

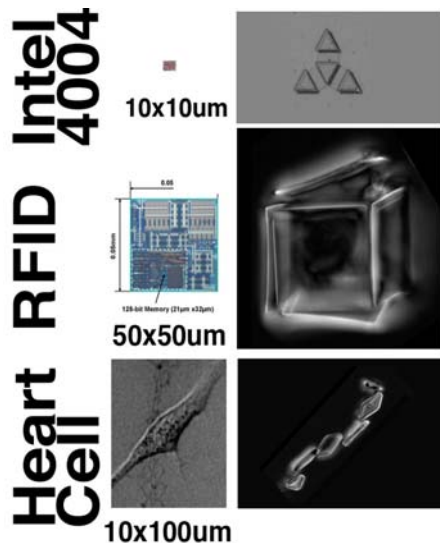
Atomic Origami: a technology platform for nanoscale machines, sensors, and robots

M. Miskin, B. Bircan, P. L. McEuen, and I. Cohen

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Abstract

What would we be able to do if we could build cell-scale machines that sense, interact, and control their micro environment? Can we develop a Moore's law for machines and robots?

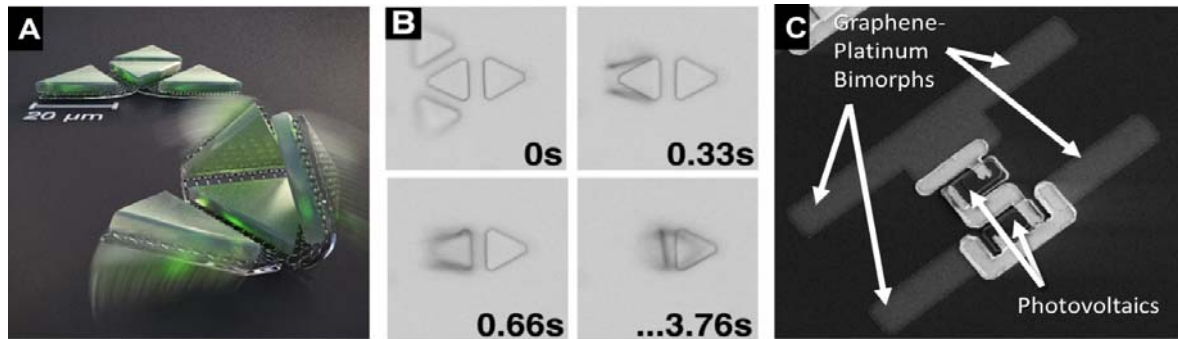


In Richard Feynman's classic talk "There's Plenty of Room at the Bottom" he foretold of the coming revolution in the miniaturization of electronics components. This vision is largely being achieved and pushed to its ultimate limit as Moore's Law comes to an end. In this same lecture, Feynman also points to the possibilities that would be opened by the miniaturization of machines. This vision, while far from being realized, is equally as tantalizing. For example, even achieving miniaturization to micron length scales would open the door to machines that can interface with biological organisms through biochemical interactions, as well as machines that self-organize into superstructures with mechanical, optical, and wetting properties that can be altered in real time. If

these machines can be interfaced with electronics, then at the 10's of micron scale alone, semiconductor devices are small enough that we could put the computational power of the spaceship Voyager onto a machine that could be injected into the body. Such robots could have on board detectors, power sources, and processors that enable them to make decisions based on their local environment allowing them to be completely untethered from the outside world.

Origami inspired fabrication presents an attractive platform for building such small-scale robotic devices: origami designs are scale invariant, can be patterned with lithographic techniques, and only actuate at folds, allowing rigid electronics to be embedded in the remaining flat portions of the structure. Yet, incorporating all of these functionalities is complicated because there is currently no simple actuation mechanism that can be used to make micron scale folds, lift electronics-laden panels, and maintain electrical conductivity across each fold. Here, we show that graphene based actuators can be used as the foundation for fabricating micron sized machines that sense and respond to their environment without

sacrificing the capacity for electronic payloads. As a prototype, we bond graphene sheets to nanometer thick layers of glass to make ultrathin bimorph actuators that bend in response to small strain differentials. These bimorphs can bend to micron radii of curvature using strains that are two orders of magnitude lower than the fracture threshold for the device, thus maintaining conductivity across the structure. By patterning 2 μm thick rigid panels on top of bimorphs, we localize bending to the unpatterned regions to produce folds. Even though the graphene bimorphs are only nanometers thick, they can lift these panels, the weight equivalent of a 500 nm thick silicon chip. Using panels and bimorphs, we can scale down existing origami patterns to produce a wide range of machines. These machines change shape in fractions of a second when crossing a tunable pH threshold demonstrating they can sense their environments, respond, and perform useful functions on time and length scales comparable to microscale biological organisms. With the incorporation of electronic, photonic, and chemical payloads, these basic elements will become a powerful platform for robotics at the micron scale.



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