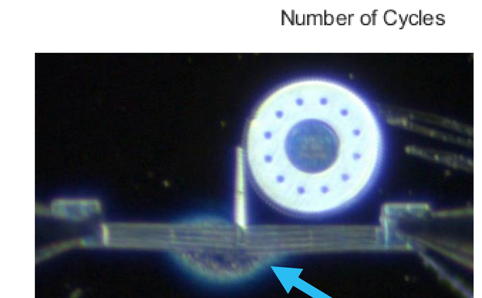


Actuation of chevron at 2V



The final design was successfully actuated at applied voltage cycles ranging from 0.5 to 2 V, and allowed to cycle until failure. The resistive heating of the polymer, if taken too far causes the chevron structure to melt. Higher applied voltage induced larger displacement, but also decreased cycles to failure.





Failed at n = 58 due to overheating in chevron arms

Significance

This work proves that the design rules for MEMS can be adapted to be printable via 2PP additive manufacturing. Traditional MEMS have been limited by their planar manufacturing methods, and the ability to produce additively manufactured MEMS will open to door to countless new designs and functions. With enough improvement, this method may displace traditional microfabrication techniques due to its simplicity. Further work on the rotational drive assembly should work to improve the reliability, production yield, and actuation strength.

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