HAIR Based Sensing and Actuation

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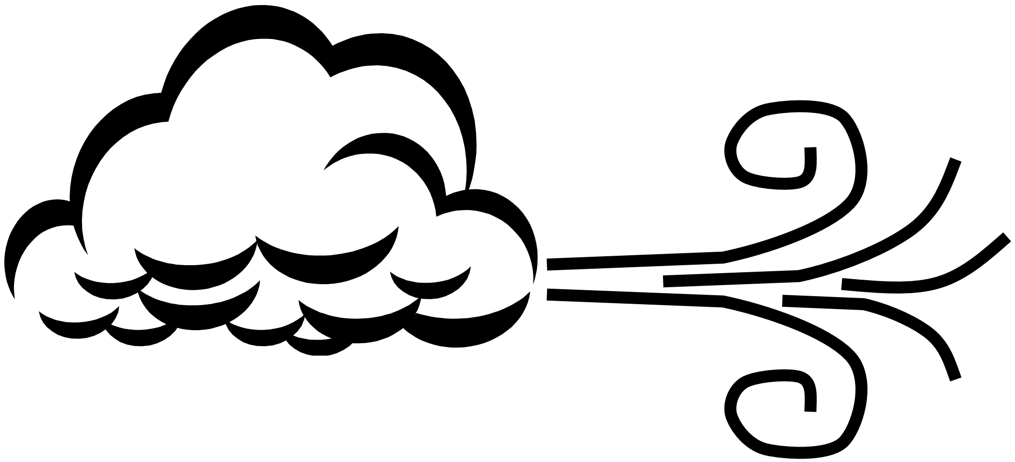
Prescribed by ANSI Std Z39-18

Biomimetic HAIR-Based Sensing and Actuation

- **Our focus: new sensor/actuators to meet constraints (SWaP + cost + performance) for micro air vehicles for ARL's MAST program, where COTS are unsuitable**
- **Example:** *Air flow sensor for wind gust state estimation for stable MAV control*
- MAST air flow sensor requirements
  - Low power, stand-alone, robust
  - Measure gusting air flow in range of 0.1 to 10+ meters/sec
  - Fast sensor response for dynamic flight control: > 30 Hz, ideally 100 Hz
  - Determine gust direction: minimum resolution is four in-plane quadrant directions



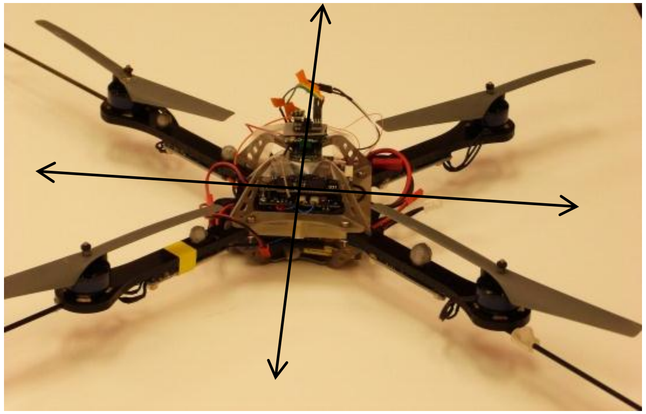
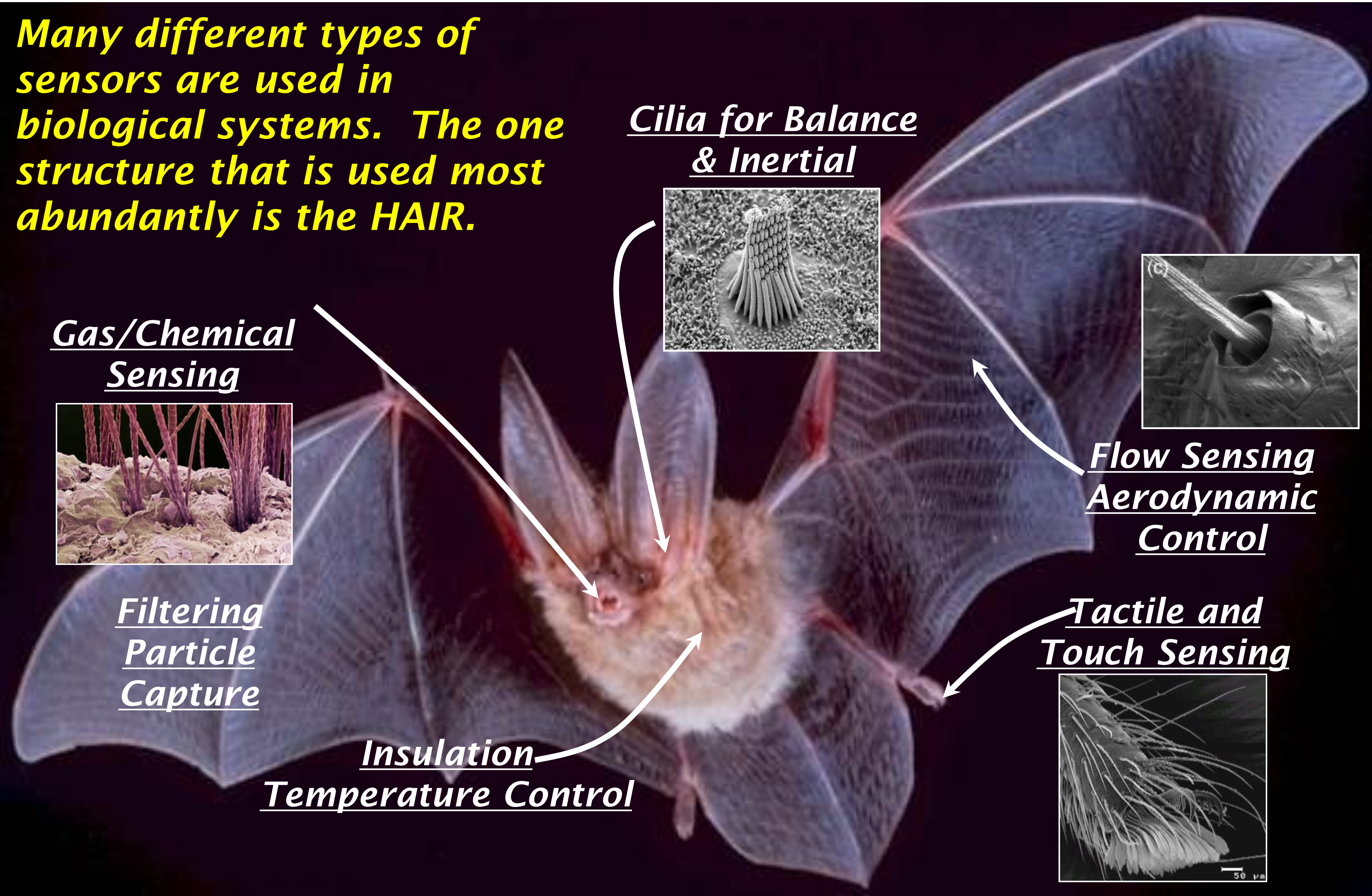
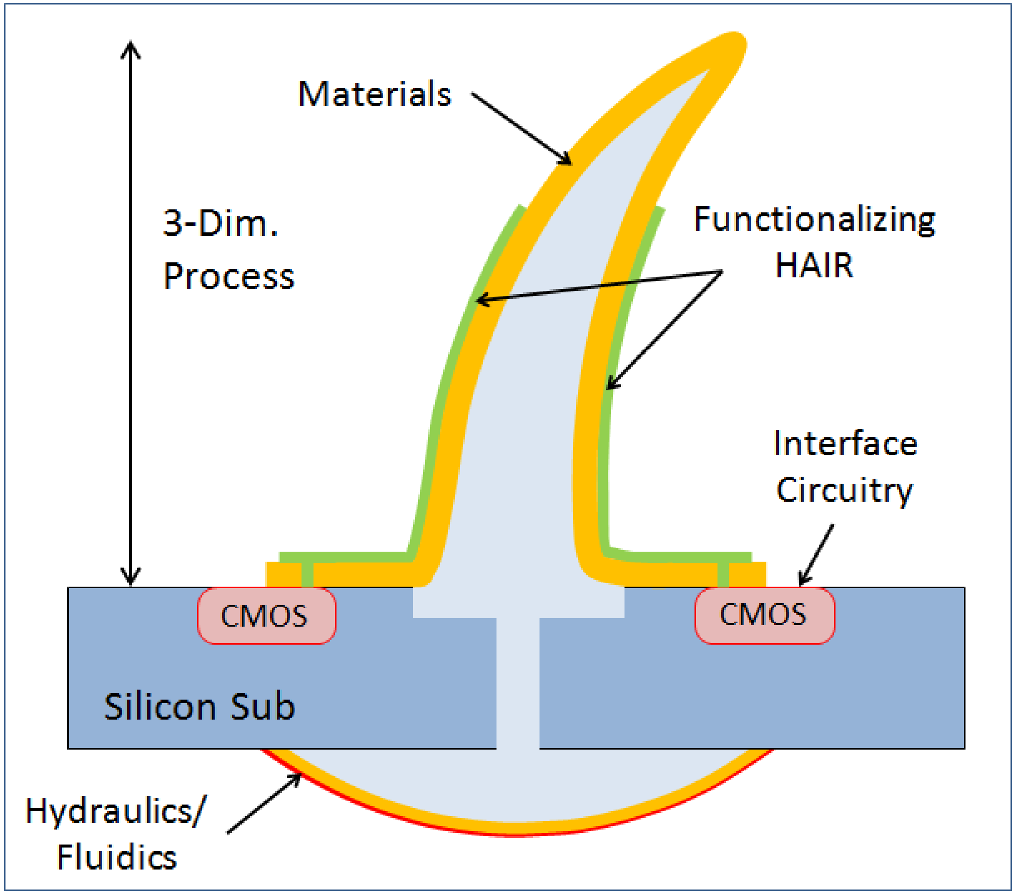


Image of U Maryland (J. Sean Humbert) macro-quadrotor

Biomimetic Sensing

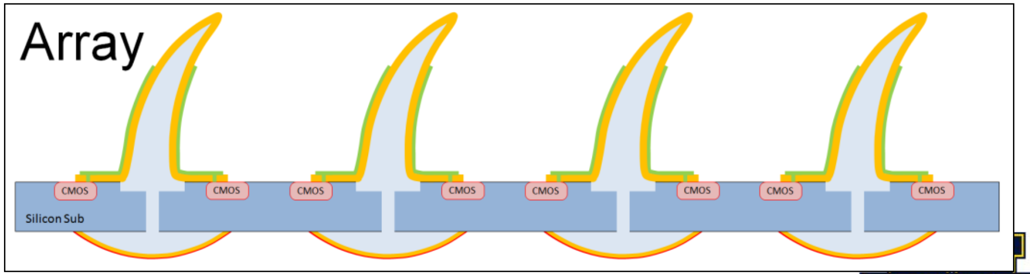


High-performance, Actuation and Integrated sensing Research (HAIR)



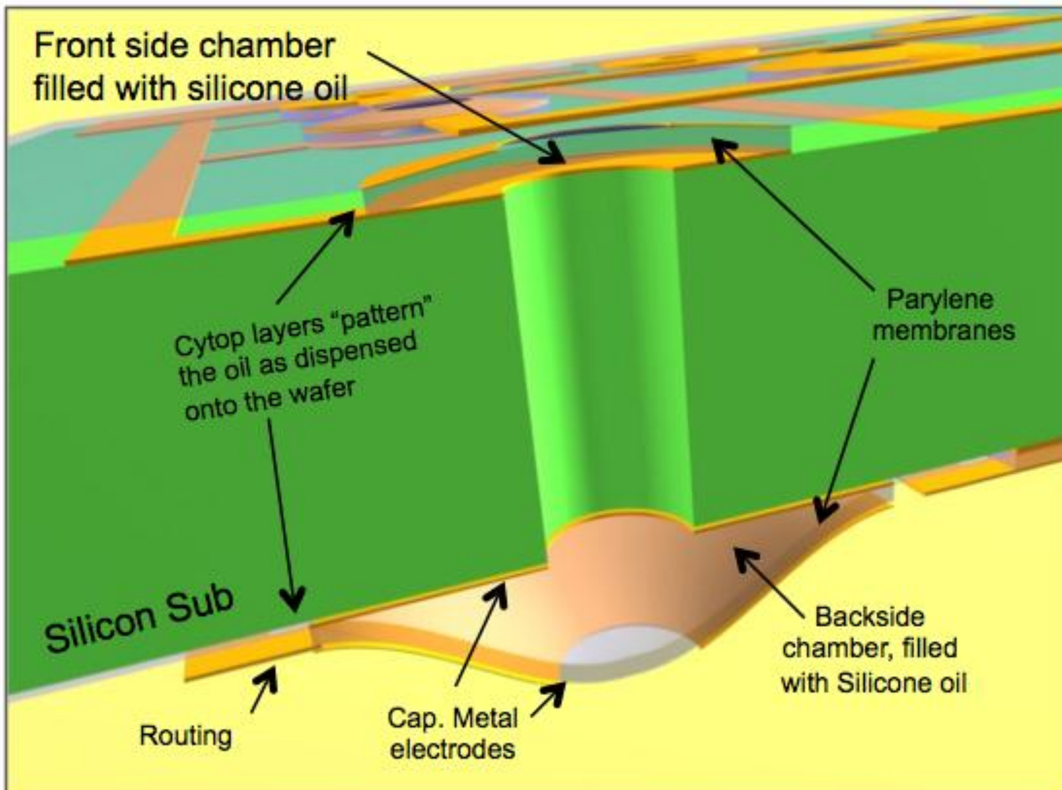
Key biomimetic components

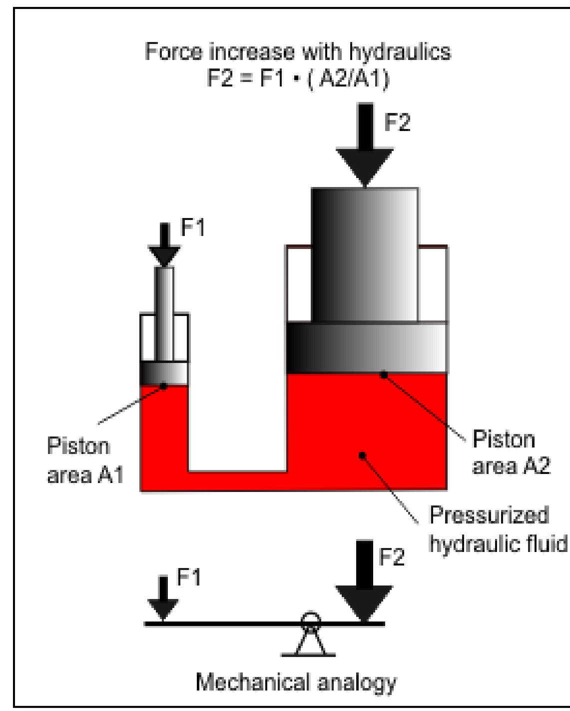
1. Material
2. 3-D Process
3. Hydraulics / fluidics
4. Functionalization
5. Circuit Integration
6. Array



Electrostatic Micro-hydraulics

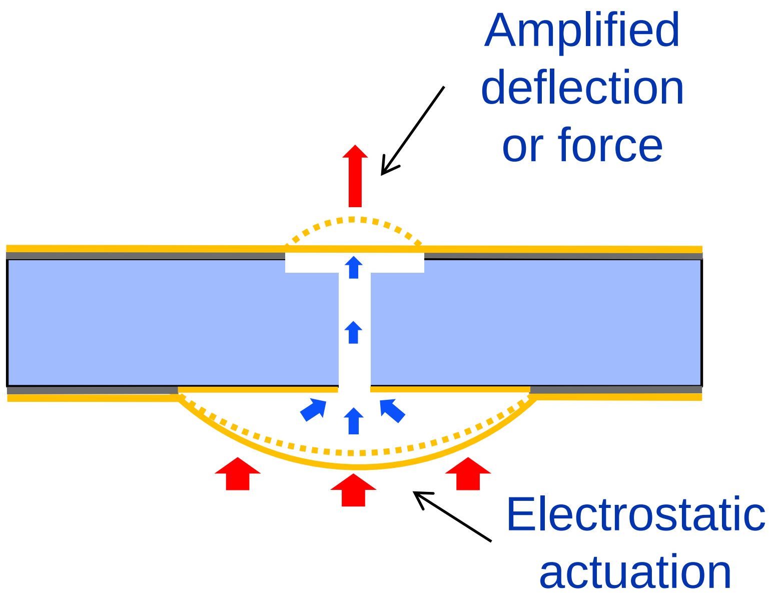
- Key concept: combine electrostatics & micro-hydraulics for large-force, large-deflection, low-power actuation and low-power, high-dynamic range sensing
- Structural features
  1. Two connected chambers on opposite sides of a wafer, capped with membranes
  2. Capacitive metal electrodes allow electrostatic actuation or sensing
  3. Encapsulated incompressible liquid dielectric constant > 1 (i.e., air) increases capacitance thus improving electrostatic coupling





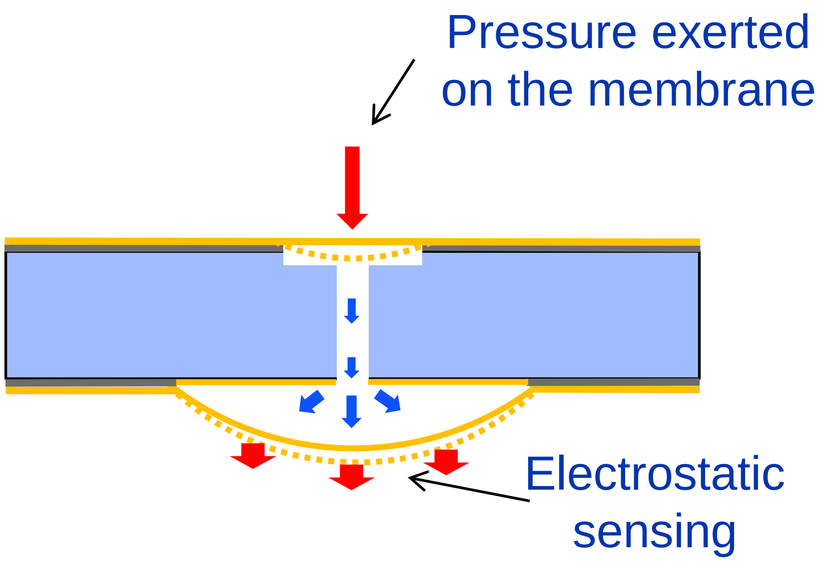
Sensing & Actuation through Micro-Hydraulics

Actuation Mode



- **Electrostatic actuation**
- Hydraulic amplification of force or deflection

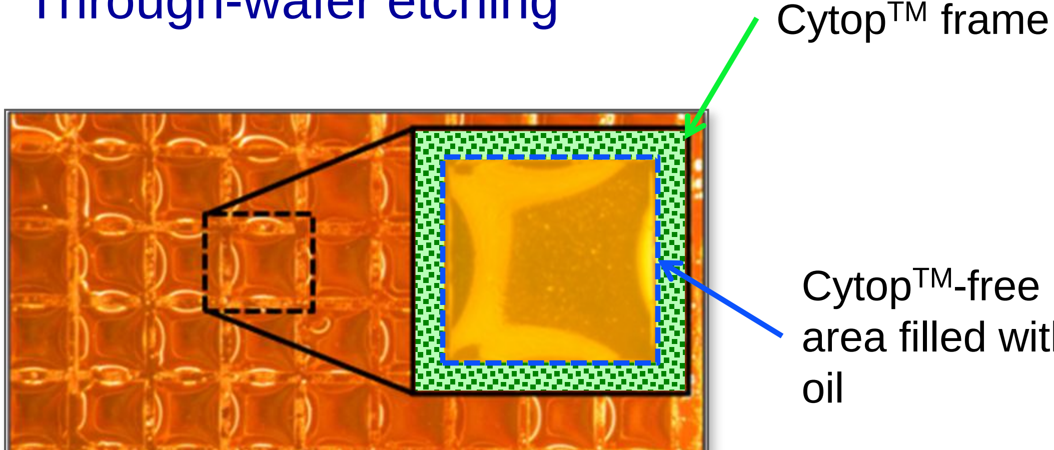
Sense Mode

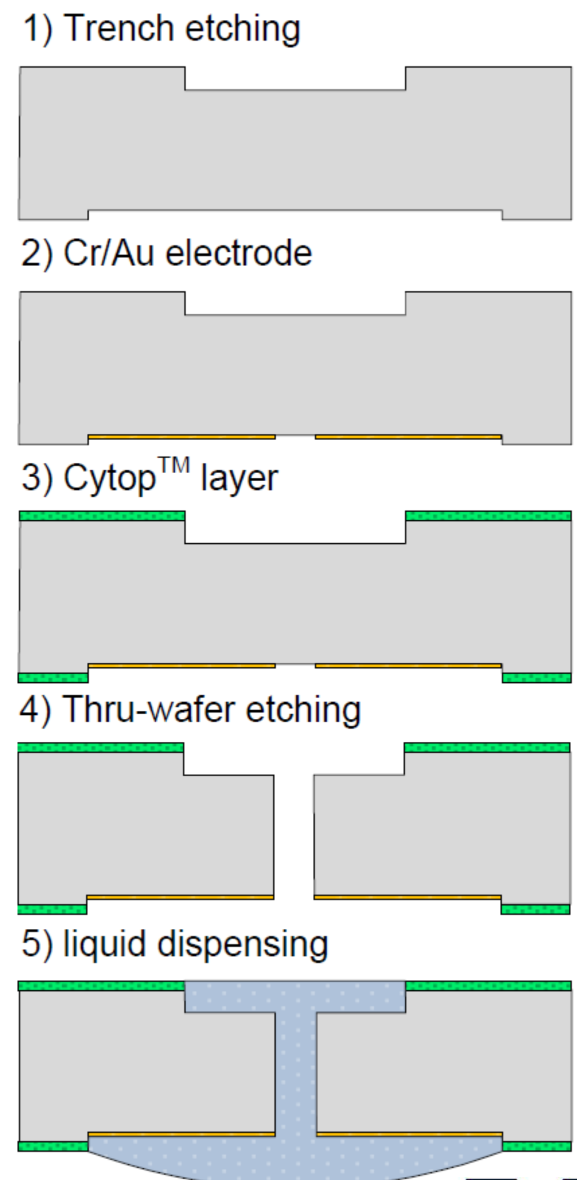


- External pressure applied (via touch, air flow, etc.)
- Hydraulic amplification of force or deflection
- **Electrostatic Sensing**

Micro-Hydraulic Fabrication Process

1. Recess on both sides
   - Definition of capacitance gap
   - **Shape formation** of the liquid
2. Electrode on one/both side(s)
   - Actuation and/or sensing
3. Cytop™ layer and channel formation
   - Hydrophobic layer repels the silicone oil
   - Liquid will be contained in all the Cytop™-free areas
4. Through-wafer etching

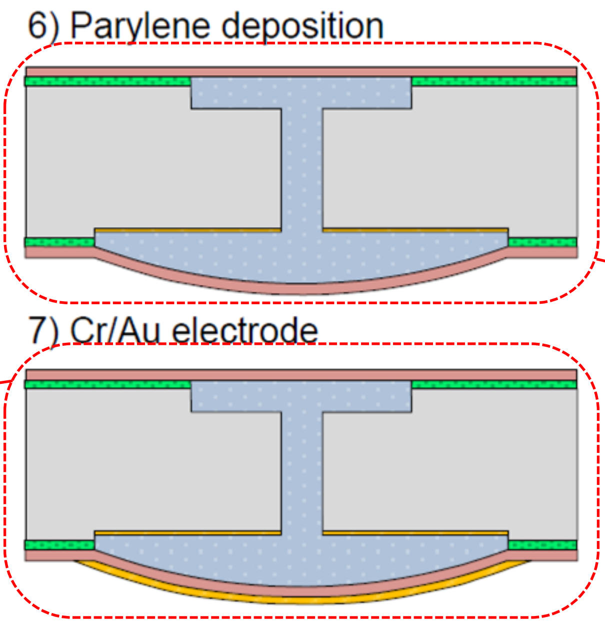




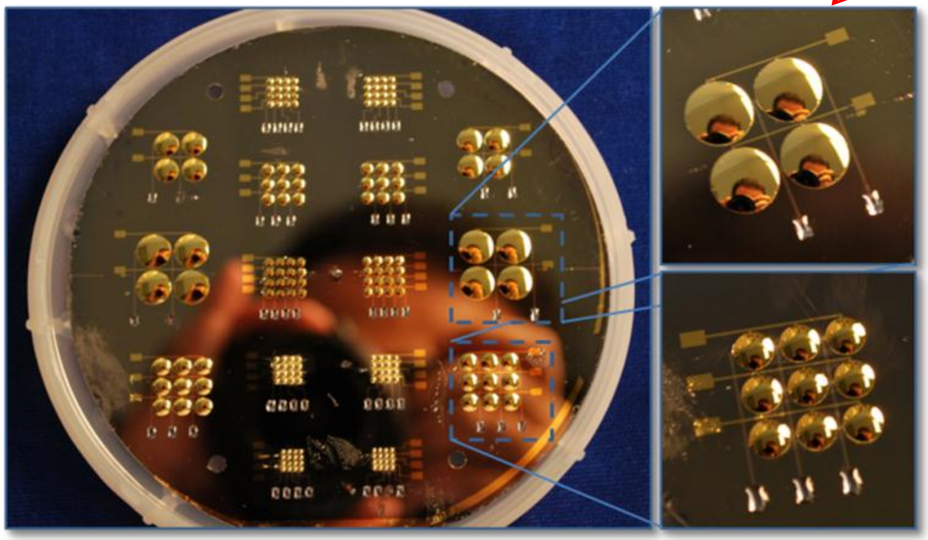
Sadeghi, Kim and Najafi, Digest MEMS 2010, pp. 15-18

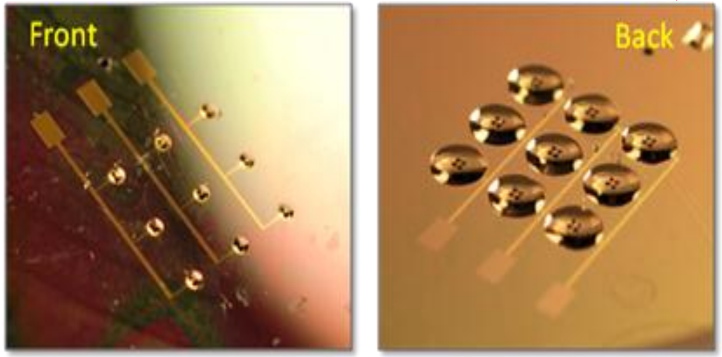
Micro-Hydraulic Fabrication Process

5. Liquid dispensing
   - Liquid weight and surface tension on the back side are at equilibrium
   - → **double-sided process**
6. Parylene coating
7. Second electrode deposition



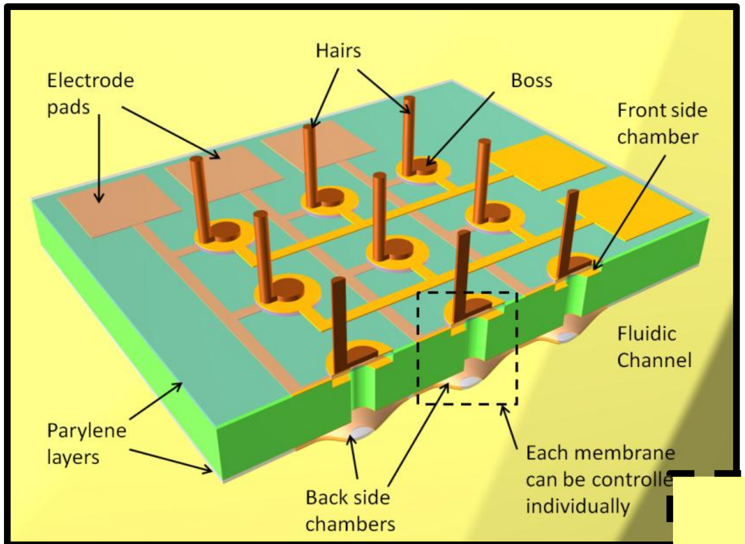
Wafer level process for bubble-free liquid encapsulation

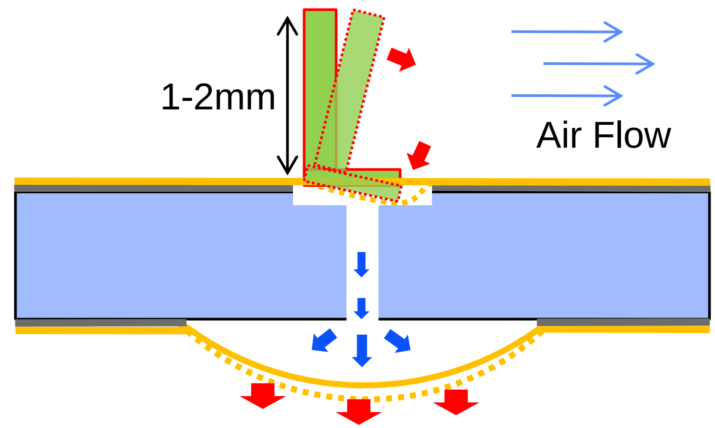




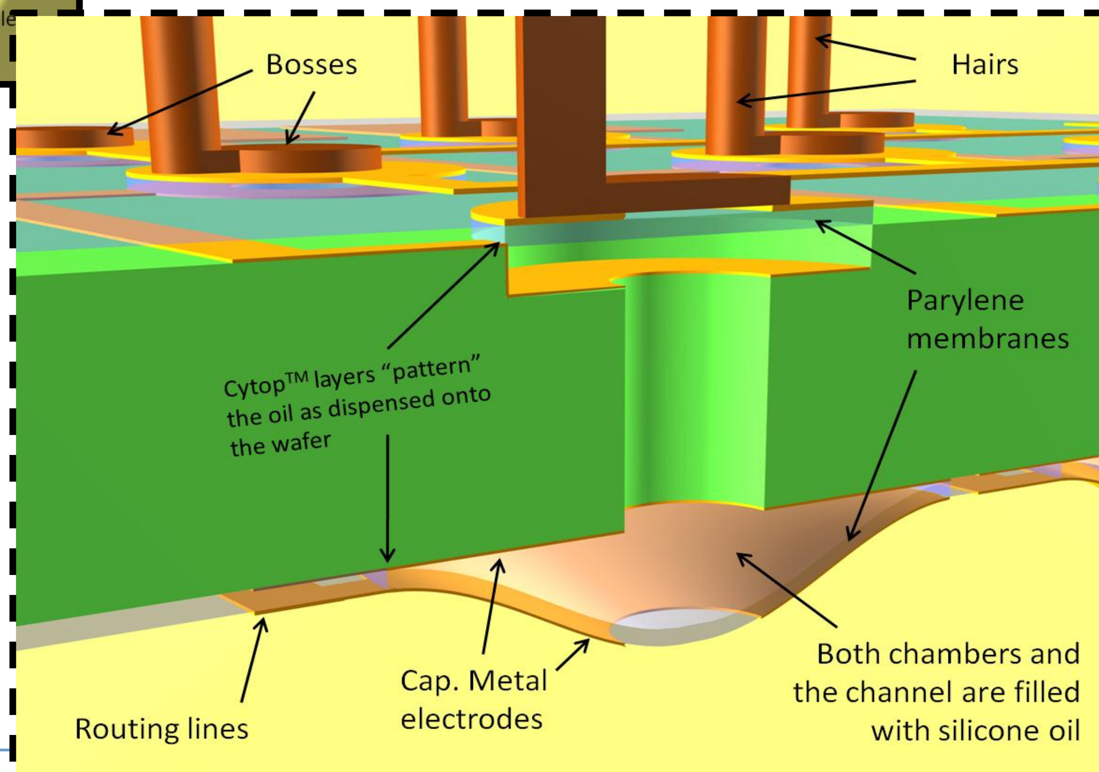
Sadeghi, Kim and Najafi, Digest MEMS 2010, pp. 15-18

Airflow Sensor using Micro-Hydraulics



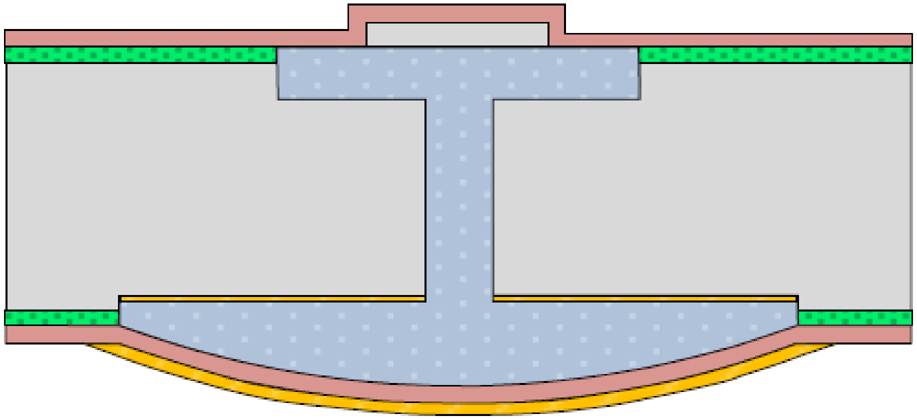


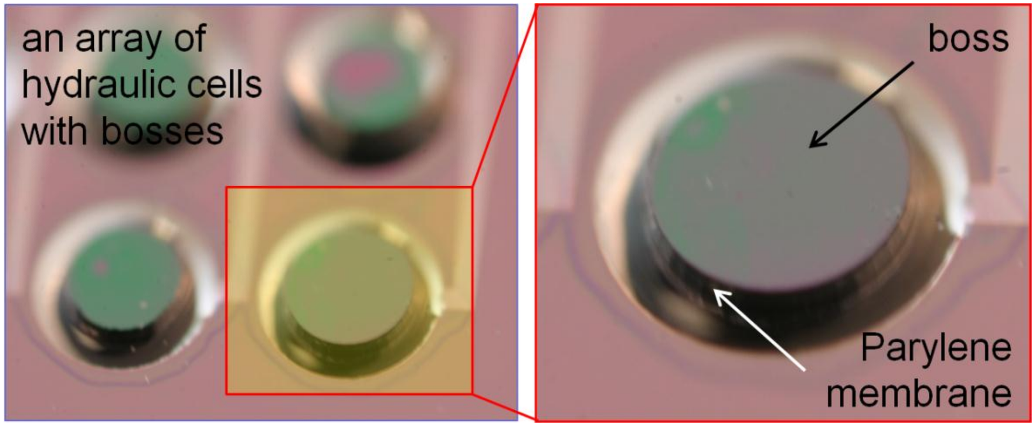
- **3-D boss + hair**: converts fluid drag force into pressure
- **Micro-hydraulics:** converts ΔP into capacitance change
- **Arrays:** offer sensing of flow directionality

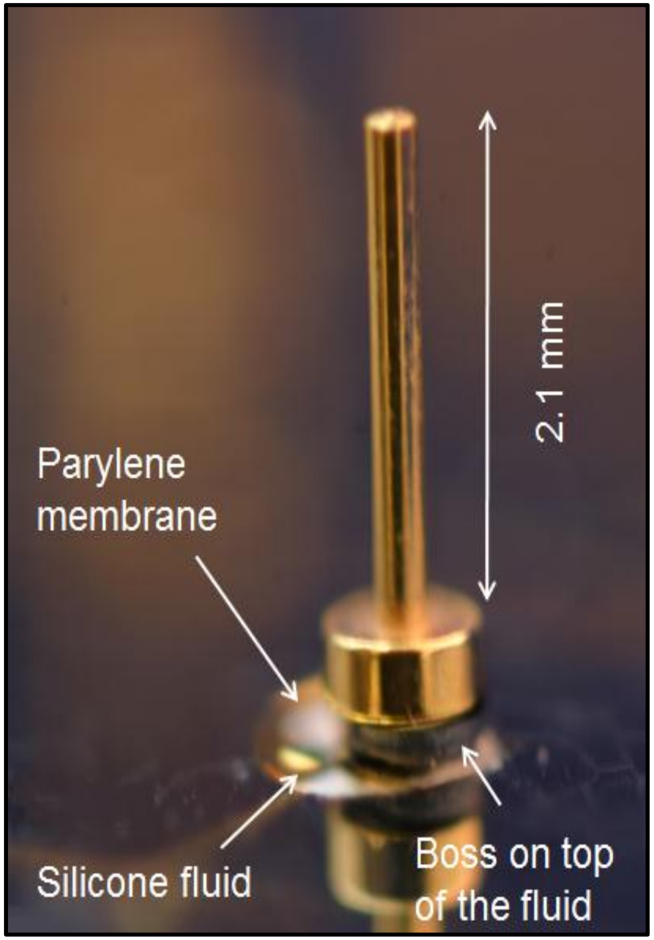


Integration of Boss

- Self-aligned silicon boss acts as platform for attaching hairs
  - Boss is placed after liquid dispensing
  - After Parylene encapsulation, cilia is attached over boss

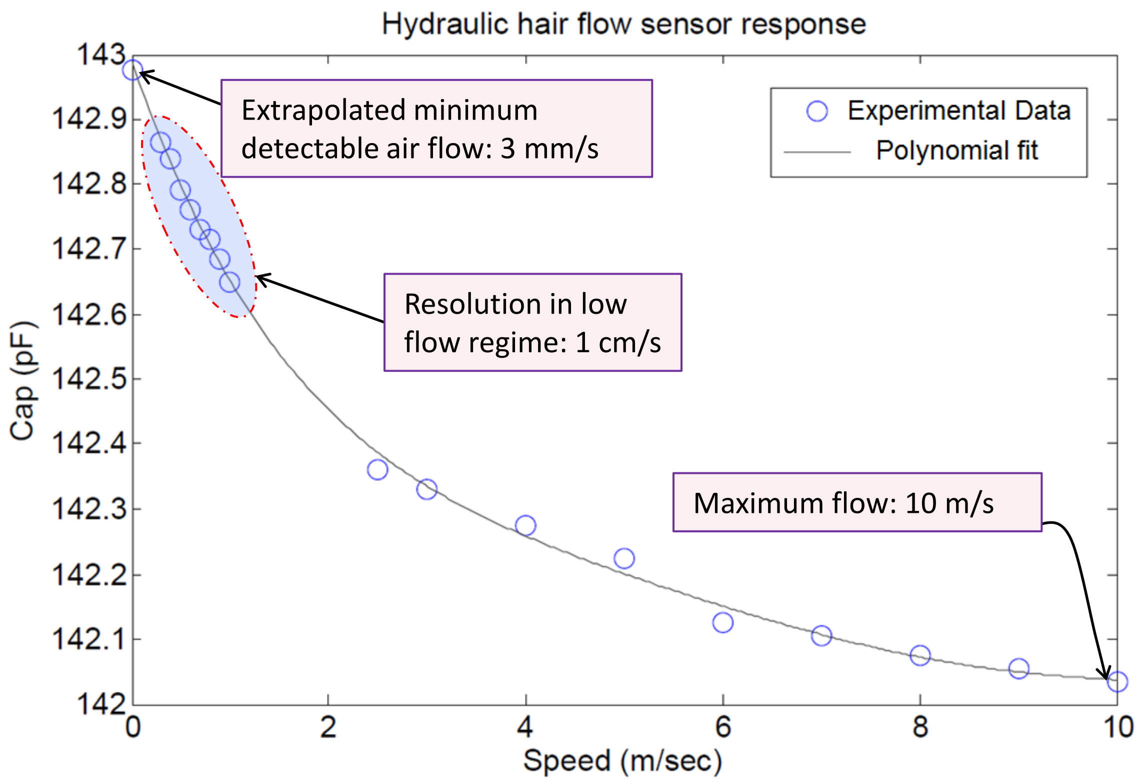






1st Generation Device, Experimental Results

- Average sensitivity* = 333 fF/(m/s)
- Extrapolated minimum detectable air flow: **3 mm/s** assuming 1fF ΔC detection
- Full scale range : **10 m/s**
- **But slow time response**

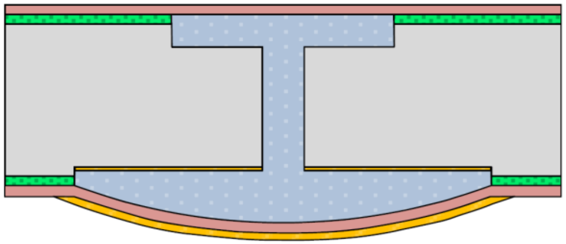


Sadeghi, Peterson and Najafi, Digest IEDM 2011, pp. 29.4.1-4

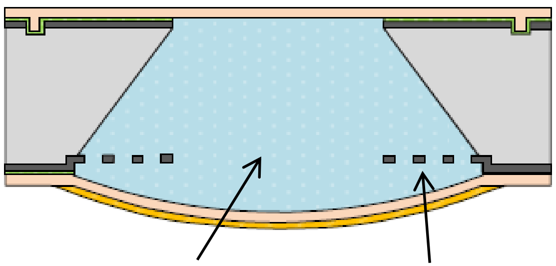
* Tests on multiple samples of the same size yielded sensitivities of 230 to 440 fF/ms^{-1}, with an average of 333 fF/ms^{-1} over 10 m/s range (based on 5 samples)

Reducing sensor response time

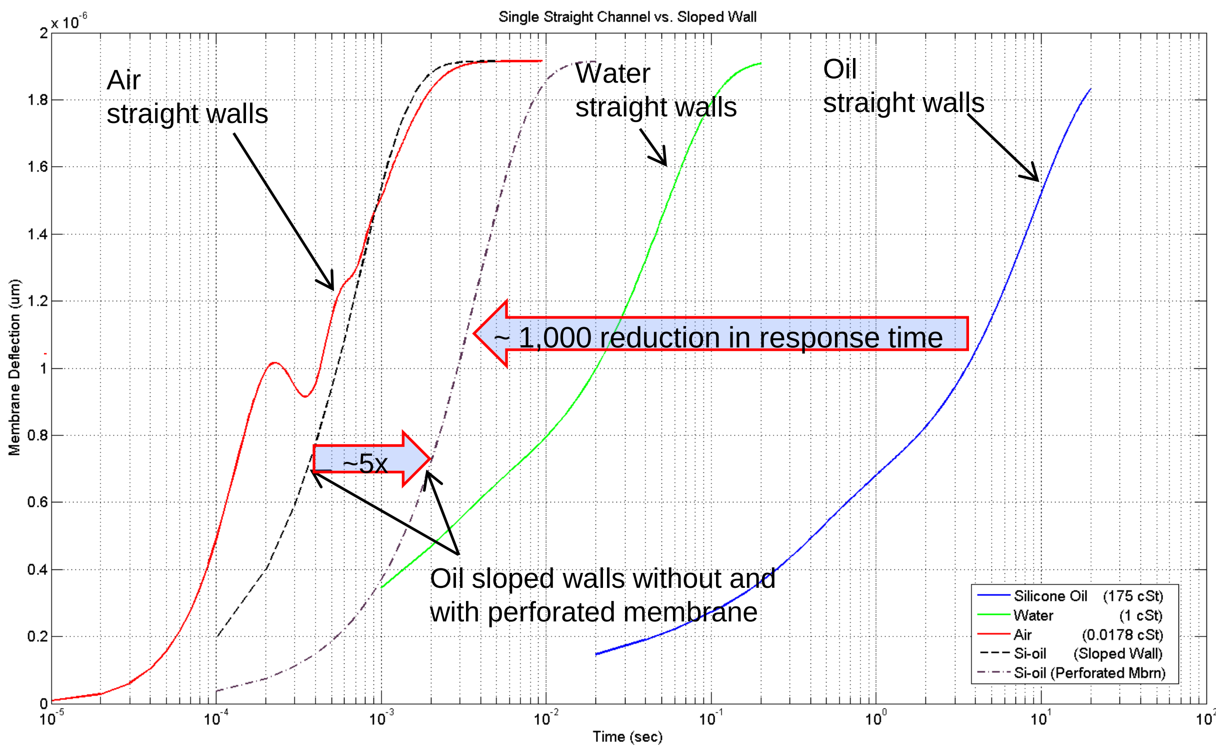
Straight wall channel



Sloped wall channel



Straight vs. Sloped Walls Response time



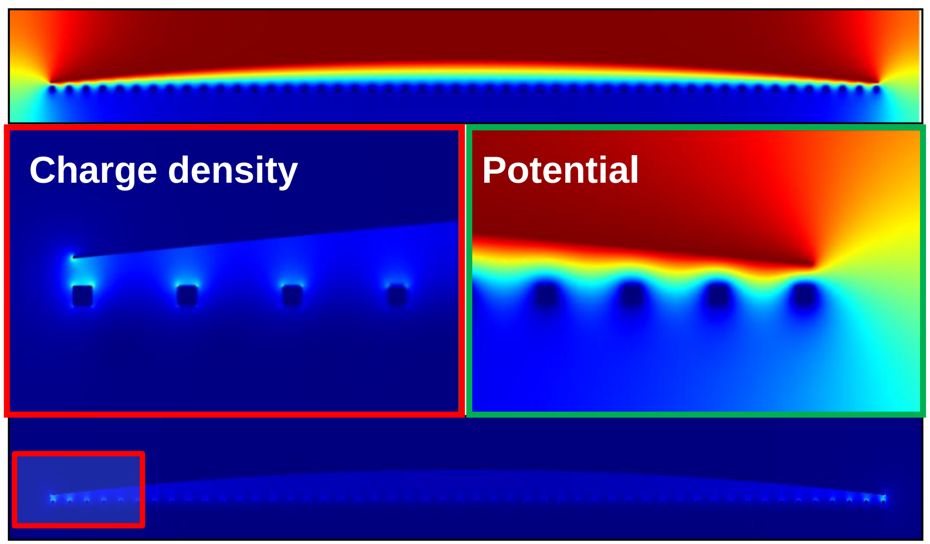
- Could reduce viscosity of fluid, but integration challenges
- Sloped wall design sufficiently reduces response time by ~1,000x

FEM to optimize perforated membrane

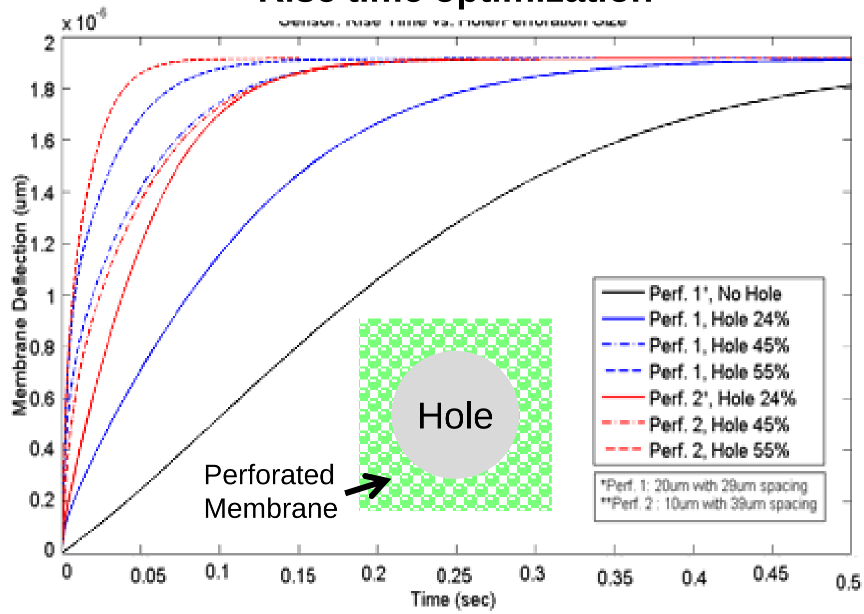
- Trade off between area (i.e. capacitance and therefore sensitivity) and fluidic resistance (i.e. time response)
- Optimize Parylene thickness for symmetric rise/fall response → 2µm

Greatest capacitance contribution comes from edge where gap is narrow → put hole in membrane

Using perforations at periphery speeds up fluid flow but only slightly reduces capacitance



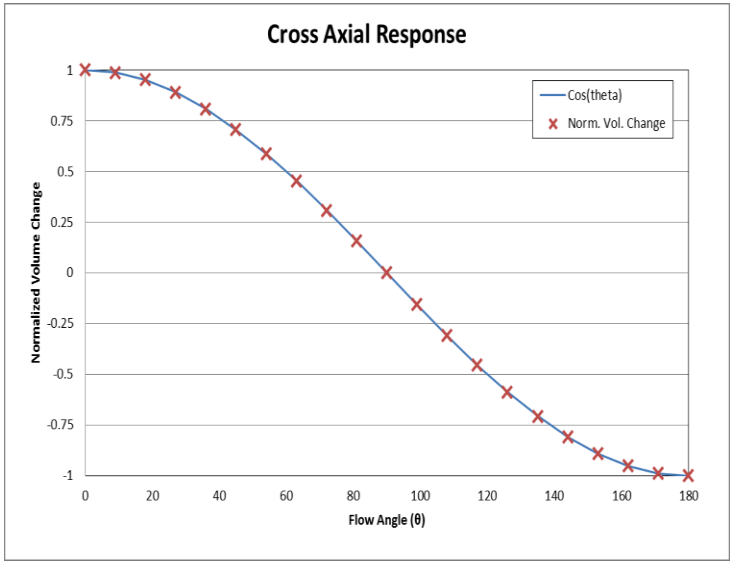
Rise time optimization

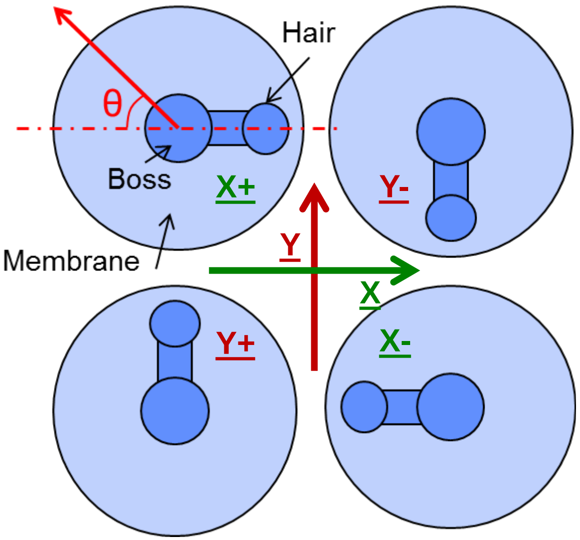


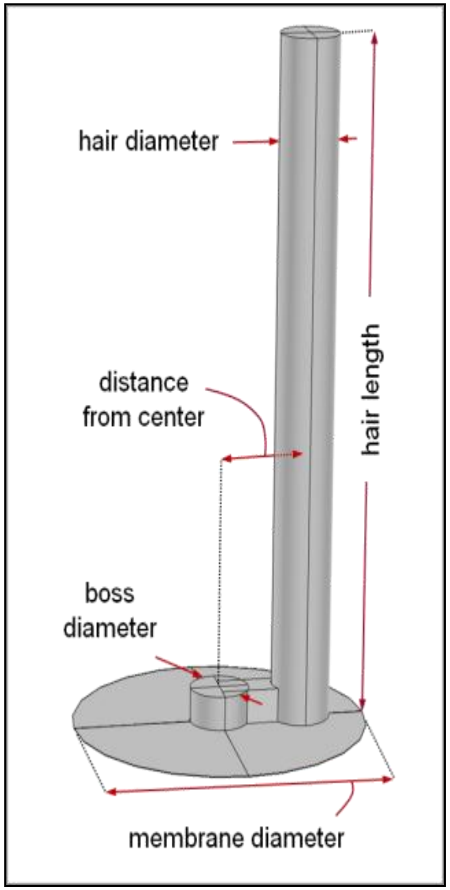
Hair placement and sensor array for directionality

- **Optimize hair/boss location**
  - Hair location to maximize membrane deflection → 56% of radius
  - Boss size to maximize deflection → 50µm

- **Directional Sensing**
  - Four cells / two pairs, each responsible for one direction

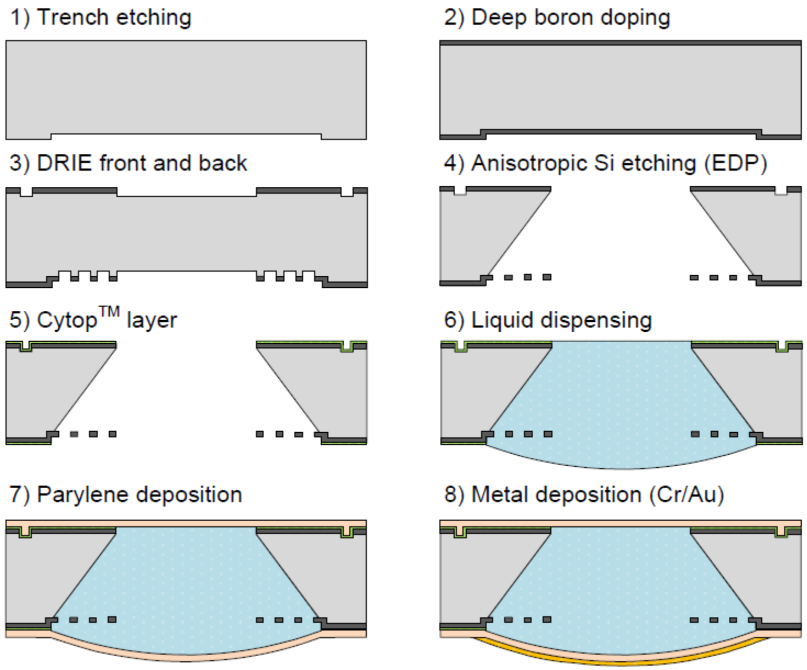


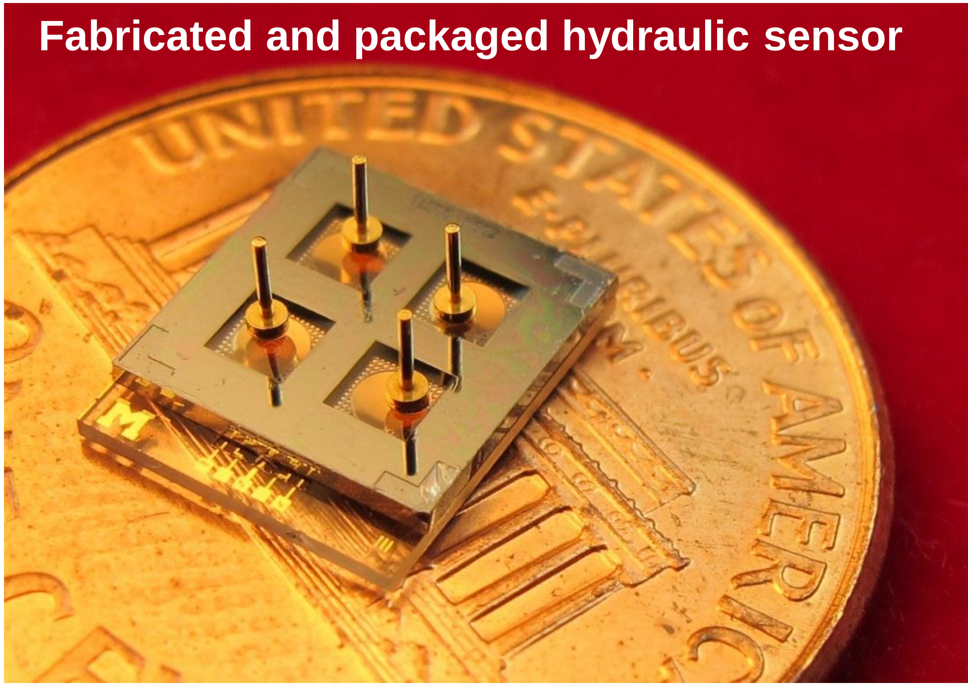


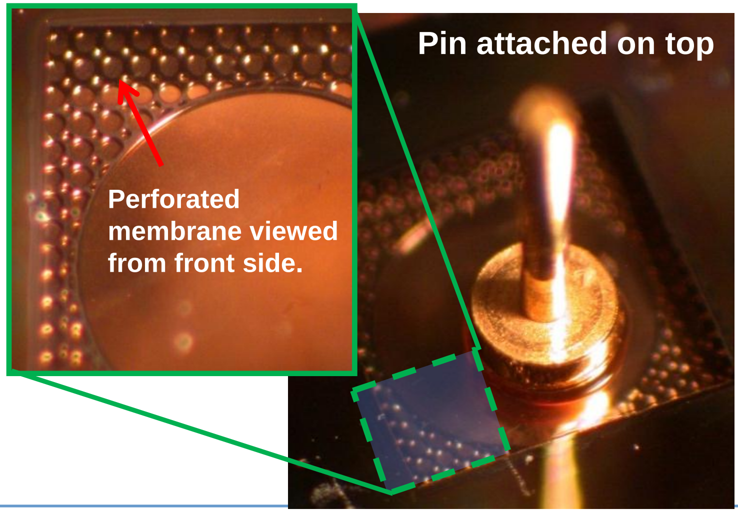


2nd Generation Hydraulic Fabrication

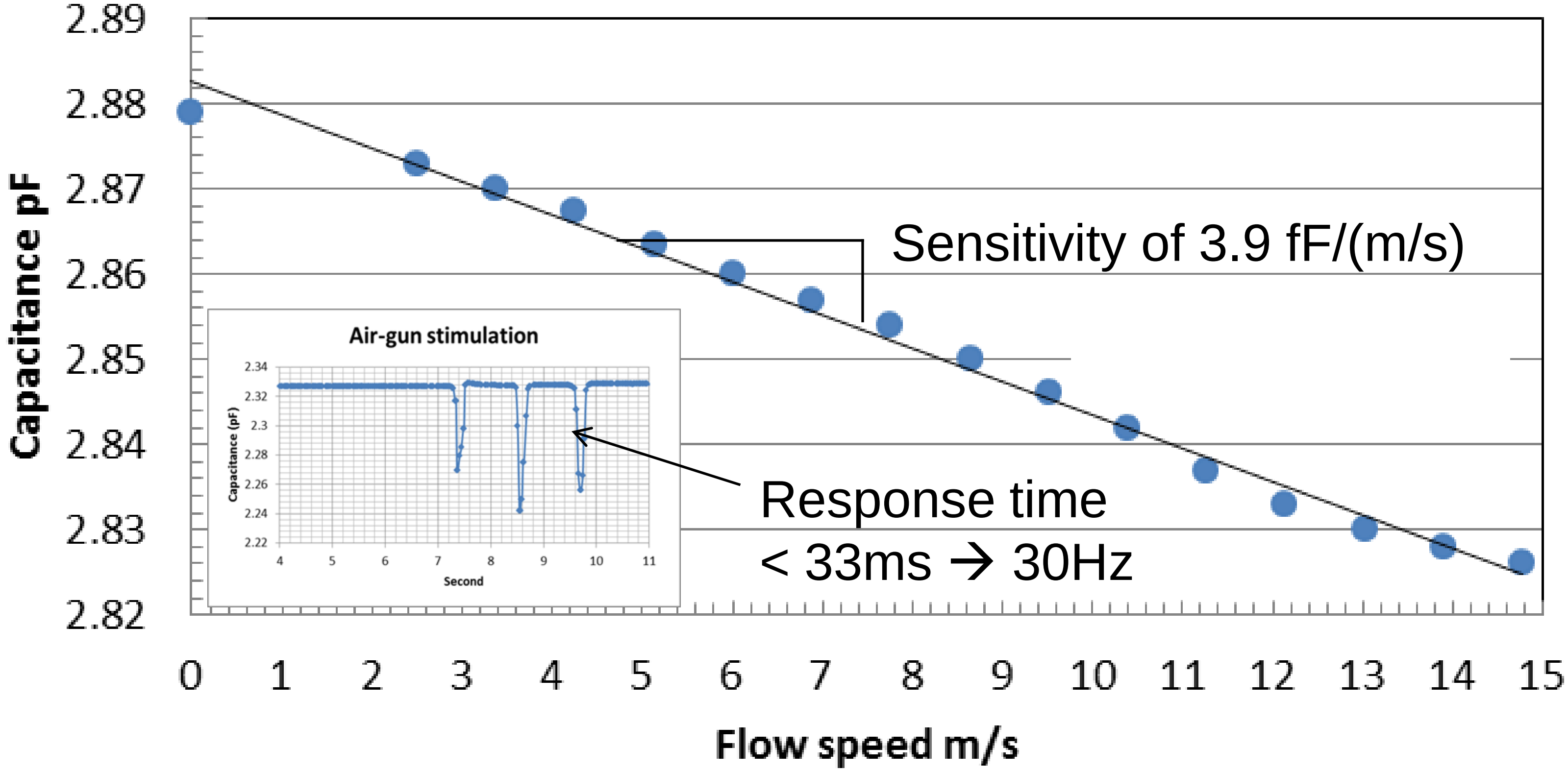
New process steps





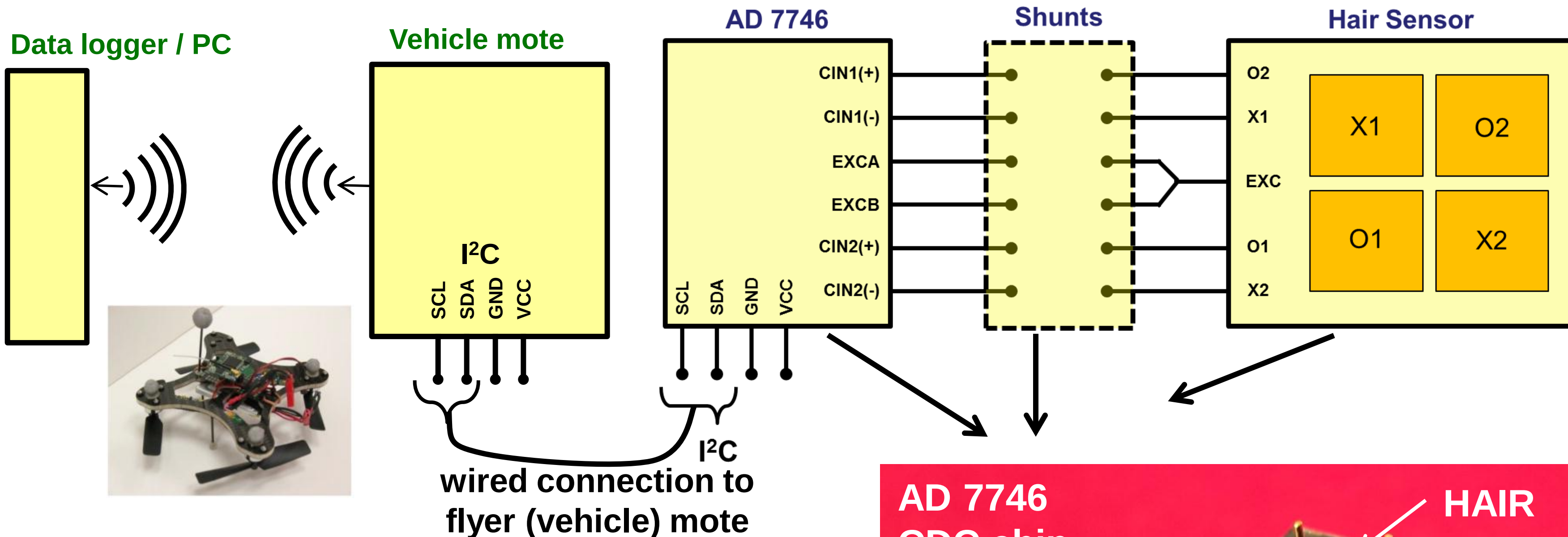


Wind Tunnel and Air gun Tests



- Linear sensor output with sensitivity of 3.9 fF/(m/s) air flow
- **Full scale range: > 15 m/s**
- **Resolution: ~ 2 cm/s**, when in single-ended mode (noise = 80 aF)
- **Response bandwidth ~ 30 Hz**

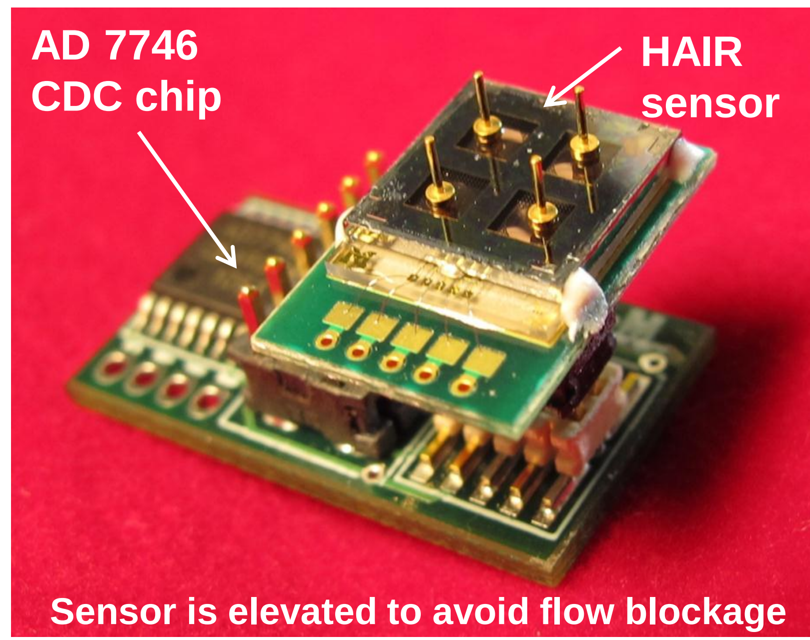
Air Flow Sensor Integration & Performance Summary



Range*	0 – 15 $m.s^{-1}$
Sensitivity	3.9 fF/(m/s)
Resolution*	~2.0 $cm.s^{-1}$
Response time	~30 ms
Supply	3.3 -5 V
Power	3.5 mW
Weight**	1.2-1.5 g
Output	I^2C

* When read in single ended mode. Resolution in 2 channel mode is ~0.5 m/s, and the range decreases to approx. 2.5-15 m/s.

** 1.2g without header, 1.5g with header

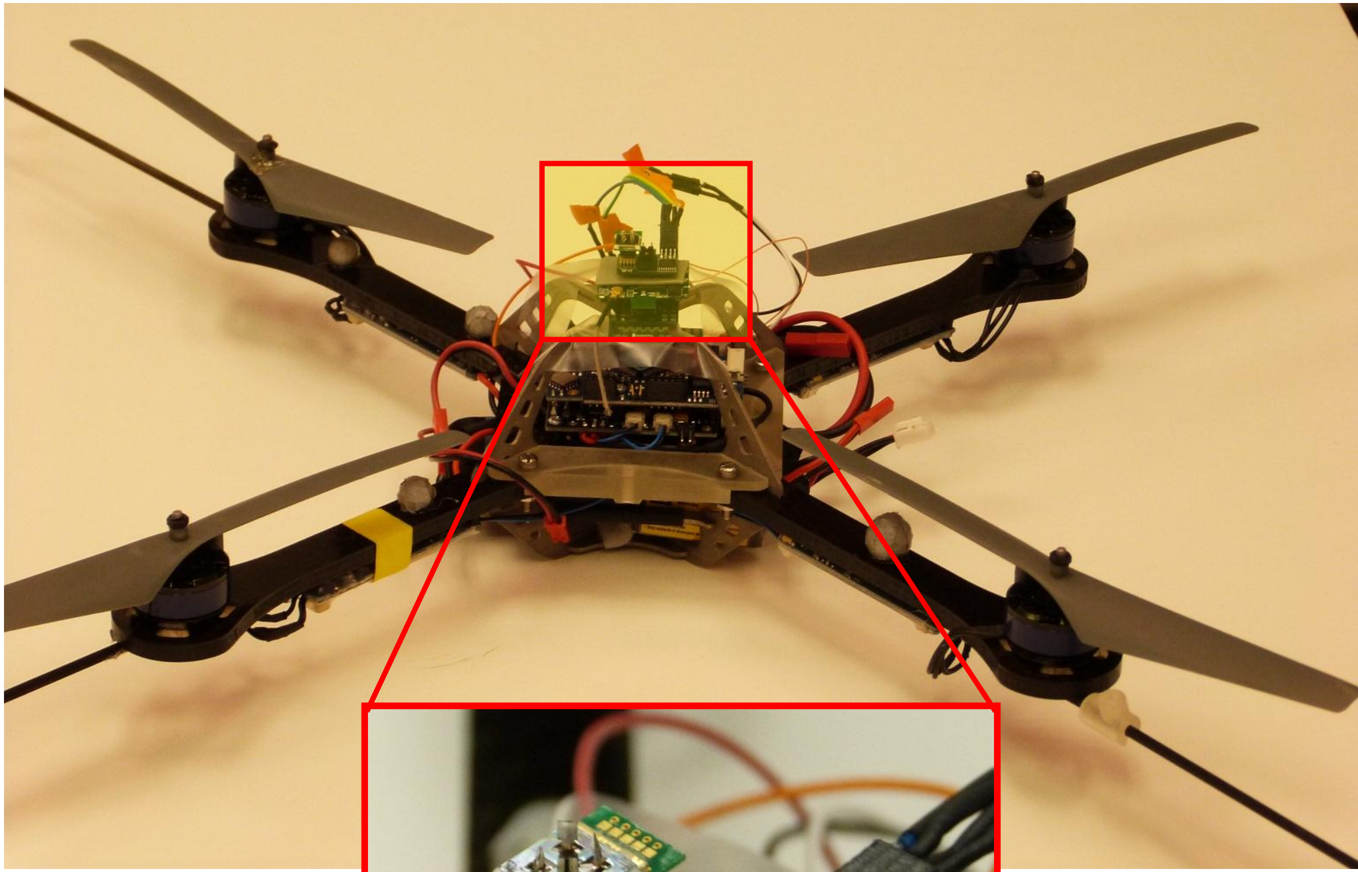


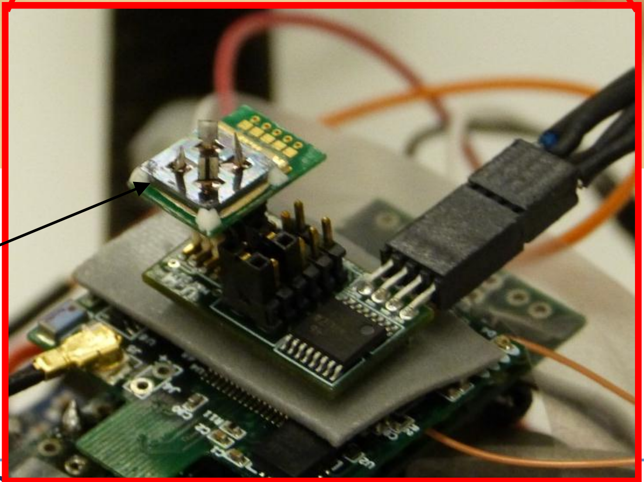
Air Flow Sensor Integration on Flyers

Collaboration with Prof. Sean Humbert, UMD

Wind gust detection with hydraulic HAIR directional air-flow sensors:

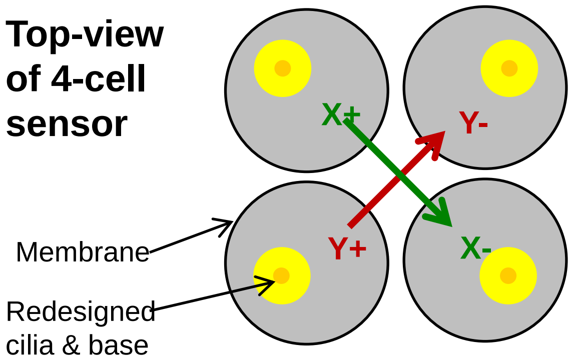
- ✓ Sensor is integrated with flyer mote
- ✓ Data transfer established
- ✓ Closed loop control of vehicle forthcoming

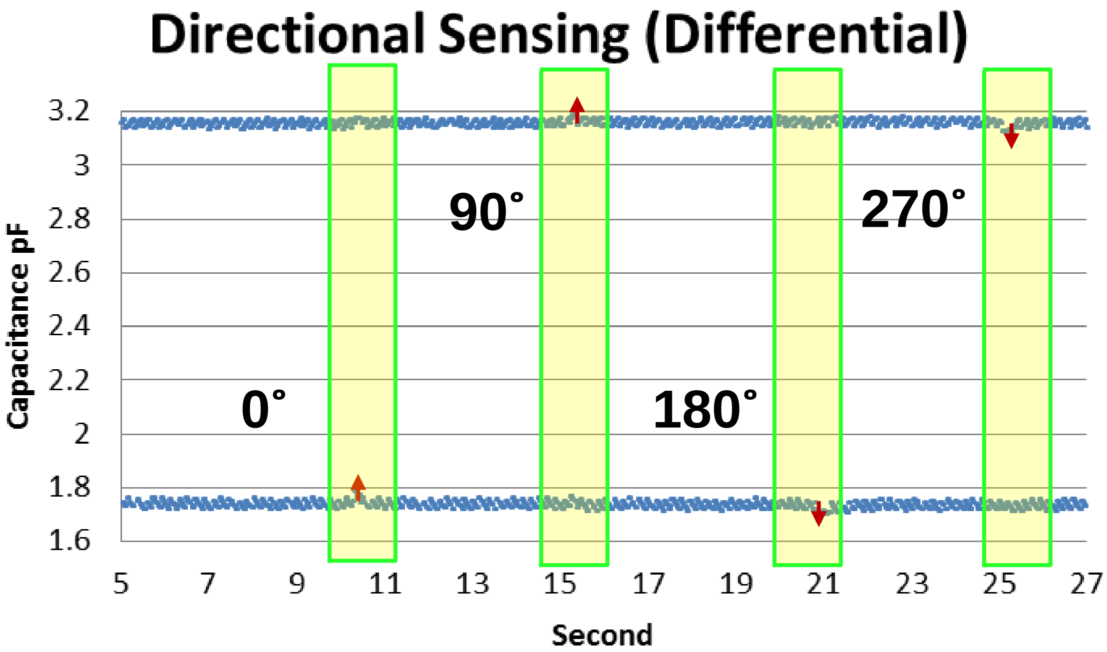




Air flow sensor and circuit

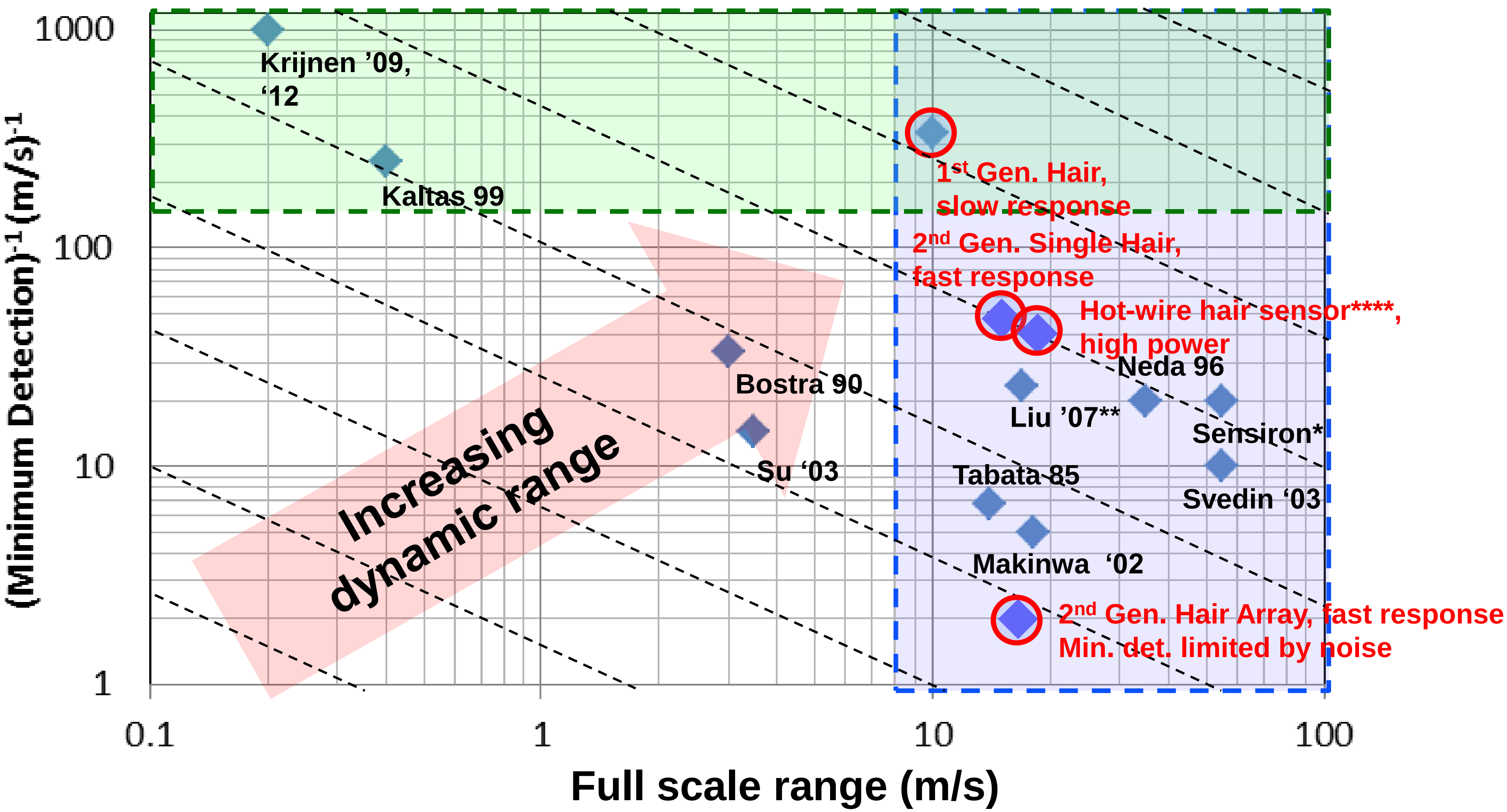
Preliminary Results on Directional Sensing





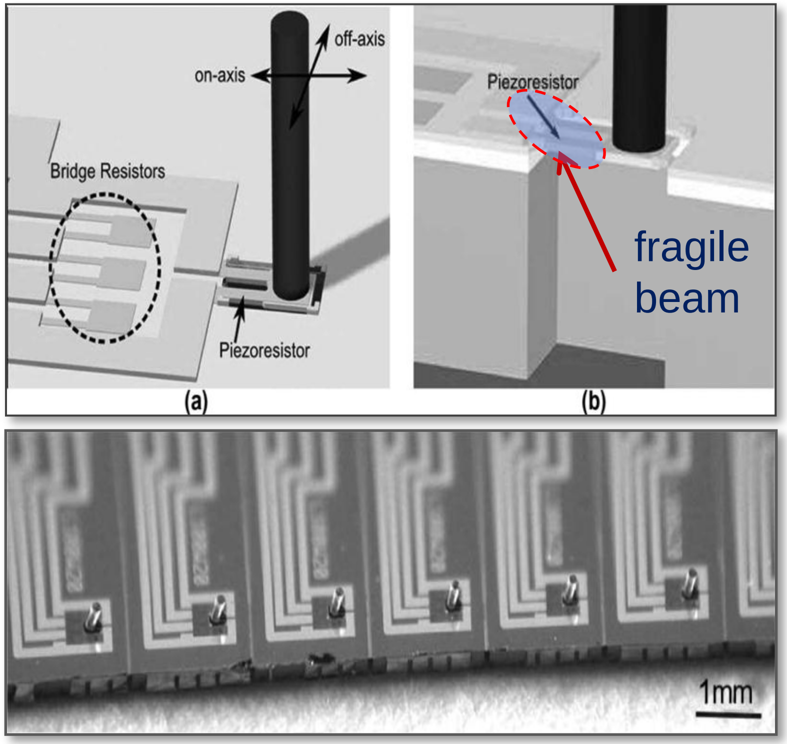
- For dynamic flight control, need flow directionality
- Redesign cilia + two sensor pairs for in-plane flow vector determination
- Each pair is differentially measured by AD7746 CDC
- Resolution is reduced due to ~100x higher noise level: noise increases from 80aF (single-ended mode) to 10fF (dual channel mode)
- Circuit improvement are ongoing

Trade off between full-scale range and min. detection

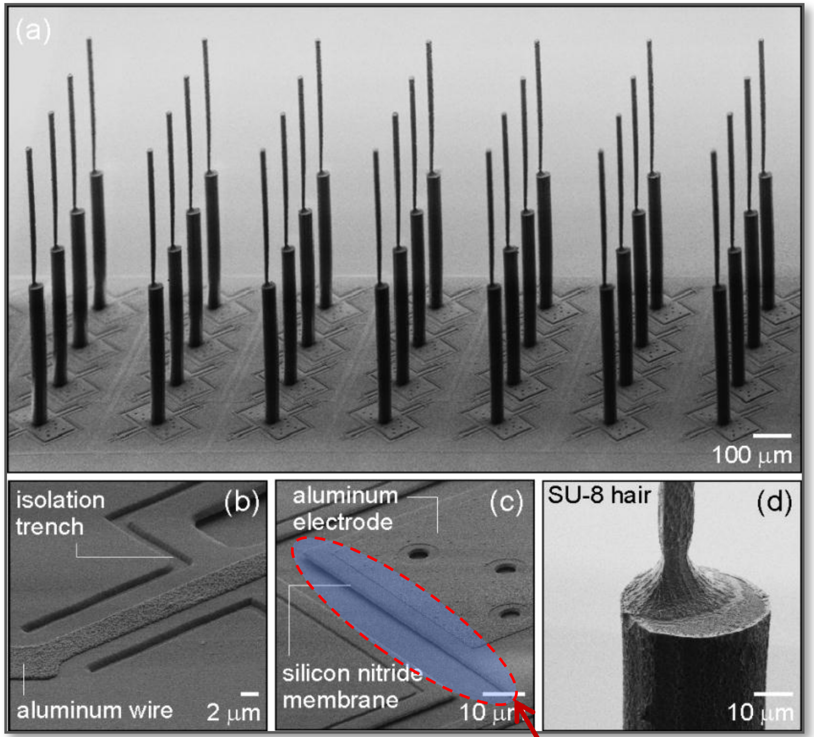


* One of the finest commercially available MFS, Converted data from DS
** The paper states min det. for water flow, not air. 5cm/s is based on our calculation
*** Minimum detection limits for data points that are not stated clearly are extracted from measurement graph data points, or assumed to be 0.01 of full-scale range.
**** Published at the Army Science Conference 2010 by Sadeghi, Peterson & Najafi

Alternate Hair-Sensing Schemes



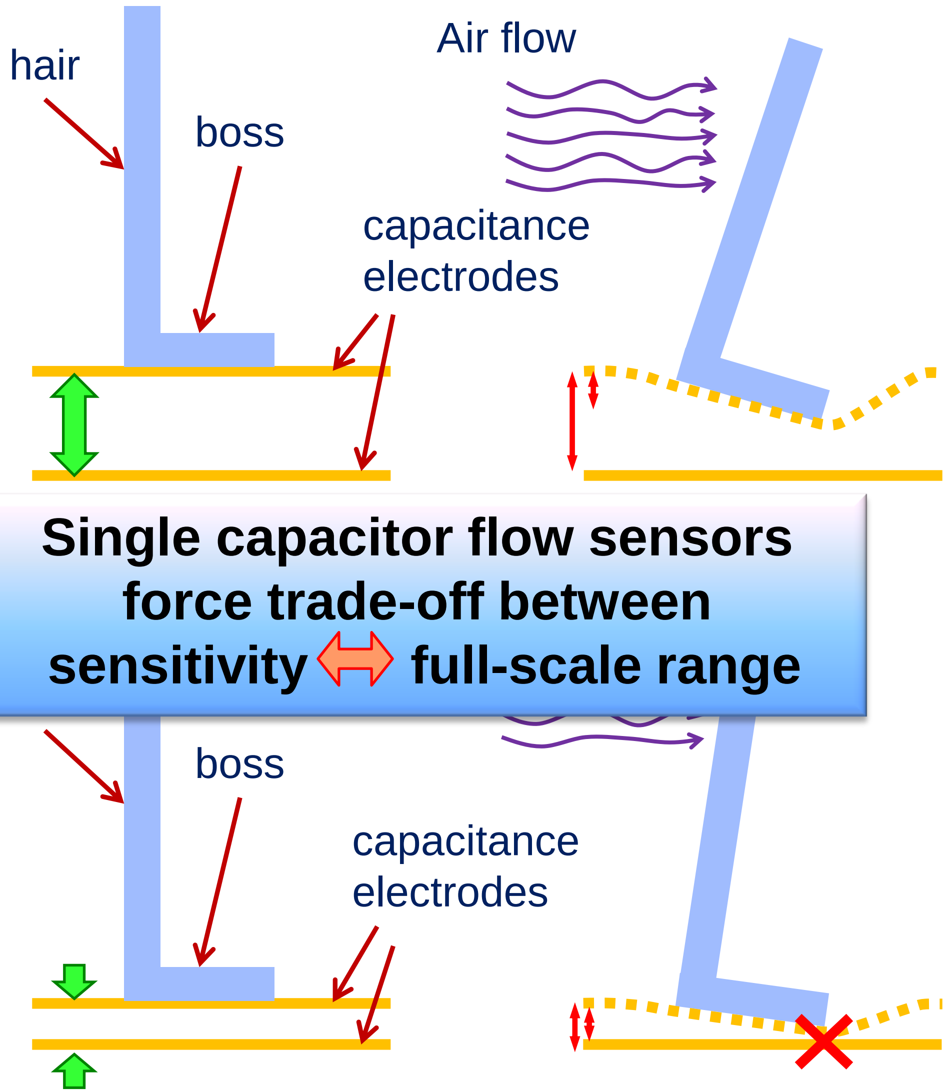
Chang Liu, et al. JMEMS 2007



G.J.M. Krijnen, et al. MEMS '09

- Existing approaches: Exposed piezoresistive beam or capacitive gap
- Liquid encapsulation encloses the capacitive gap, offering **robustness and improved dynamic range/resolution,** and **enables new applications** such as sensing in liquid or harsh ambient environments

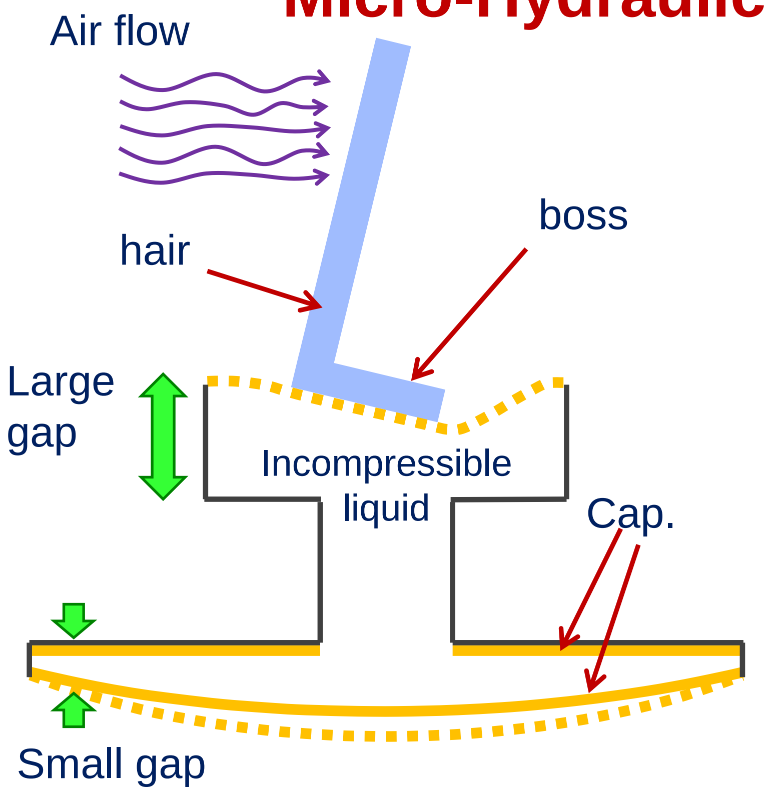
Single Capacitive Flow Sensor vs. Micro-Hydraulic



Single capacitor flow sensors force trade-off between sensitivity ⇔ full-scale range

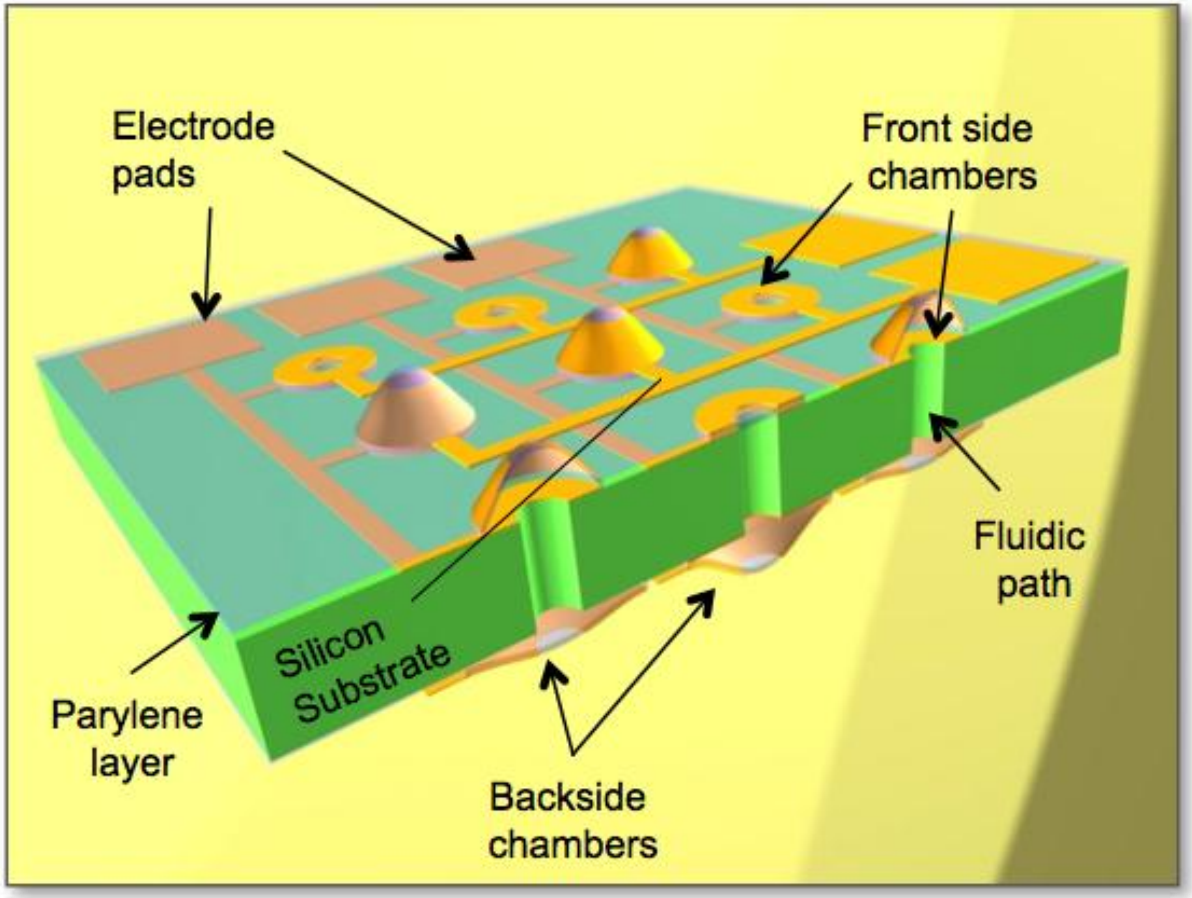
Small single gap

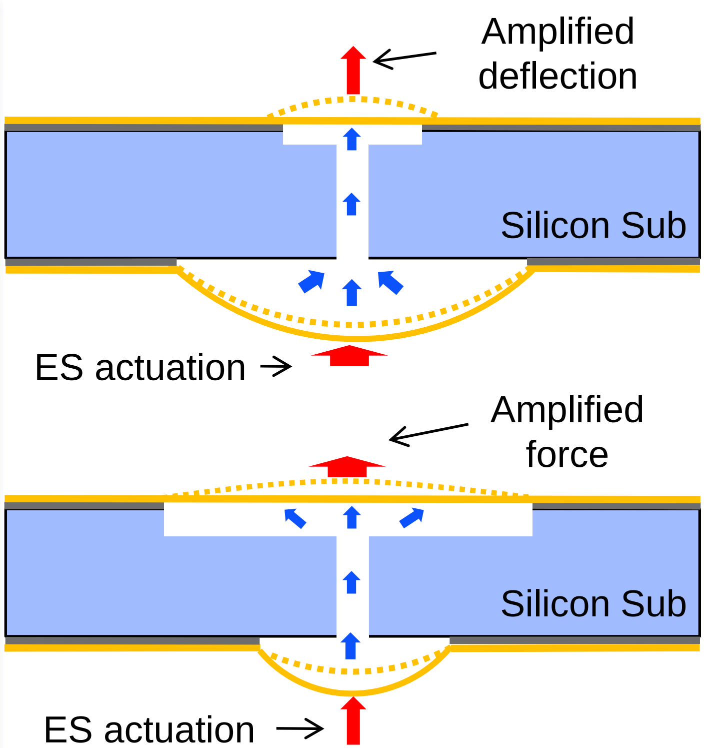
Micro-Hydraulic



High dynamic range, but viscous fluid flow reduces bandwidth

Electrostatic Micro-hydraulic Actuation (EMA)

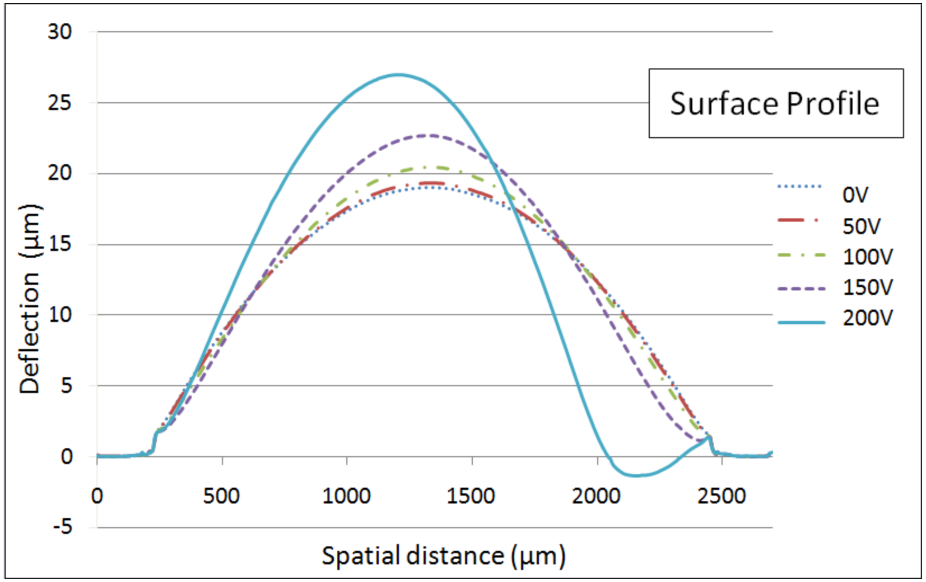


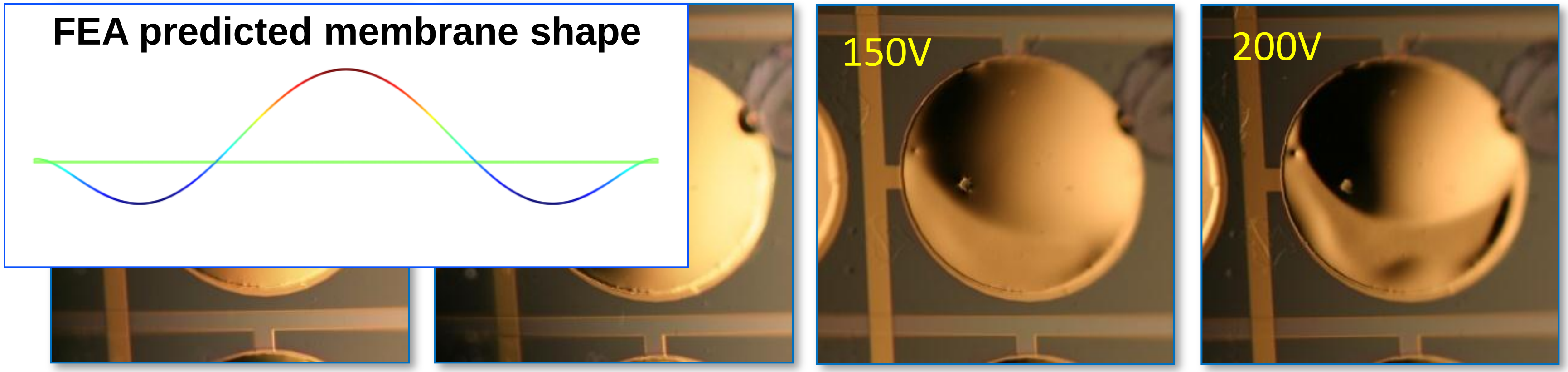


- Integrated electrostatic actuation, wafer-level process
- Array of individually actuated cells; addressability
- Hydraulic amplification for large-force/large-deflection actuation

Experimental Results: Deflection vs. Voltage

- Applied voltage 0-200V
- Bubble height is measured with profilometer; volume change confirmed by LEXT confocal microscopy
- Non-uniform deflection and asymmetric bulging due to edge pull-in

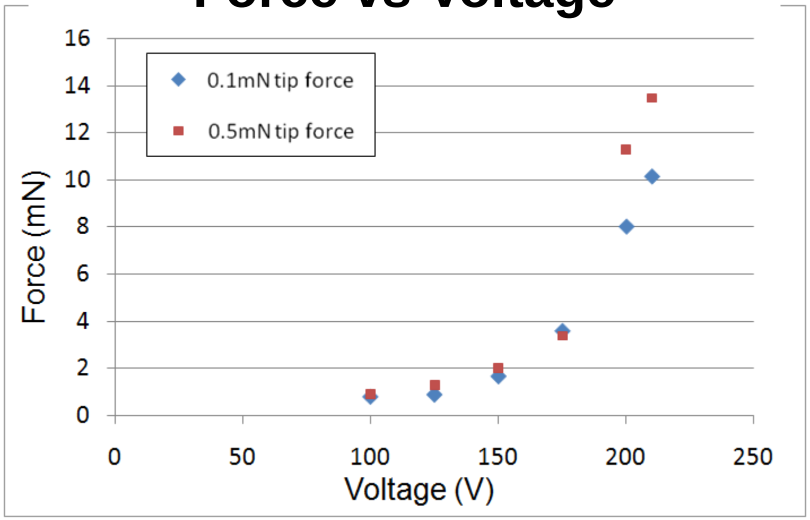




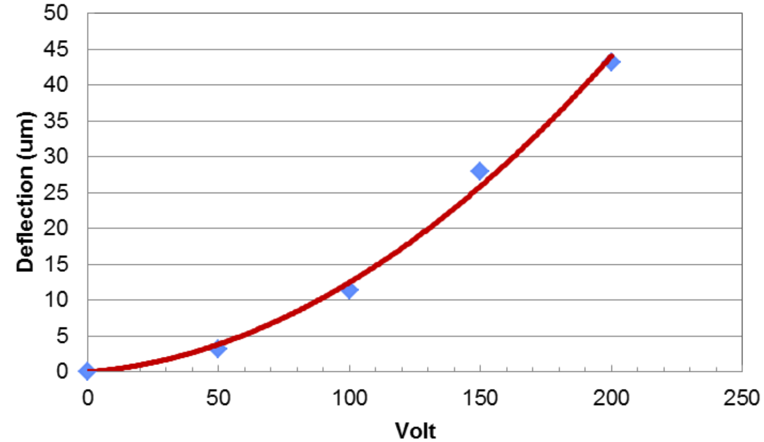
Optical images of one cell with D=2.2mm at 0, 100, 150 and 200V

Experimental Results: Force, Power, Frequency

Force vs Voltage

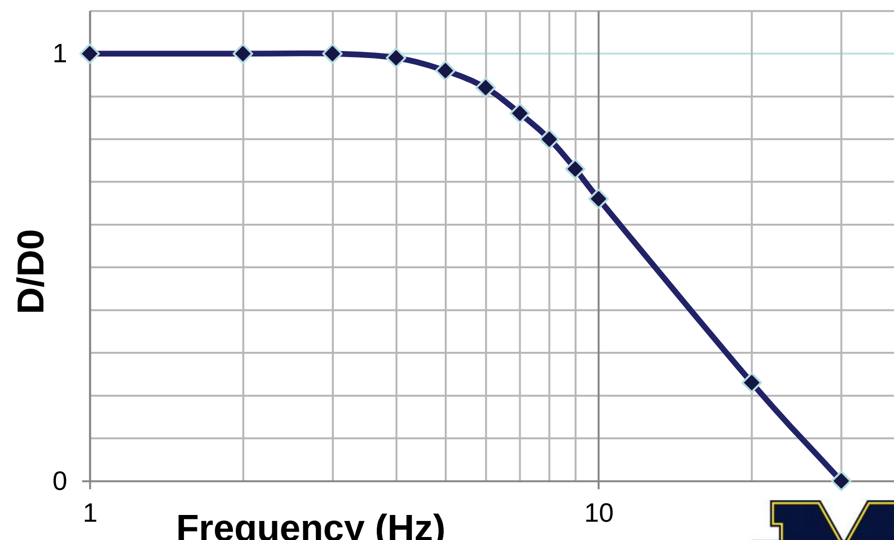


Deflection vs Voltage



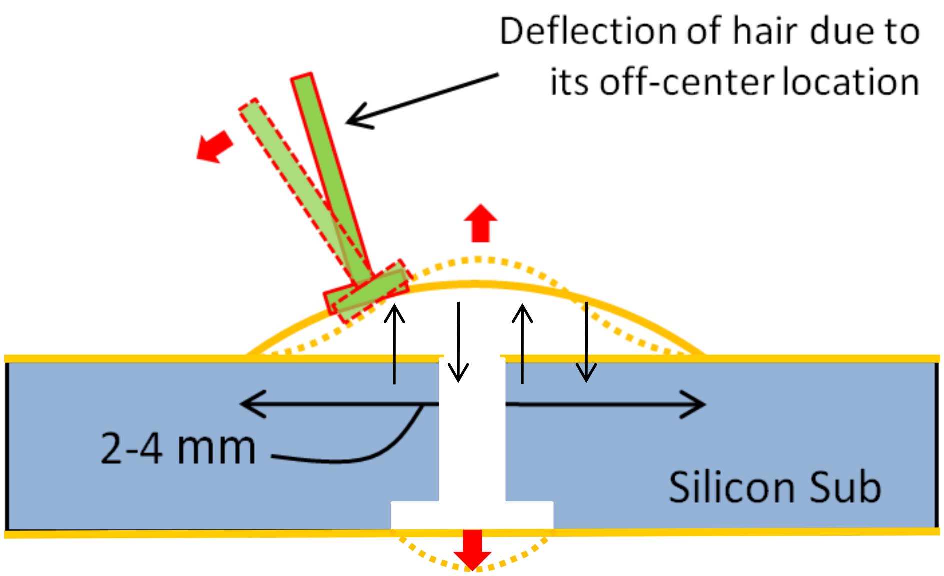
- **Force > 12mN**
- **Deflection > 40 µm**
- **Power max 24 µW per cell per cycle**
- Frequency: DC to 10 Hz (straight wall design)

Deflection vs. Frequency



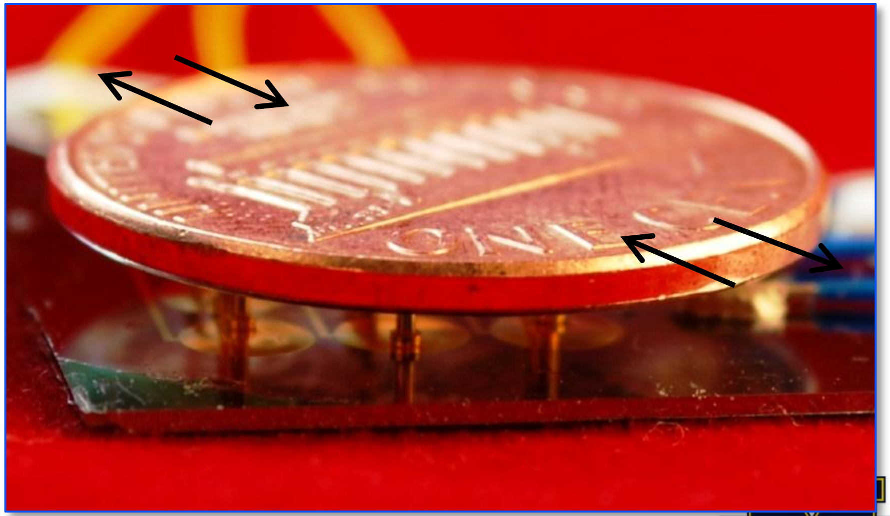
Actuation for Locomotion

- Phase deflection of multiple membranes creates 'stride'; maximize deflection by off-center positioning of the cilia on membrane
- The device can carry ~5x its own weight, almost 2.5 gram



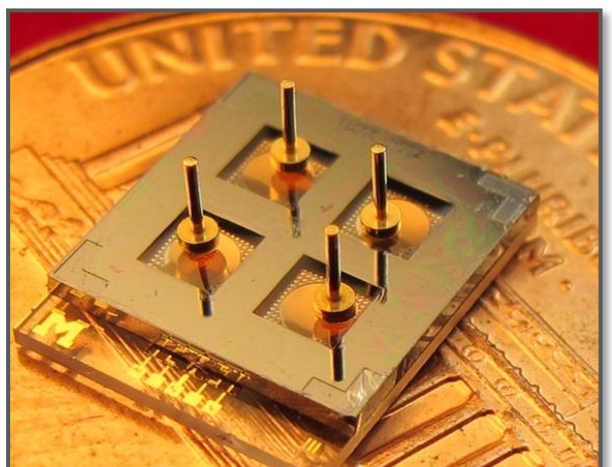
2 Hz actuation

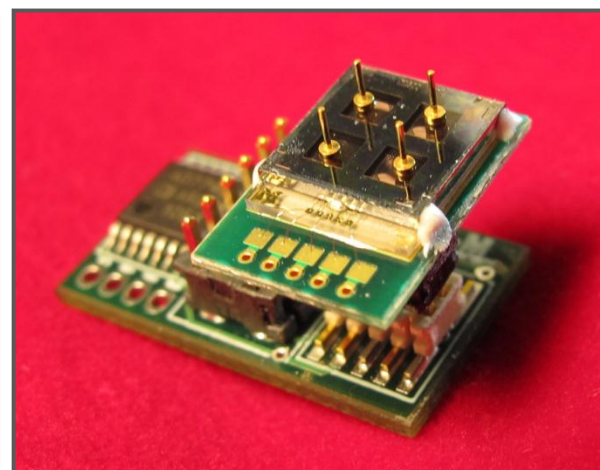
Hairs holding the coin



Conclusions

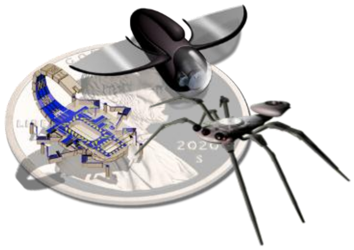
- Novel wafer-level liquid encapsulation for HAIR-like sensing and actuation based on micro-hydraulic, electrostatic architecture
  → new design element in MEMS
- Air flow sensors with record dynamic range and suitable response time for control loop insertion for MAST MAVs (work ongoing)
- High-force/high-deflection micro-hydraulic actuators
- Ongoing and future work on interface circuits, tactile sensing, air foil control, and other hair functionalization





Acknowledgments

- This project is funded by the Micro Autonomous Systems and Technology (MAST) Program of the Army Research Lab under Award Number W911NF-08-2-0004.



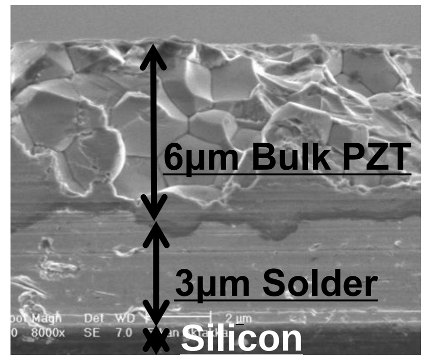
- Dr. Will Nothwang, ARL Lead for Microelectronics Center of MAST
- Lurie Nanofabrication Facility, a member of the National Nanotechnology Infrastructure Network, supported in part by NSF
- Undergraduate researchers Bing Zhang and Michael T. Chaney

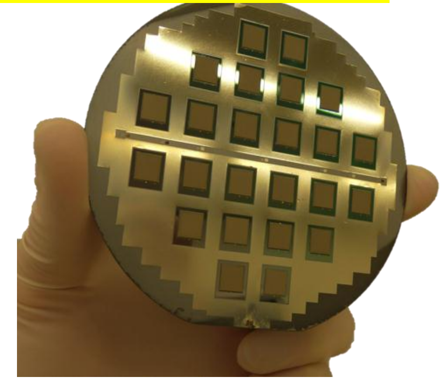
Integration of Bulk Piezoelectric Materials

Ethem Erkan Aktakka, Rebecca L. Peterson, Khalil Najafi

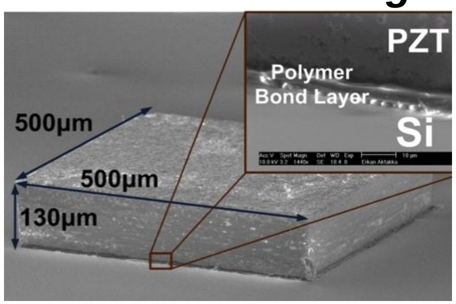
Aktakka, *et al.*, Transducers'09, IEDM'10, PowerMEMS'11, HiltonHead'12

- Characterized bonding & lapping process
- Wide range thickness control (5-100µm)
- Wafer-level thickness uniformity (±0.5µm)
- Conserved piezoelectricity & polarization
- Post-CMOS compatible process

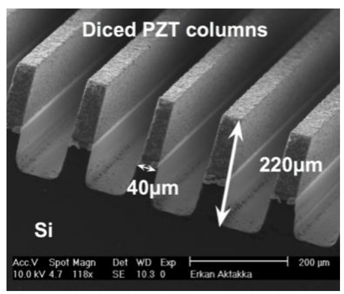




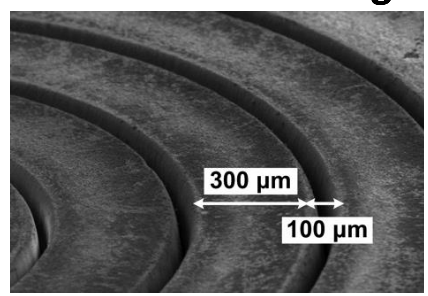
Die-level bonding



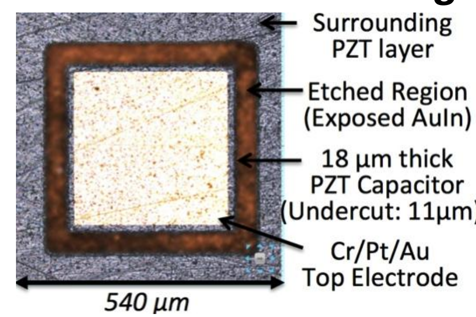
Precision Dicing



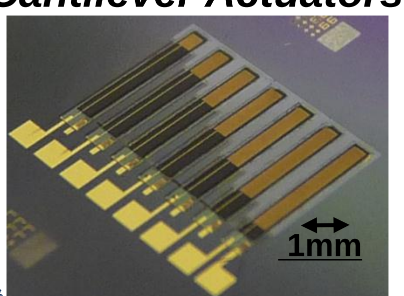
Laser Machining



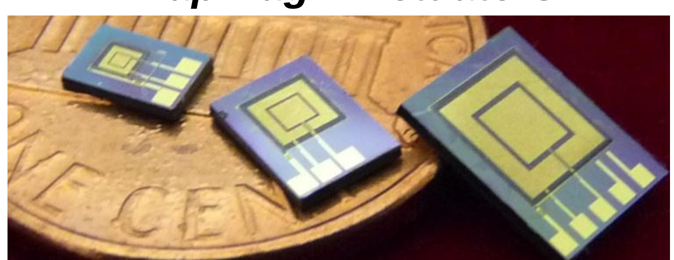
Wet-Etch Patterning



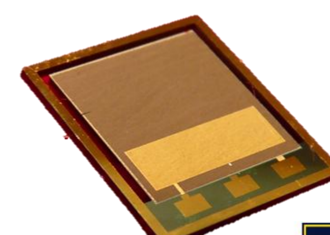
Cantilever Actuators



Diaphragm Actuators



Micro Energy Harvesters



Funded by DARPA HI-MEMS & DARPA PASCAL

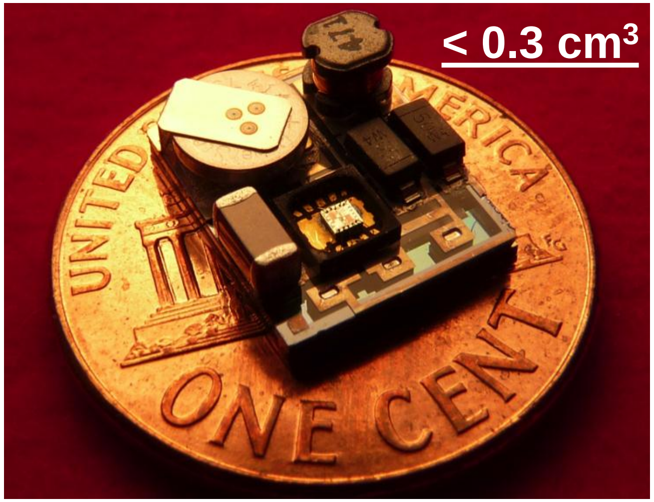
Self-Supplied Inertial Piezoelectric Energy Harvester with Power Management IC

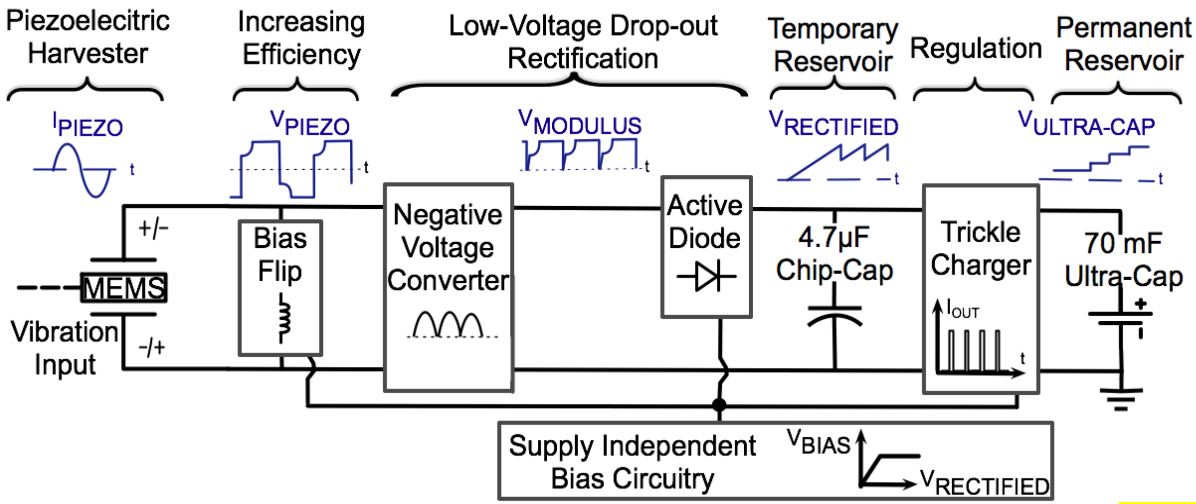
Ethem Erkan Aktakka, Rebecca L. Peterson, Khalil Najafi

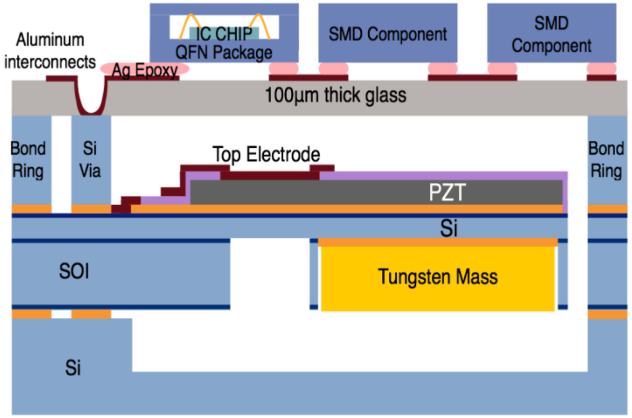
Goal: Self-contained vibration energy harvester for industrial applications or vehicle instrumentation

Results:

- High power density (205 μW at 1.5 g vibration)
  - Large bandwidth (14 Hz)
  - Low frequency operation (155 Hz)
- Autonomous charging of an ultra-cap (0 V to 1.85 V)
- No requirement for a pre-charged battery/capacitor







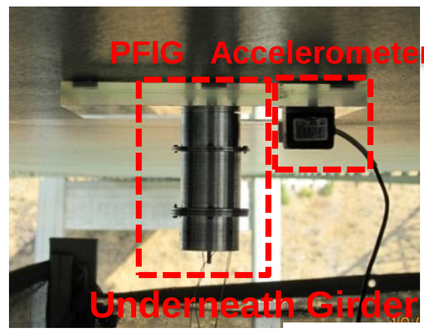
IEDM'10, ISSCC'11, Transducers'11

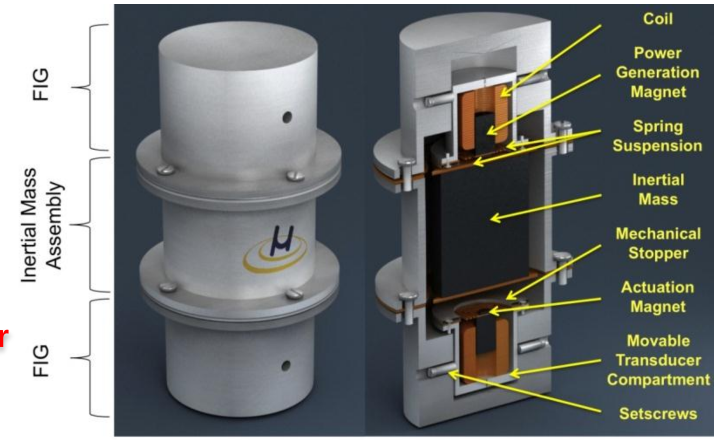
Funded by DARPA HI-MEMS

A Vibration Harvesting System and Electronics for Bridge Health Monitoring Applications

James McCullagh, Tzeno Galchev, R. L. Peterson, and Khalil Najafi

Goal: Harvest low-acceleration, low-frequency, non-periodic vibration energy from bridge to power wireless sensor network for structural health monitoring

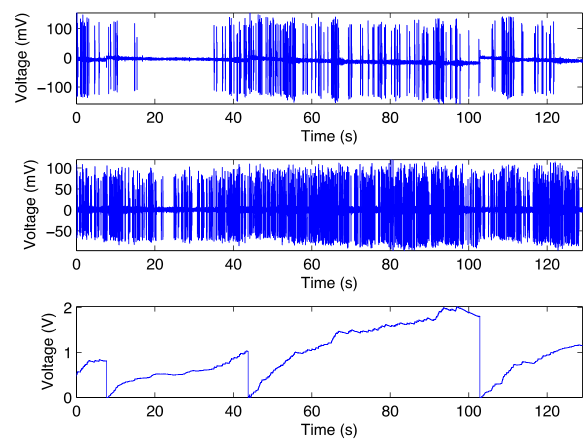




PFIG architecture and installation on suspension bridge

Results:

- 5th Generation **Parametric Frequency Increased Generator (PFIG)** built
- Achieved record low threshold acceleration of 35mg (1g = 9.8m/s^2)
- Increased avg. power to 131 µW at 11 Hz
- Testing PFIG + circuit on bridge to generate DC output voltage



PFIG output voltage 1

PFIG output voltage 2

Storage Capacitor, (discharged manually)

Galchev, *et al., J. Micromech. Microeng.* 21, 1, 2011; Two papers at Transducers 2011; PowerMEMS 2010

Sensing & Sys

Funded by NIST TIP

HAIR Based Sensing and Actuation

Mahdi M. Sadeghi, Becky (R. L.) Peterson, and Khalil Najafi

Electrical Engineering and Computer Science (EECS) Dept.
University of Michigan

The 2nd Multifunctional Materials for Defense Workshop
August 1, 2012
Arlington, VA