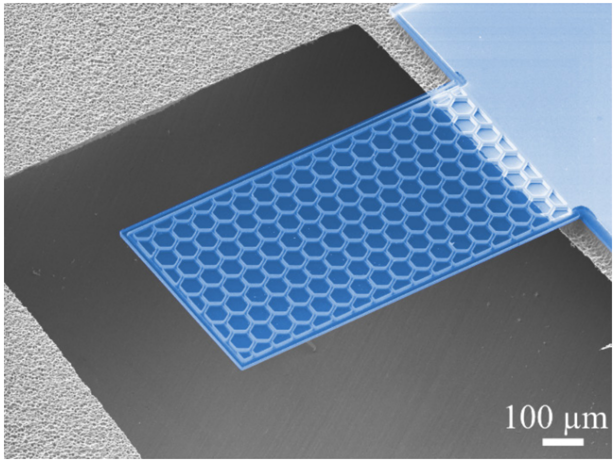
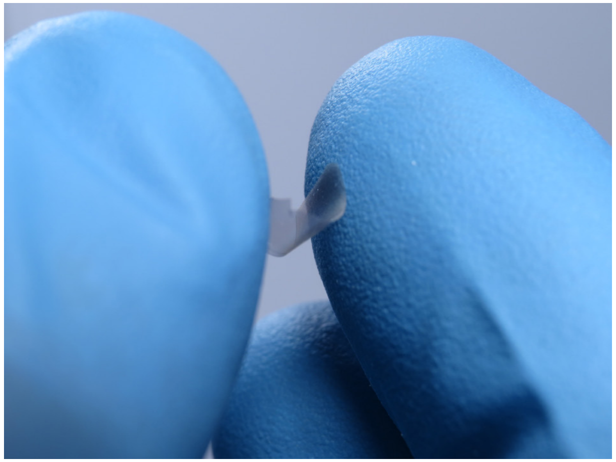
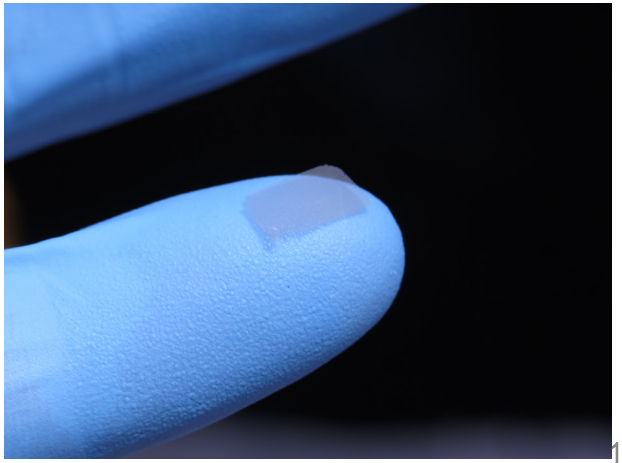
UNIVERSITY of PENNSYLVANIA

Plate mechanical metamaterials

Igor Bargatin

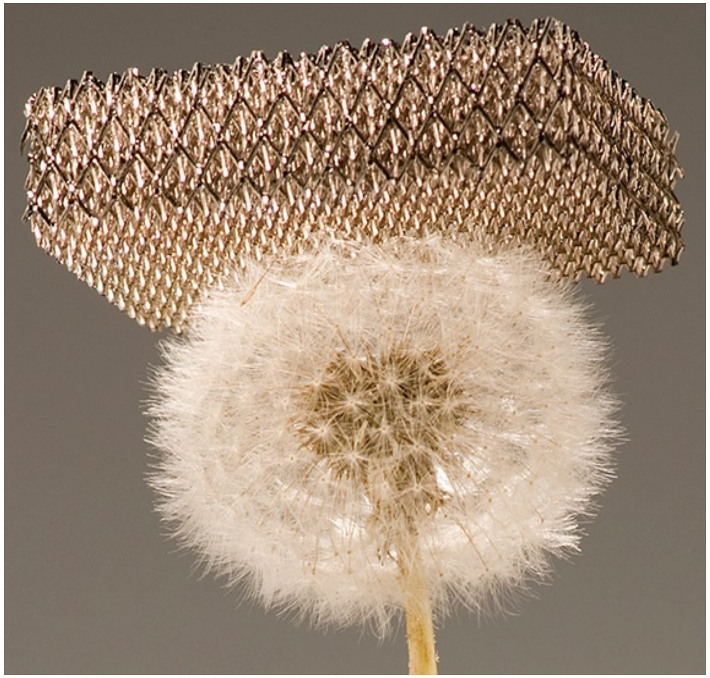






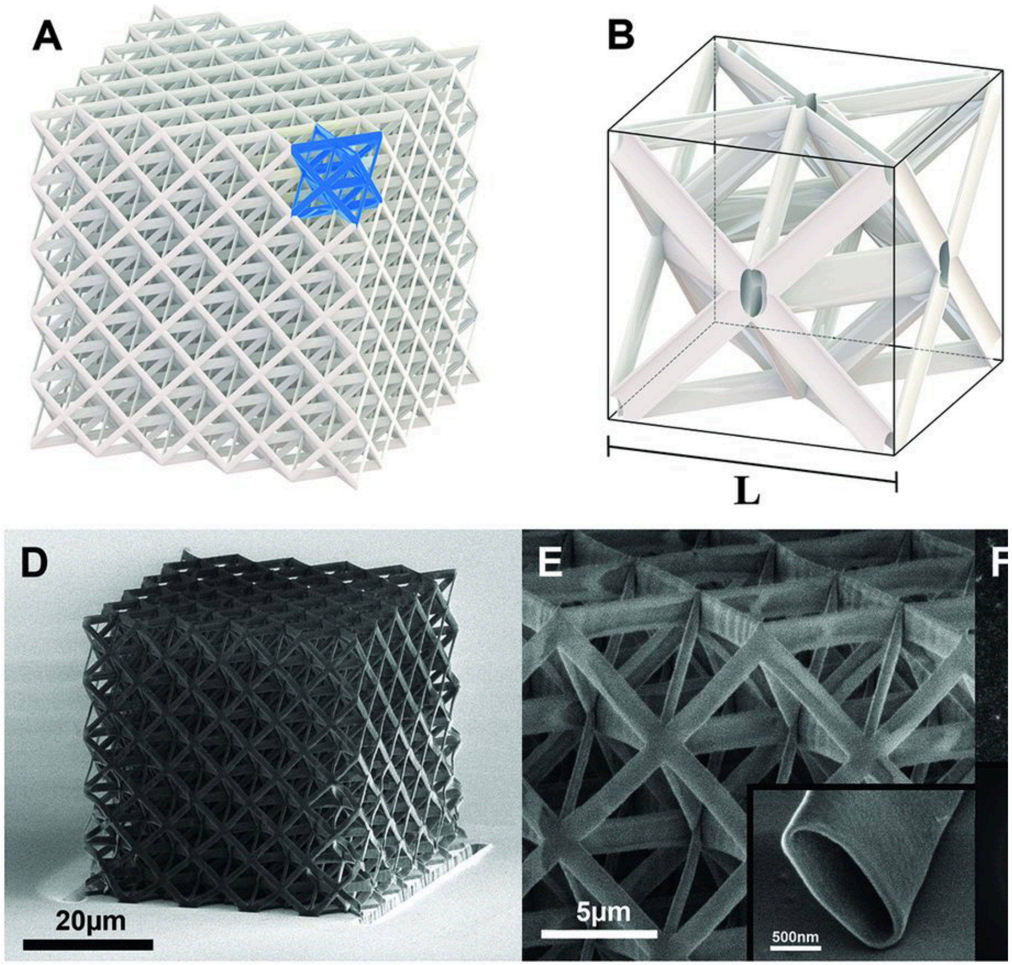
Mechanical metamaterials

artificial structures with unique mechanical properties that are defined by their carefully designed and controlled geometry (usually periodic) at the micro scale



http://www.jrgreer.caltech.edu/research.php

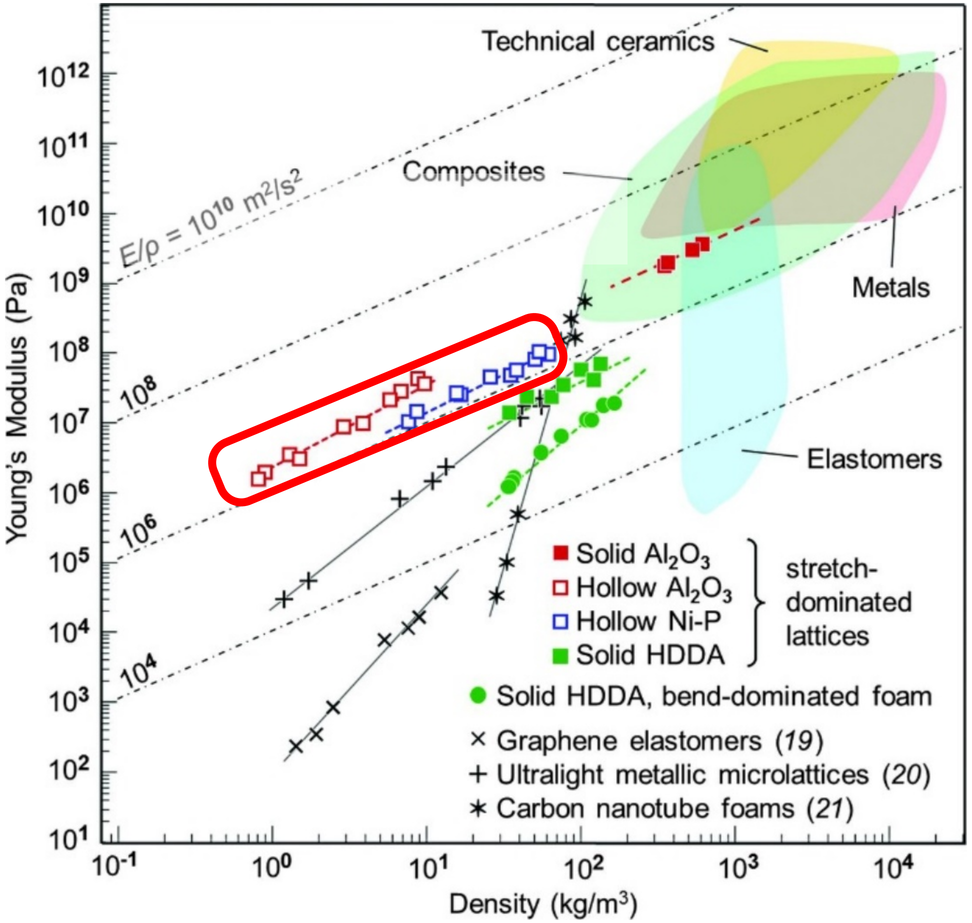
If fabricated out ultra-thin films, the resulting structures can be remarkably lightweight ($\sim 1\ \mathrm{kg/m^3}$) and recover from very large deformations

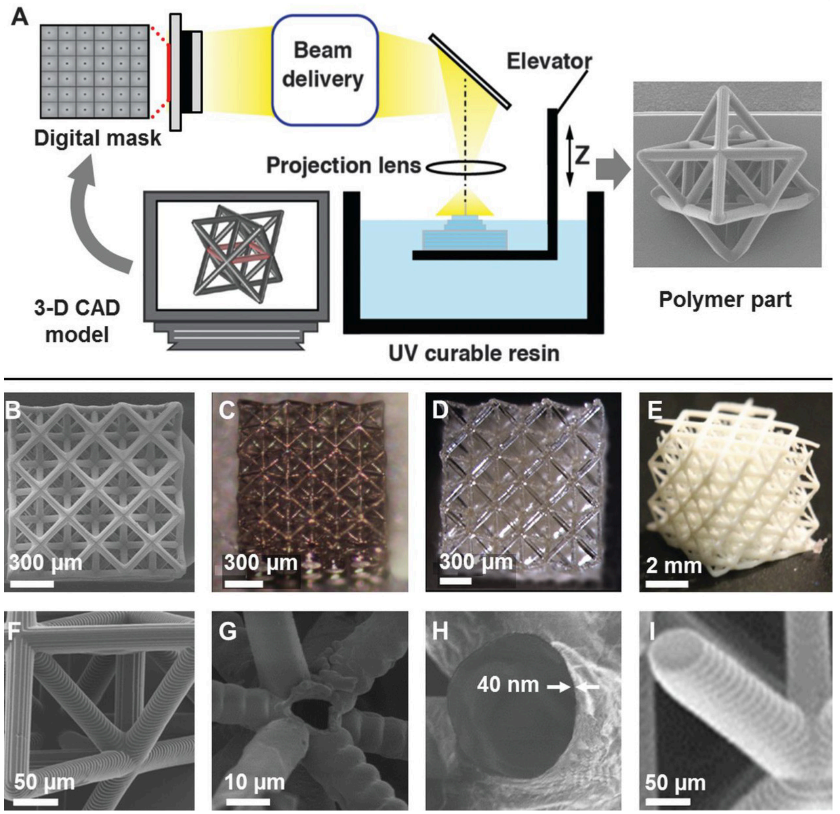


Meza et al, Science 344, pp. 1373-1377 (2014)
Zheng, Spadaccini, *et al*, *Science* **344**, 1373–1377 (2014)

Microtrusses/nanolattices

These “bulk” mechanical metamaterials can have very high stiffness for such low density:





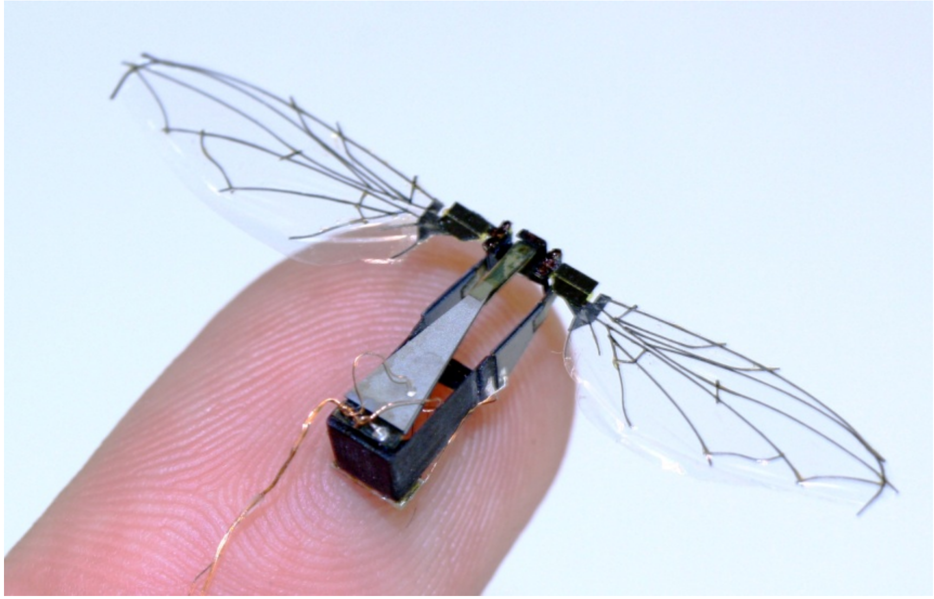
Zheng, Spadaccini, *et al*, *Science* **344**, 1373–1377 (2014

Fabricated by 3D-printing a polymer scaffold, coating it with a thin film, and etching the polymer scaffold

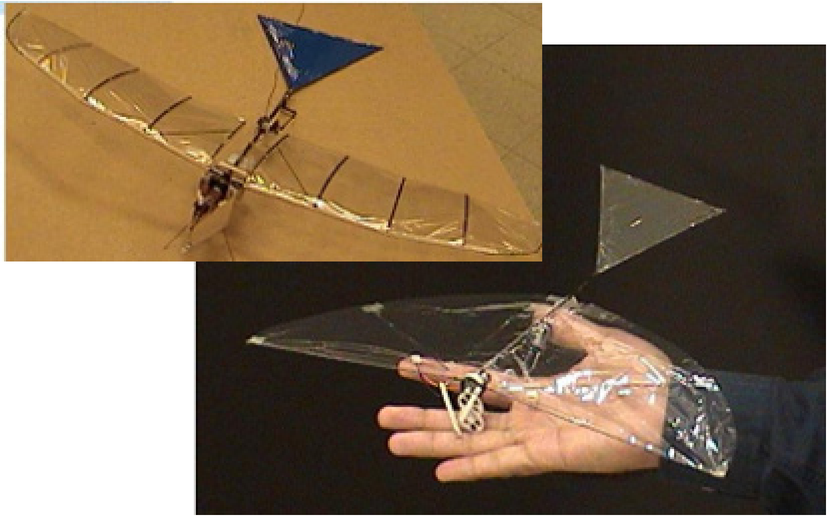
This fabrication process is relatively slow and difficult to scale to macro sizes

What about plates/mebranes?

Many applications require **lightweight** and **continuous** plates:



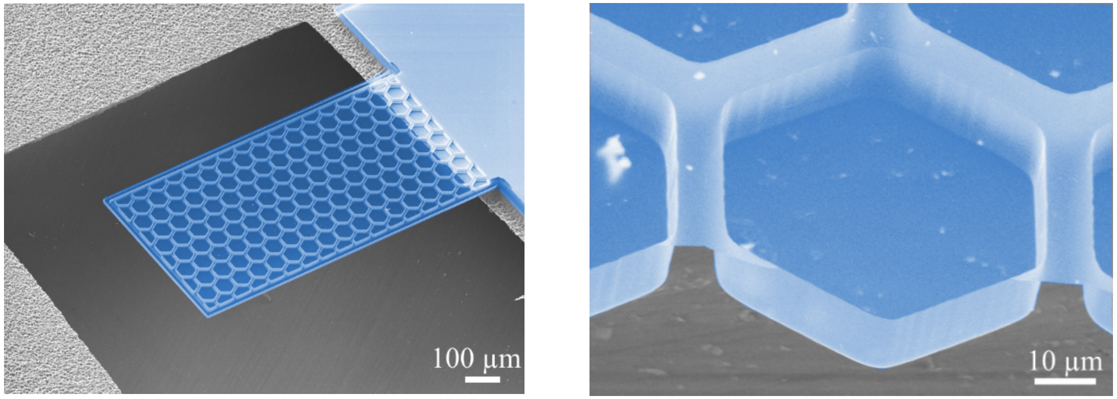
A three-centimeter flapping-wing robotic fly
(Harvard Microrobotics Lab)



Flapping Wing Micro Aerial Vehicles
http://roar.me.columbia.edu/projects/flapper/
http://lentinklab.stanford.edu/publications

Lattice metamaterials cannot be easily adapted for these applications

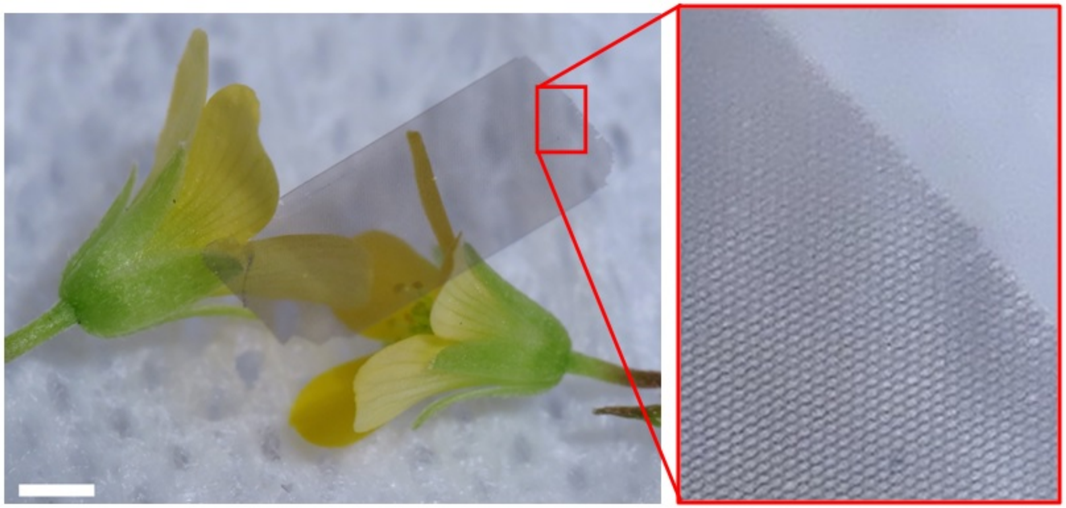
Plate mechanical metamaterials (PMMs): Ultrathin (<100nm) continuous plates



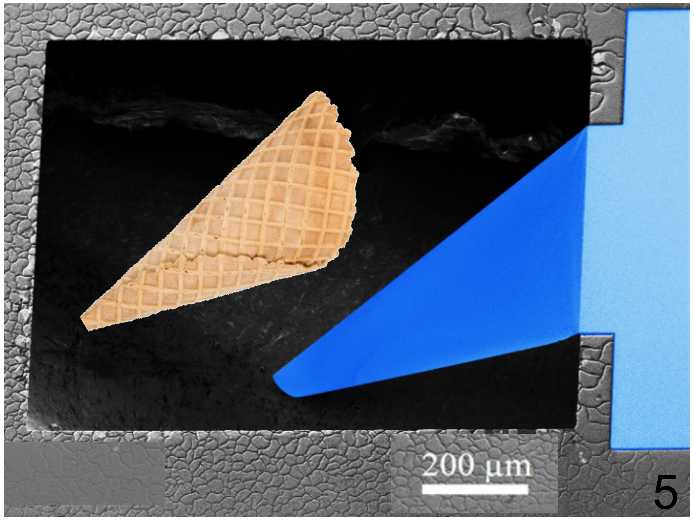
Free- standing ALD alumina (Al2O3) plates

- 25-100 nm (thinnest macro-scale structures)
- ~0.1 gram/m^2 weight

Davami, Bargatin *et al.*, 2015, Nat. Commun. 6:10019 (2015)



Can be fabricated at macro scale using standard MEMS methods



Flat films curl up and/or fracture under tension due to stress gradients. A clamped cantilever curls into a shape reminiscent of a waffle cone

Same tricks have long been used to increase stiffness at the macroscale

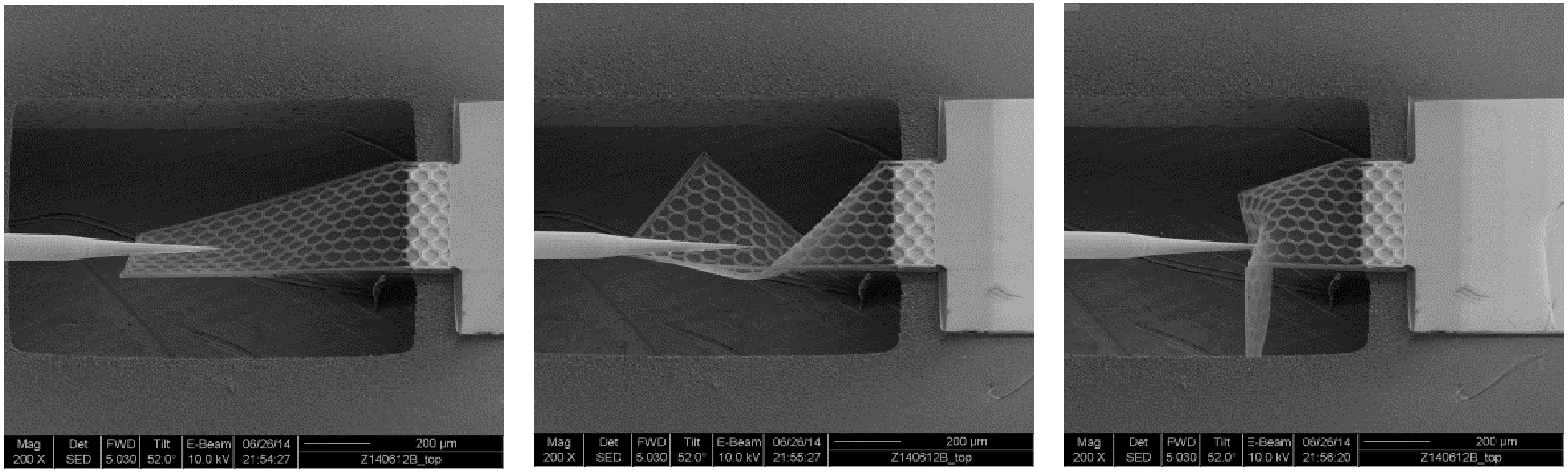
3D patterning with vertical "ribs" can increase bending stiffness by orders of magnitude relative to flat films

"2D" corrugated sheets have long-been used in architecture

http://www.nauticexpo.com/prod/bellotti-spa/sandwich-panels-plywood-honeycomb-wood-30295-197074.html

Honeycomb sandwich structures are ubiquitous in construction, aviation, or even musical instruments

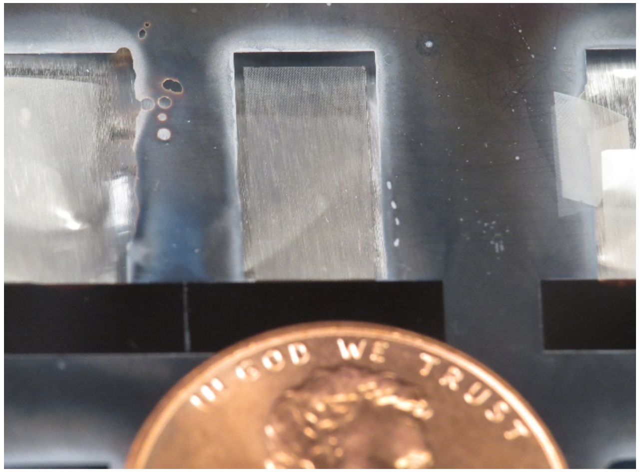
What is different at the nanoscale?



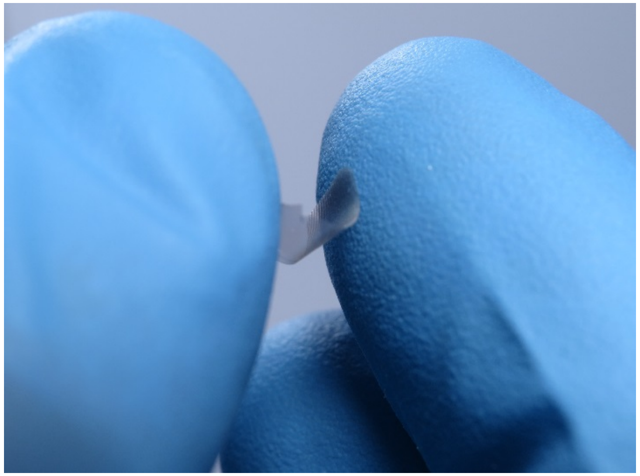
Davami, Bargatin *et al.*, 2015, Nat. Commun. 6:10019 (2015)

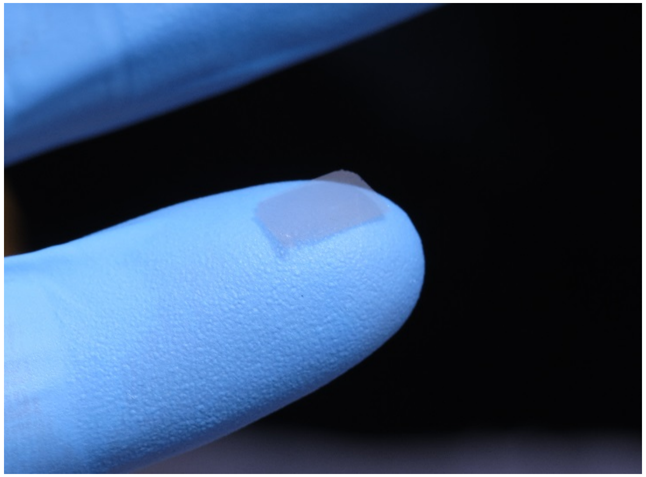
We got the expected flatness and increase in stiffness (measured by AFM), but we also found flexibility and robustness that seemed very unusual for alumina (a brittle ceramic)

Mechanical robustness allows scale-up to cm-sized plates



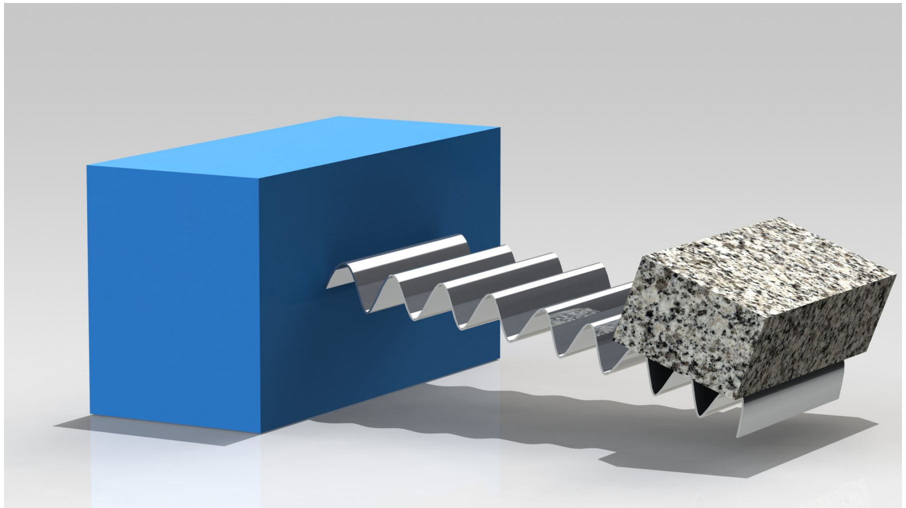
Freestanding plates with nanoscale thickness can be made into relatively robust macro-scale objects for experiments that are quite literally "hands-on"





Weigh as little as 0.1 g/cm^2 – the thinnest plates that can be picked up by hand

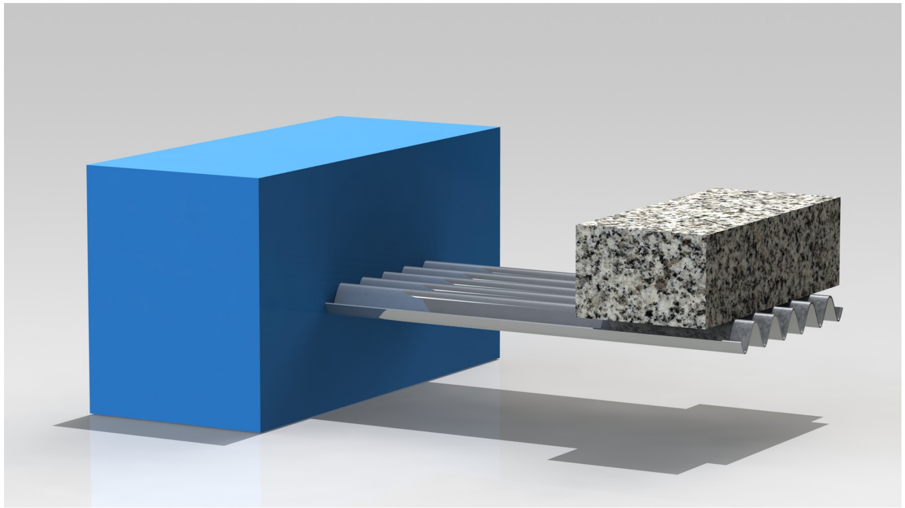
Plates with standard unidirectional corrugation are highly anisotropic



In the soft direction, they have essentially the same stiffness as completely planar plates:

$$D_\perp \approx D_{planar} = \frac{Et^3}{12(1-\upsilon^2)},$$

where t is the thickness of film



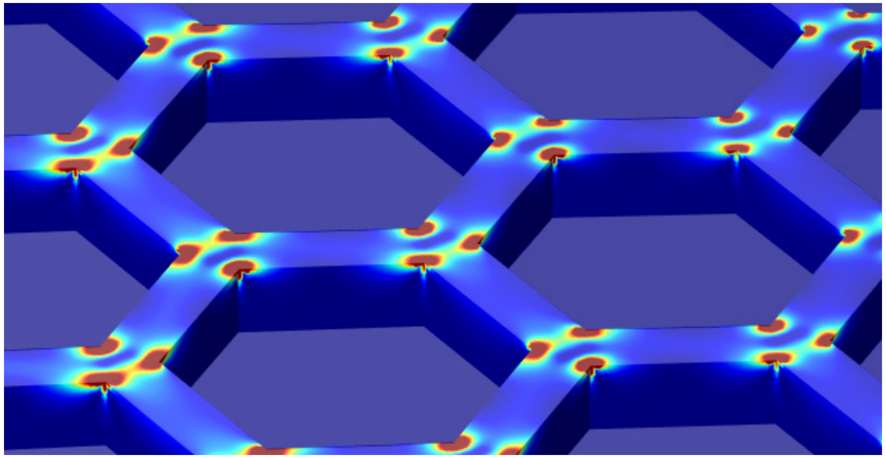
In the stiff direction, the moment of inertia is larger and the stiffness increases by an enhancement factor (EF)

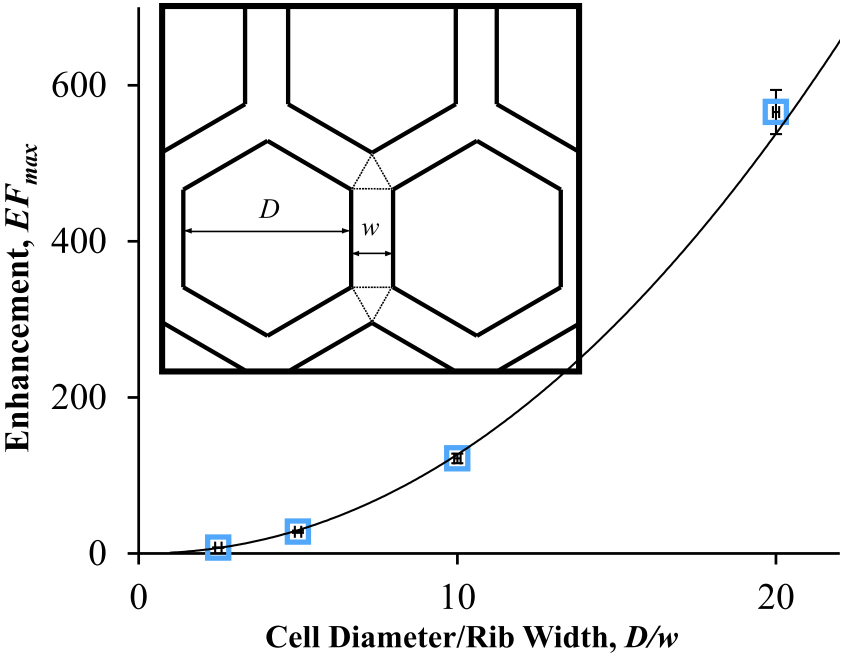
$$EF_{corr} = D_{||}/D_{planar} \propto \left(\frac{h}{t}\right)^2$$

The *EF* depends only weakly on the period of the corrugation and its profile

Our multidirectional corrugation is very different!

From AFM experiments and FE modeling, our honeycomb plates are approximately isotropic and can be characterized by a single enhancement factor in both directions: $EF_{hc} = D_{hc}/D_{planar}$



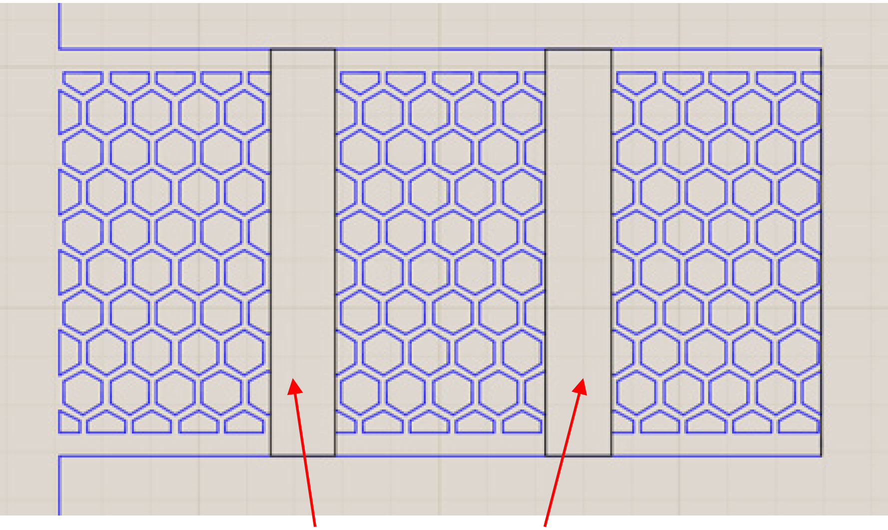


Above a certain height of corrugation (~1 µm), the EF depends only weakly on height and instead is determined by in-plane parameters: $EF_{honecomb} \approx \left(\frac{D}{w} + 1\right)^2$

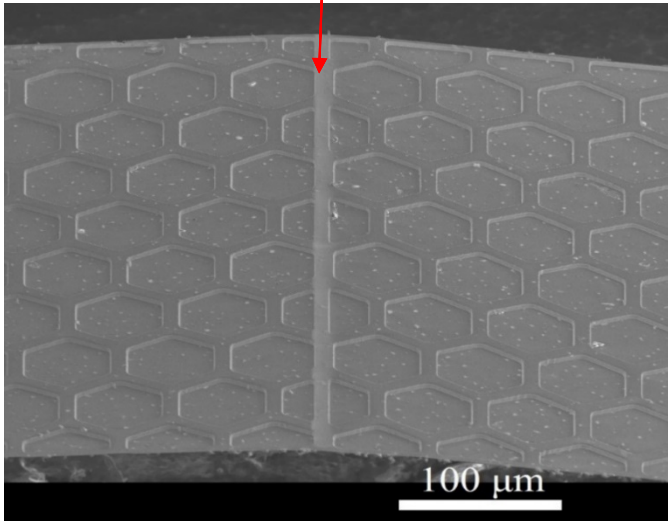
Stiffness increases as the area occupied by vertical ribs decreases!

There is no general analytical theory for plates with multidirectional corrugation

Current project: Folding plates

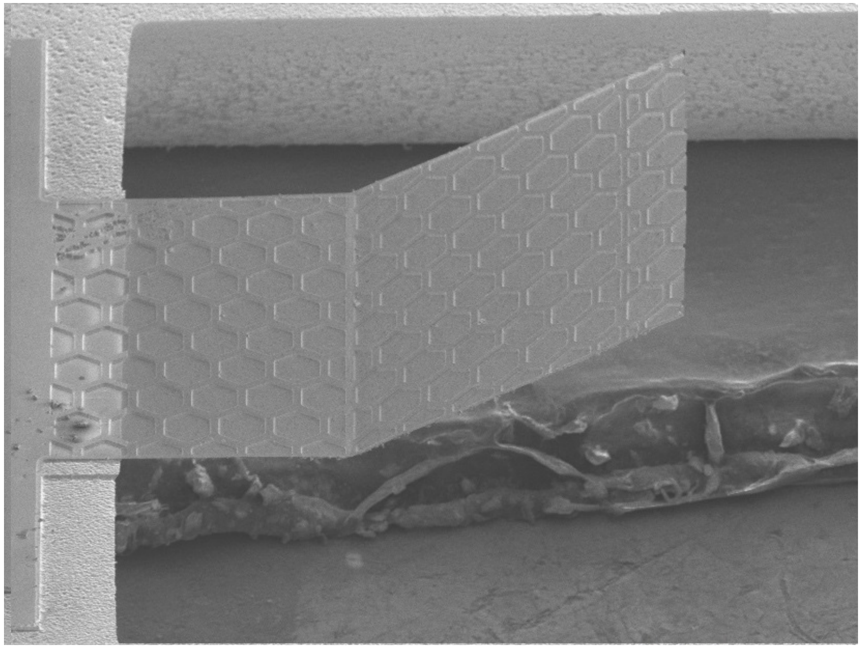


Crease/fold areas



By leaving some areas planar (i.e., not patterned with hexagons) we can create fold lines, creating origami-like foldable structures

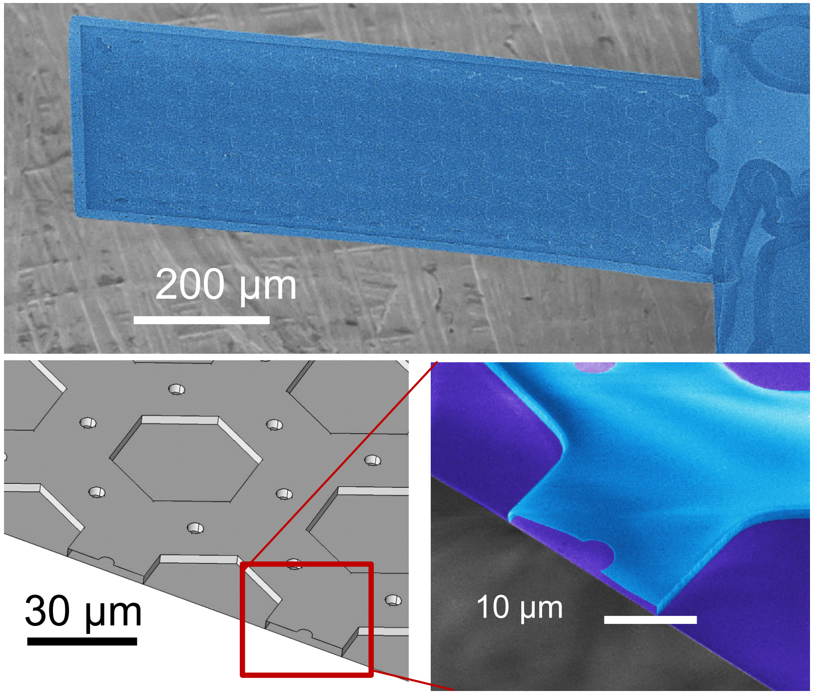
Note that the thickness remains the same everywhere



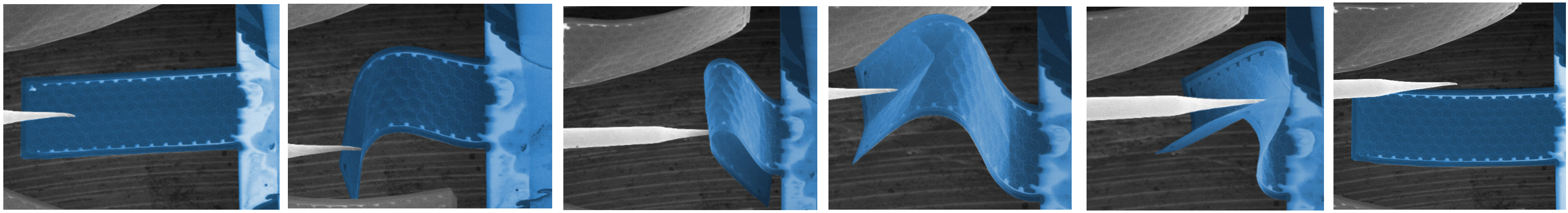
Deforming due to ion beam

Current project: Nanocardboard

https://en.wikipedia.org/wiki/Cardboard



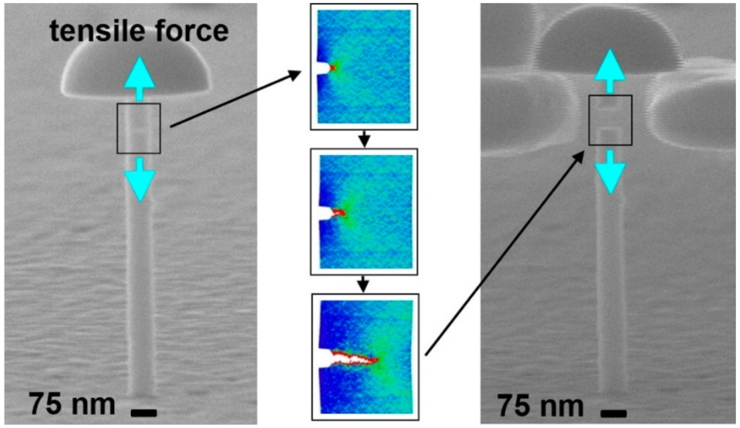
By attaching multiple sheets together, corrugated cardboard can further increase stiffness while preserving low weight and robustness



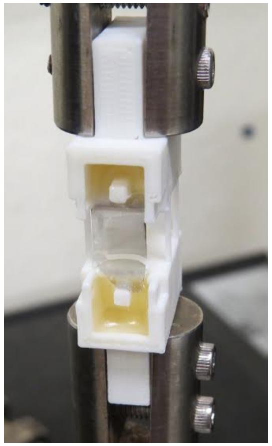
In nanocardboard, we have not seen any irreversible buckling or fractures – surprising and different from the usual cardboard and sandwich composites

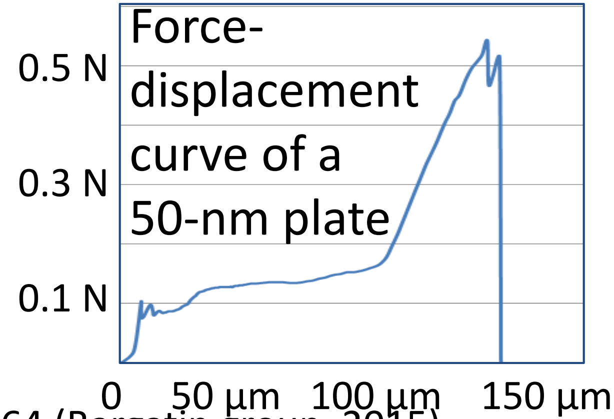
Possible applications

1. Nanoscale size effects on strength of materials in macroscale structures



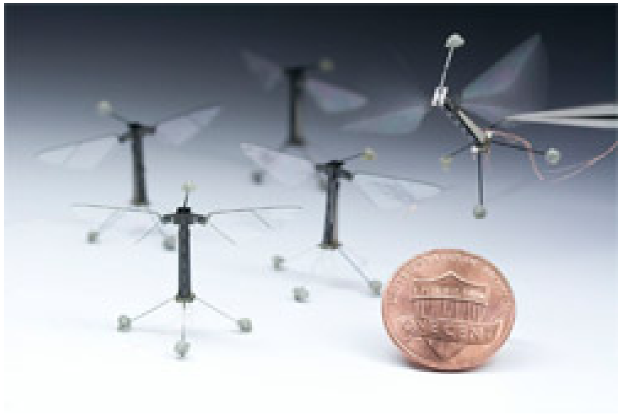
Gu et al, Nano Lett. **DOI:** 10.1021/nl5027869





Instron Model 5564 (Bargatin group, 2015)

2. Materials for microflyers/robots (continuous membranes)



Sources: Wikipedia, http://micro.seas.harvard.edu/

We can make wings more than an order of magnitude thinner and lighter than any wings created by nature (~ 10 µm) or man (>0.5 µm) so far