Electrochemical Thin Film Actuator Enabled Microrobots and Micromachines for Fluid Manipulation, Shape Morphing and Neural Probing

CNF Project Number: 2416-16

Principal Investigator(s): Itai Cohen, Paul L. McEuen

User(s): Qingkun Liu, Wei Wang, Jacob T. Pelster

Affiliation(s): Kavli Institute at Cornell for Nanoscale Science, Applied and Engineering Physics, Laboratory of Atomic and Solid-State Physics, Department of Physics; Cornell University

Primary Source(s) of Research Funding: National Science Foundation, Contract DMR-1719875; EFMA-1935252, Army Research Office, Contract W911NF-18-1-0032; National Institutes of Health, Grant 1R21EY033080-01

Contact: itai.cohen@cornell.edu, plm23@cornell.edu, ql59@cornell.edu, ww459@cornell.edu, jtp246@cornell.edu

Primary CNF Tools Used: Oxford ALD FlexAL, Arradiance ALD Gemstar-6, Oxford 81/100 Etchers, ABM Contact Aligner, SC 4500 Odd-Hour, AJA Sputter Depostition, AJA Ion Mill, Oxford Cobra ICP Etcher, Heidelberg DWL2000, Oxford Endeavor, Oxford PECVD

Abstract:

The ability to efficiently actuate structures at the micro- and nanoscale is an essential technology for the development of microbots and micromachines. Our team is developing a class of electrochemically driven thin film bending actuators with low voltage input and high energy density. These actuators are compatible with complementary metal-oxide-semiconductor (CMOS) technologies, which we use to interface with controlling integrated circuits. We use these actuators for three novel devices: artificial cilia that can manipulate microscale fluid fields, metamaterial robots with the ability to change shape and locomote, and a novel minimally invasive neural probe.

Summary of Research:

We developed bilayered thin film actuators that can bend in response to an electrical voltage signal [1,2]. These thin film actuators are composed of a passive layer, and an active layer, which generates strain in response to certain electrochemical reactions. Upon the application of a voltage to the active layer, the resulting strain in the active layer generates differential stresses between the two layers, triggering the actuation of bending. These actuators work in an aqueous environment and are programmable with low-voltage signals. Here we demonstrate three different applications of the actuators for developing artificial cilia [3], metamaterial robots, and neural probes.

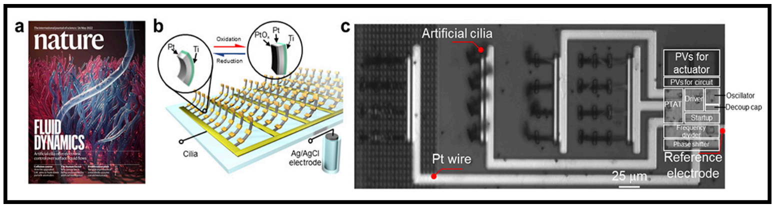

Figure 1: Current and proposed artificial cilia platforms. a) Electronically actuated artificial cilia featured in the May 26th issue of Nature. *b) Electrochemical mechanism of cilia. c) Phase delayed actuation of CMOS circuit integrated cilia arrays.*

Cilia Metasurfaces for Electronically Programmable Microfluidic Manipulation. Cilial pumping is a powerful strategy many microorganisms use to control and manipulate fluids at the microscale. However, the development of an efficient artificial cilial platform that can functionally manipulate fluids remained elusive. Utilizing the thin film electrochemical actuators, we have developed a new class of electrically controlled artificial cilia that can programmably control micro- and nanoscale flow fields (Figure 1a). These cilia are comprised of nm thin films of Pt capped on one side by Ti. By oxidizing and reducing the platinum thin film, the induced expansion and contraction with respect to the inactive capping layer drives cilial beating, and generates a surface flow (Figureure 1b). These cilia were used to create an active cilia metasurface that can generate

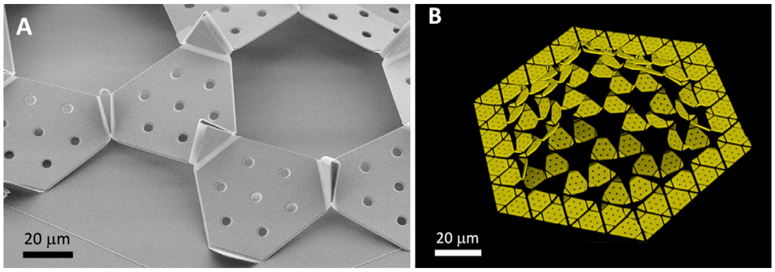

Figure 2: (a) SEM image of the active origami-inspired hinges connecting passive SiO panels. (b) Confocal image of a metarobot that transform into dome shape.

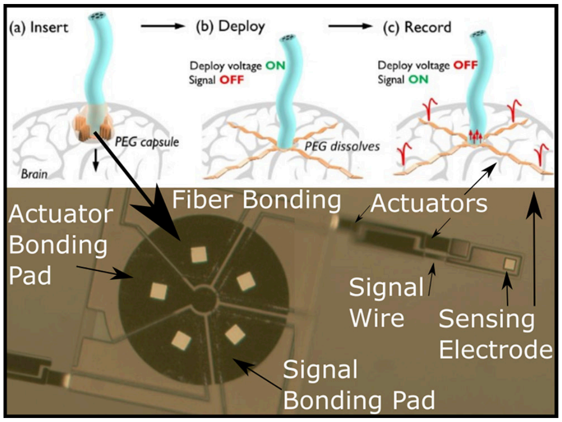

Figure 3: (Top) Schematics of the proposed probe working principle with low invasiveness. (Bottom) Structure of the prototype probe.

and switch between any desired surface flow patterns. We also integrated the cilia with a light-powered CMOS clock circuit (Figure 1c) to demonstrate wireless operation. As such, we envision numerous applications of cilia metasurfaces for fluidic manipulation with solar-powered lightweight devices in the near future.

Metamaterial-Based Microrobots. We demonstrate electrically programmable, micrometer-sized metamaterial-based robots (metarobots) that can form three-dimensional (3D) surfaces from two-dimensional patterns, cycle among different shapes, and locomote in a biocompatible solvent. These metarobots have a hierarchical structure: the repeating panels are linked by origami-based splay hinges, which are controlled by applying voltage to atomically thin surface electrochemical actuators (Figure 2A). The actuator consists of a 7 nm thick platinum layer capped on one side by a 2 nm titanium layer. Under application of potentials in the range of 1 volt, ions oxidize the platinum, create a differential in stress between the two sides, and cause the structure to bend. The splay hinge contains a single mountain and two valley folds, which convert the out-of-plane bending of the nanoactuator into in-plane rotation of the panels. When we apply a voltage, the local expansions of the unit cells alter the local Gaussian curvature of the metarobots, allowing it to reconfigure into a 3D surface. We used confocal optical microscopy to image the 3D structures of the metarobots (Figure 2B). The Gaussian and mean curvatures are then calculated from the experimental 3D images. We show that the metarobots can transform into a rich class of 3D shapes by locally actuating different subsets of the splay hinges. As a demonstration, if the inner region of the sheet is activated, the metarobot morphs into a dome shape, whereas if the outer region is activated, it transforms into a saddle shape. Furthermore, by applying a phase delay between the actuation signals of different parts of the metarobot, we break both the spatial and temporal symmetry, and drive the metarobots to locomote in a biocompatible solution.

Extendable Neural Probes. Neural probes have cemented themselves in the minds of researchers and medical practitioners as a valuable instrument with multiple applications ranging from early detection of chronic disease, to brain stimulation and prosthetic interfaces. However, conventional probes are fabricated as thin, long structures inserted perpendicular to the surface of the brain. If transverse measurement is desired, multiple probes must be inserted as an array, requiring the removal of the skull over the entire recording area. One approach to minimizing the area of skull removed is to develop a deployable probe, which actuates after insertion to increase the area of transverse measurement. Such an approach requires the use of actuators that can generate enough force to achieve transverse motion through biological tissues. We developed such an actuator based on a bilayer structure of palladium and titanium, which can now be combined with a series of 120 µm wide fiber probes, signal wires, and rigid panels to create a deployable probe. Our vision is that the entire device will be released from the substrate, and inserted into the brain in one hole only slightly larger than the (contracted, 150 µm) probe. The device will then expand transversely into the brain, allowing a much larger measurement area than the invasive area (Figure 3 top).

References:

[1] Miskin, M. Z.; Cortese, A. J.; Dorsey, K.; Esposito, E. P.; Reynolds, M. F.; Liu, Q.; Cao, M.; Muller, D. A.; McEuen, P. L.; Cohen, I., Electronically integrated, mass-manufactured, microscopic robots. Nature 2020, 584 (7822), 557-561.

[2] Liu, Q.; Wang, W.; Reynolds, M. F.; Cao, M. C.; Miskin, M. Z.; Arias, T. A.; Muller, D. A.; McEuen, P. L.; Cohen, I., Micrometer-sized electrically programmable shape-memory actuators for low-power microrobotics. Science Robotics 2021, 6 (52), eabe6663.

[3] Wang, W.; Liu, Q.; Tanasijevic, I.; Reynolds, M. F.; Cortese, A. J.; Miskin, M. Z.; Cao, M. C.; Muller, D. A.; Molnar, A. C.; Lauga, E., Cilia metasurfaces for electronically programmable microfluidic manipulation. Nature 2022, 605 (7911), 681-686.