Smart Microscopic Robots

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Principal Investigator(s): Paul L. McEuen[1,2], Itai Cohen[1,2], Alyosha C. Molnar[3], Marc Z. Miskin[4]

User(s): Michael F. Reynolds[1], Alejandro J. Cortese[1,3], Qingkun Liu[1], Wei Wang[1,5], Samantha Norris[1], Zhangqi Zheng[1], Sunwoo Lee[3]

Affiliation(s): 1. Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca NY USA; 2. Kavli Institute at Cornell for Nanoscale Science, Cornell University, Ithaca NY USA; 3. Department of Electrical and Computer Engineering, Cornell University, Ithaca NY USA; 4. Department of Electrical and Systems Engineering, University of Pennsylvania, Philadelphia, PA, USA; 5. Sibley School of Mechanical and Aerospace Engineering, Cornell University, Ithaca NY USA

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Contact(s): plm23@cornell.edu, mfr74@cornell.edu

Primary CNF Tools Used: ABM contact aligner, Oxford 100 ICP dielectric etcher, Oxford 80 etchers, Oxford Cobra ICP etcher, AJA sputter deposition (1&2), Arradiance ALD Gemstar-6, Oxford ALD FlexAL, Oxford PECVD, Gamma automatic coat-develop tool, Xactic xenon difluoride etcher

Abstract:

Research on microscopic robots — robots a few hundred micrometers in size or smaller — has demonstrated a variety of approaches for locomotion and simple functions but has not produced "smart microscopic robots" that can perform complex tasks autonomously. Recently, our group has demonstrated the first smart microscopic robots by integrating microactuators with complementary metal oxide semiconductor (CMOS) electronics. These robots can actuate their legs independently and walk autonomously without any input of information. This work paves the way for smart microscopic robots that can sense and respond to their environment, receive commands, perform complex functions, and communicate with the outside world.

Summary of Research:

Figure 1 shows the first smart microscopic robot. An optical micrograph of one of these robots with labeled parts is shown in Figure 1A. Its body consists of photovoltaics for powering the robot and a 180-nm node CMOS circuit with approximately 1000 transistors to control the robot. The legs of the robot consist of surface electrochemical actuators (SEAs), microactuators developed at Cornell made of ultrathin atomic layer deposition platinum that bend to micrometer-scale radii of curvature in response to small voltages in aqueous environments [1,2]. Rigid panels of SiO_2 on either side of the actuator restrict the bending direction of the SEA to form a hinge. At the top and bottom of the robot are large, exposed platinum ground pads that serve as the counter electrodes to the actuators. Figure 1B shows a microscope image of the circuit of a released robot. Using infrared light and viewing a released robot from underneath, we can see parts of the CMOS circuit that controls the robot (Figure 1B). We fabricate many robots in parallel — Figure 1C shows an array of microscopic robots with a variety of designs prior to release. Each robot is inside a 300 μm by 300 μm square, meaning that almost 100,000 robots could be fabricated on a 4-inch wafer.

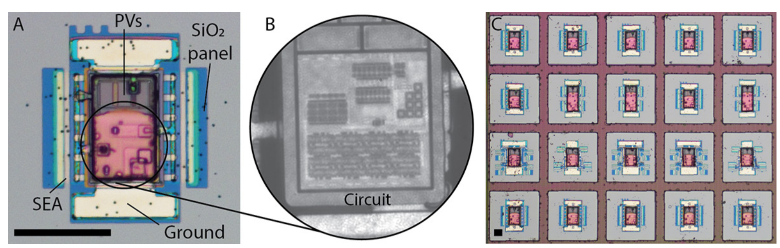

Figure 1: (A) Optical micrograph of a smart microscopic robot. (B) Infrared microscope image of a released microscopic robot showing the onboard CMOS circuit. (C) Optical micrograph of an array of microscopic robots. They are photolithographically fabricated in parallel on a silicon-on-insulator wafer. Scale bars are 100 μm.

Figure 2 shows an optical image of the circuit that controls the robot. This circuit is designed at Cornell and fabricated by X-FAB Silicon Foundries with a 180 nm node CMOS process on silicon-on-insulator (SOI) wafers. It has a simple function: to output phase-shifted square waves to the legs of the robot, allowing it to walk. We set the gait of the robot by wiring the legs of the robot to square wave outputs on the circuit with different phases. We set the frequency of the square wave outputs by wiring the I-shaped pins to the bar above them during post-processing, with frequencies ranging from about 1 Hz to about 128 Hz by factors of two.

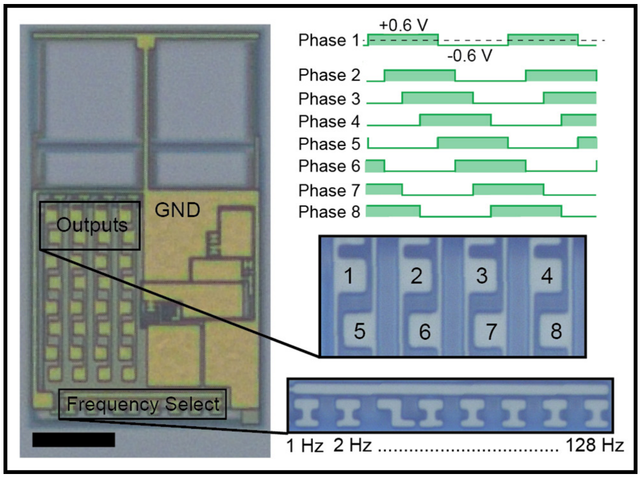

Figure 2: Optical micrograph of clockbot's integrated circuit showing the output pins for the eight phase-shifted square waves and the pins for selecting the output wave frequency. Scale bar is 20 µm.

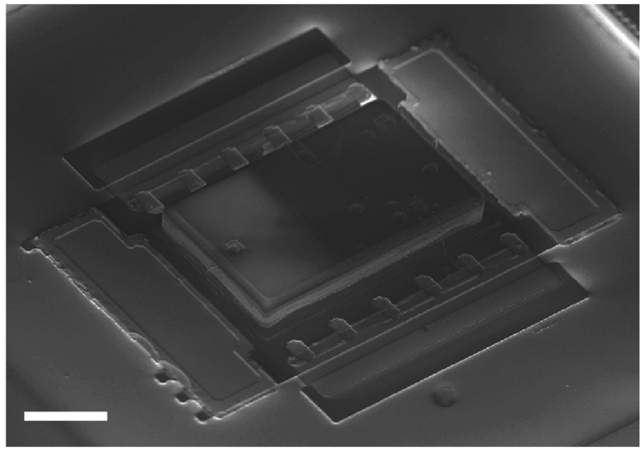

Figure 3: A scanning electron microscope image of a completed microscopic robot. The body of the robot, containing the photovoltaics and circuit, is about 15 µm tall. Scale bar is 30 µm.

After receiving the circuits from X-FAB, we perform post-processing on them to etch out the body (circuit and PVs) of the robot, create wires out from the circuit, shield the circuit from light, build legs and connect them to the circuit, and release the robots from the silicon substrate. This process is based on a variety fabrication protocols developed in our group [1-3], requires 13 layers of photolithography, and makes use of more than twenty CNF tools. A scanning electron microscope image of a completed robot is shown in Figure 3. This image shows the large topography resulting from etching out the body of the robot, about 15 µm tall. This creates several challenges during the fabrication process, requiring us to use the spray coater on the Gamma automatic coat-develop tool to coat the large vertical features completely with photoresist.

Upon completion of the fabrication process, we undercut the silicon beneath the robot and release it into an aqueous environment. Figure 4A shows a 3D model of a released robot. Upon release, the legs bend under the body of the robot. When we illuminate the robot with light, the robot moves autonomously without any additional inputs. Its design is inspired by the Purcell three-link swimmer [4]; instead of swimming, this robot walks by alternately moving its front and back legs. These robots operate in light intensities of about 1 kW/m^2, equivalent to direct sunlight outside on a sunny day. Figure 4B shows time-lapse images of a clockbot walking, with images taken at 25 s intervals.

Conclusions and Future Steps:

The robots shown here are only the beginning for CMOS-integrated smart microscopic robots. We are currently pursuing work on faster robots with more legs and more complex gaits and robots that respond to commands or following light gradients. Future designs will include robots with alternate propulsion mechanisms, additional sensors, and ways to communicate with each other and the outside world. As smart microscopic robots increase in complexity and capability, they have incredible potential for positive impact in numerous fields, from studying emergent behaviors in swarms of smart particles to performing medical procedures at the micron-scale.

References:

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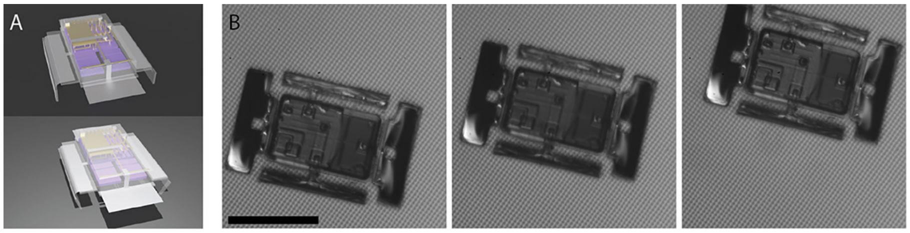

Figure 4: (A) Schematic of a CMOS integrated microscopic robot. The robot moves autonomously when powered by light. (B) A released microscopic robot walking on a glass substrate. Scale bar is 100 µm.