Microfabricated Actuators for Space Applications

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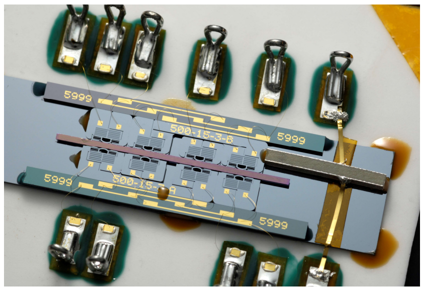
Stevens Institute of Technology

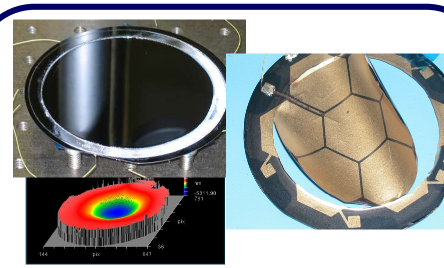
Conference Keynote at Inter PACK 07

Vancouver, Canada, July 8-12, 2007

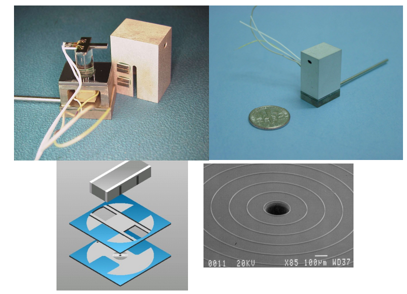
Microactuators and Nano/Micro Structures



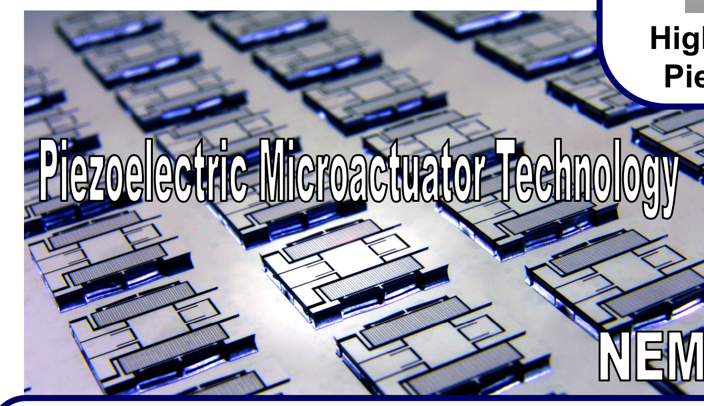
Self-Latched Linear Microactuator

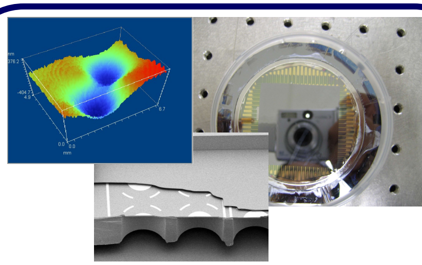


Electroactive Polymer Actuated Mirror



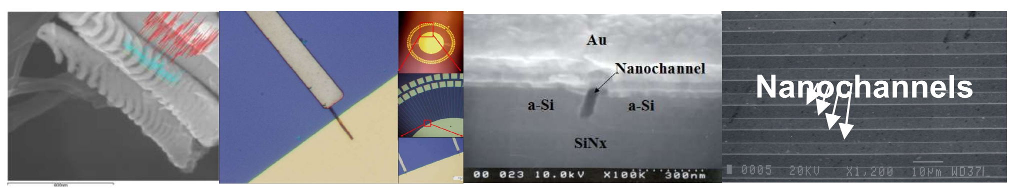
High-Pressure, Leak-Tight Piezoelectric Microvalve





Large-Stroke, Large-Area MEMS Deformable Mirror

NEMS Technology



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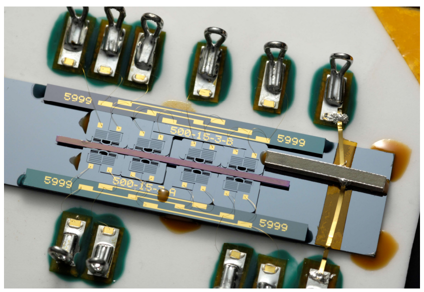
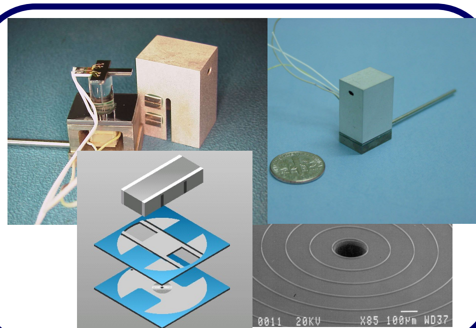
Topics that are covered in this talk



- Linear Microactuator

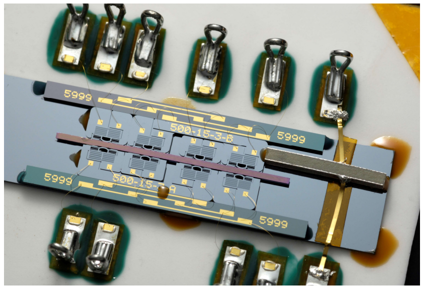
  For active wavefront correction for space telescopes



- Piezoelectric Microvalve

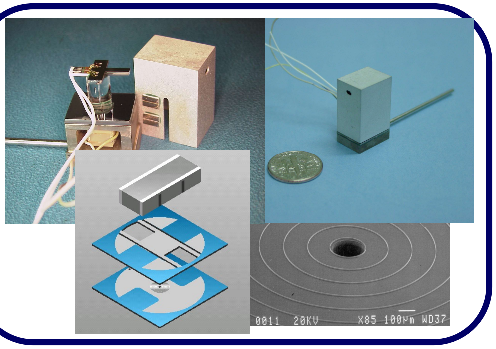
  For micropropulsion for microspacecrafts

Topics that are covered in this talk



- **Linear Microactuator**

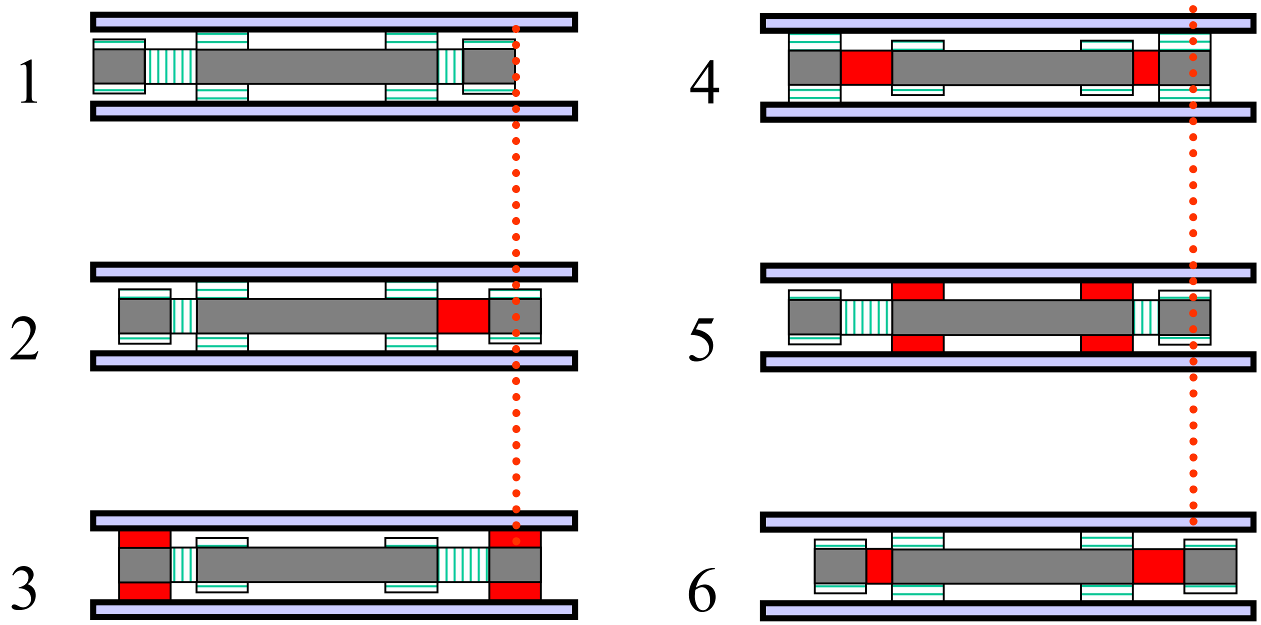
  For active wavefront correction for space telescopes



- Piezoelectric Microvalve

  For micropropulsion for microspacecrafts

Linear Actuator



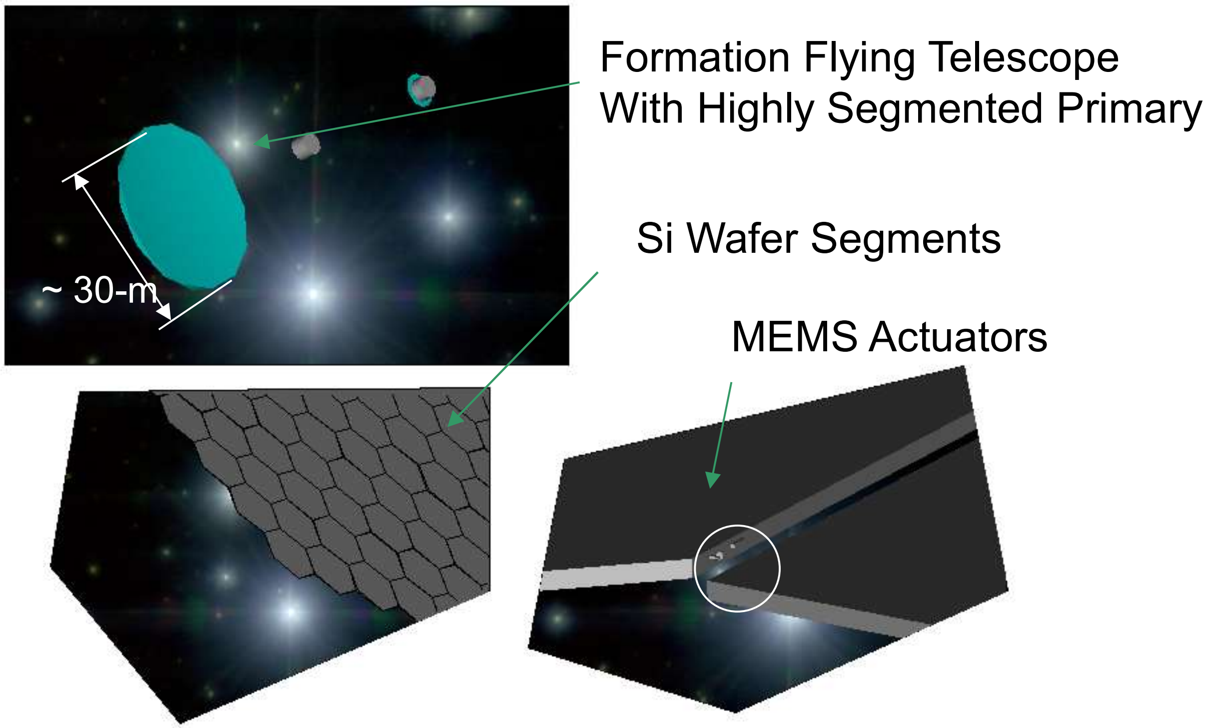
A **linear actuator** is a type of electric actuator or motor that produces overall force and motion linearly.

Typical linear (inchworm) actuation sequence

Why Linear "Micro" actuator

- Extremely large **(> 30 m),** lightweight **(< 1 kg/m^2)** space telescopes will enable substantial performance gains for future space-based imaging.
- Practical ultra-large, ultra-lightweight aperture systems will more likely be either segmented or flexible monolithic primary mirrors.
- Their large surface errors have to be corrected by active and adaptive wavefront controls.
- Using ultra-lightweight microactuators, the ultra-large mirror system can be designed to have very low areal density.

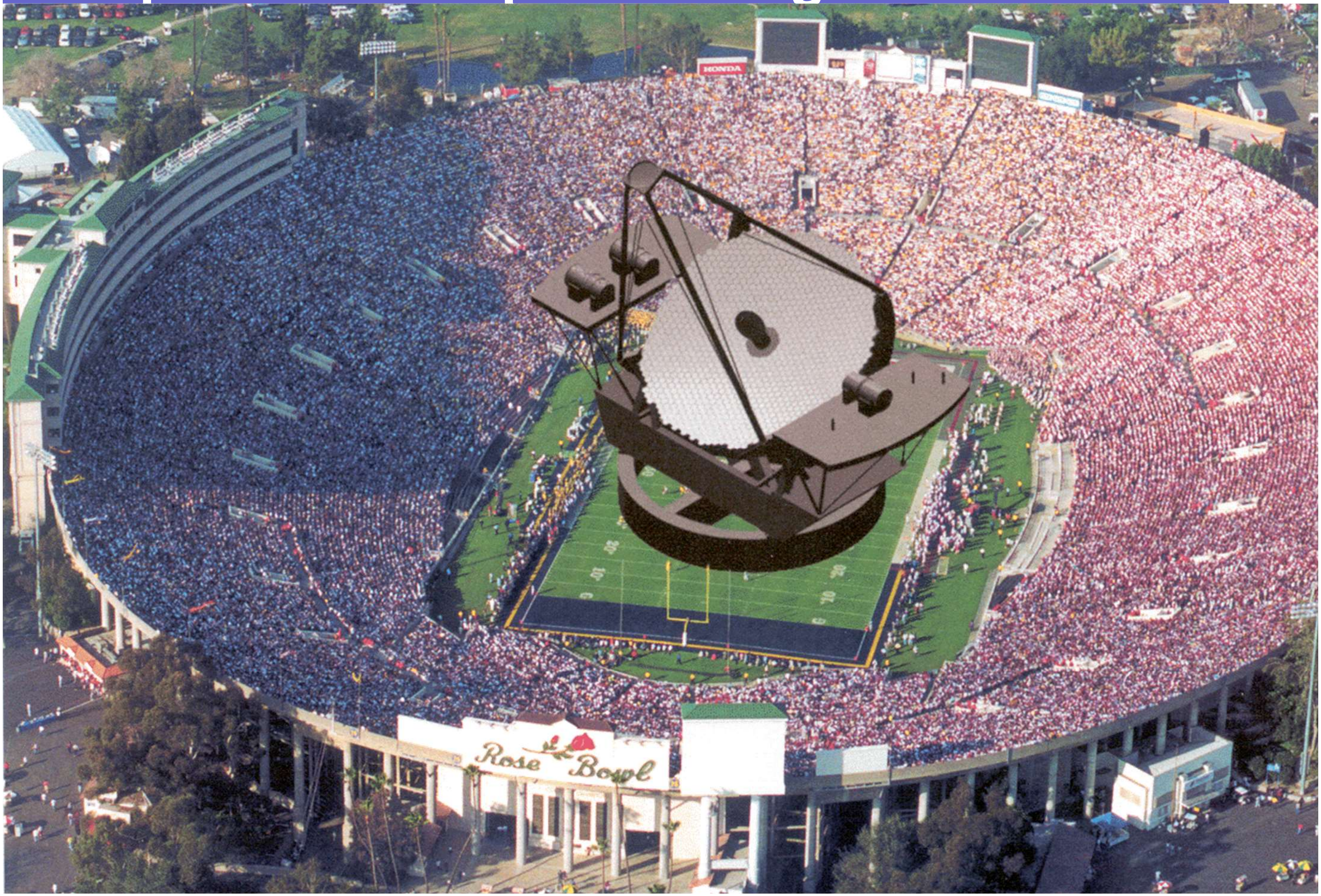
Applications of Linear Microactuators



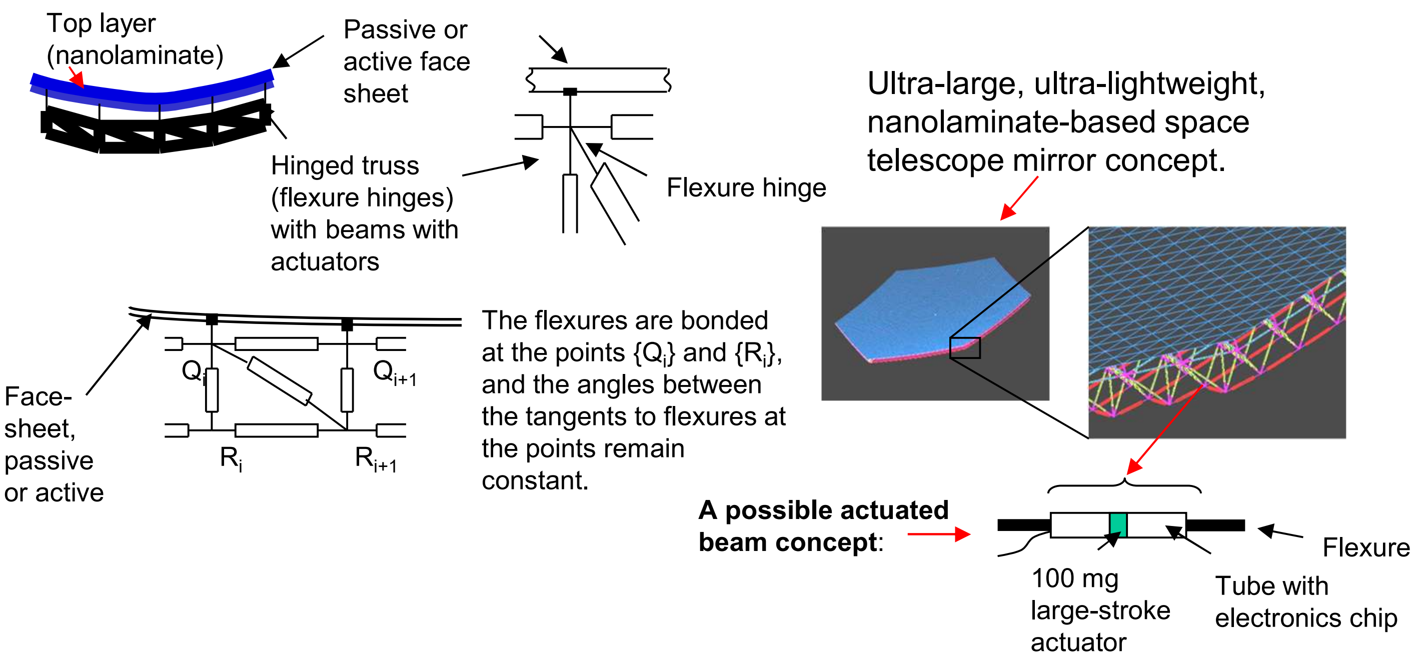
For segmented mirrors

E. H. Yang, R. Dekany and S. Padin, "Design and Fabrication of a Large Vertical Travel Silicon Inchworm Microactuator for Advanced Segmented Silicon Space Telescope (ASSiST)," *SPIE Photonics West, Micromachining and Microfabrication Conference*, San Jose, California, USA, January 2003.

Space Telescopes as Large as This…



Applications of Linear Microactuators



For Monolithic mirrors

S. N. Gullapalli, **E. H. Yang** and S. –S. Lih, " New technologies for the actuation and control of large aperture lightweight optical quality mirrors," *IEEE Aerospace Conference*, Big Sky, Montana, USA, 2003.

Actuator Target Performance

• Max. Freq.	~1 kHz
• Stroke	**> 1 mm**
• Resolution	<30 nm
• Force	**> 30 mN**
• Power	**100 μW → 0**
• Mass	**~ 100 mg**

•The actuator is for correcting the surface figure of a segmented or thin-monolithic mirror (**mass density < 1 kg/m^2**) after deployment in space.

•If microactuators weighing a100-mg are available, a hundred such microactuators per square meter will add only about 0.01 kg/m^2.

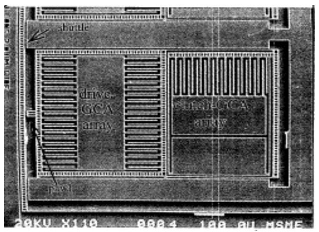
Actuator Target Performance

• Max. Freq.	~1 kHz
• Stroke	**> 1 mm**
• Resolution	<30 nm
• Force	**> 30 mN**
• Power	**100 μW → 0**
• Mass	**What if 100 g**

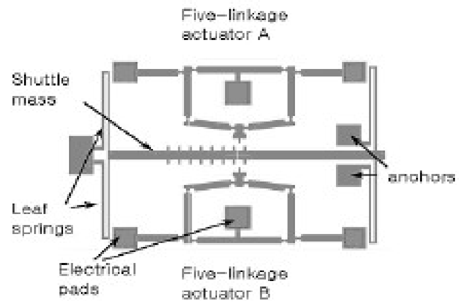
• **mass density goal < 1 kg/m^2**

•If actuators weighing a100-g are used, a hundred such actuators per square meter will add about **10 kg/m^2**.

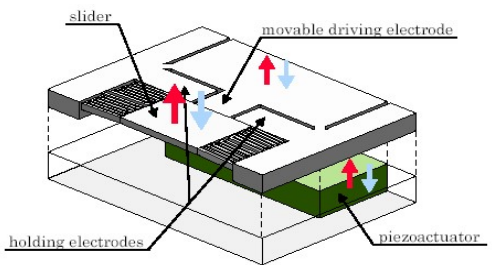
Existing Linear "Micro" Actuators



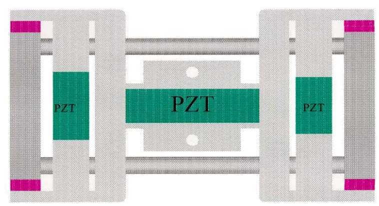
UCB Si MEMS linear: : 3mmx1mmx50μm size, 80μm travel and 260μN force.



GIST (Korea): Thermal linear: large (~ microns) step size



Ritsumeikan (Japan) linear: Vertical motion. Poor performance

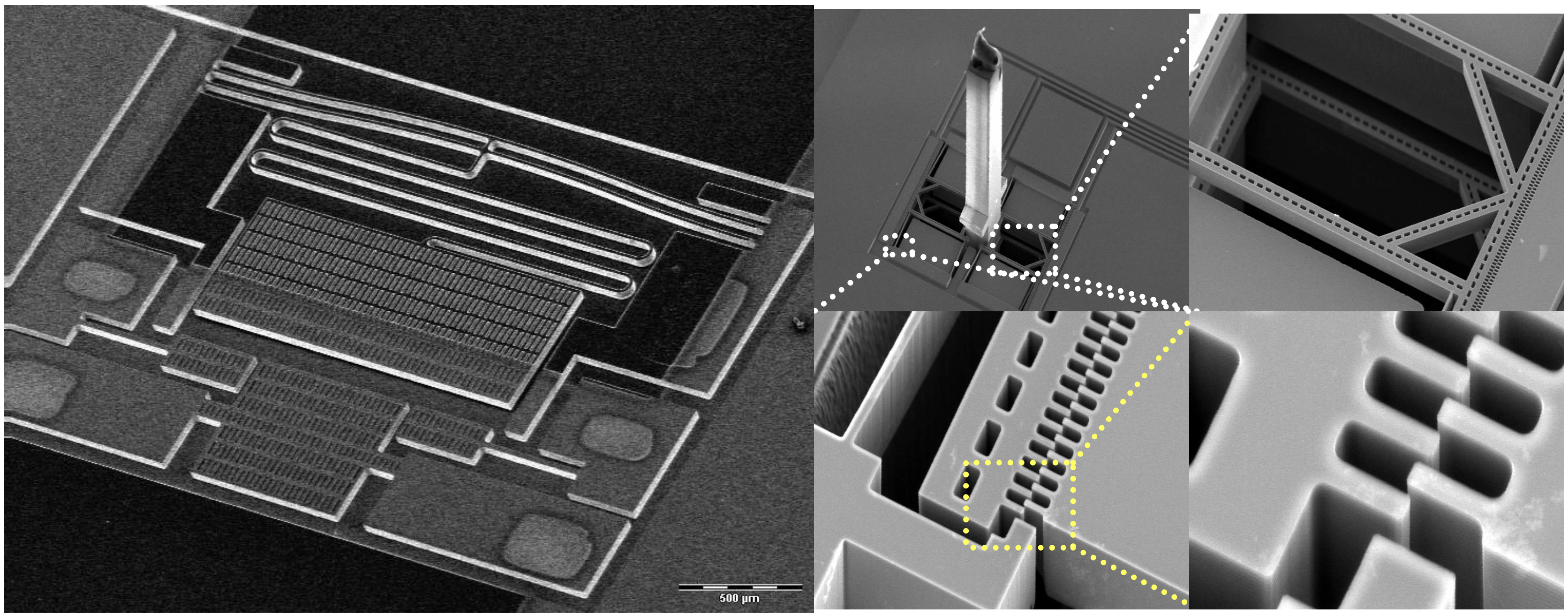


UCLA linear: 2cm size and provide 100 lb output force, 10mm/s stroke velocity, and 1mm displacement. **(Bulky: 100g)**

- MEMS linear actuators [1~3]: 50~500μN max push force. No self-latching.
- Macro linear actuators [4]: 100g (mass)

[1] R. Yeh, *et al.,* MEMS 01, Interlaken, Switzerland, Jan. 21-25, pp.260-264, 2001.
[2] H. N. Kwon, J. H. Lee, MEMS 02, Las Vegas, pp. 586-593, 2002.
[3] M. P. de Boer, *et al.,JMEMS*, Vol. 13, pp. 63-74, 2004.
[4] Q. Chen, *et al.,* MEMS 98, Heidelberg, Germany, pp. 384-389, 1998.

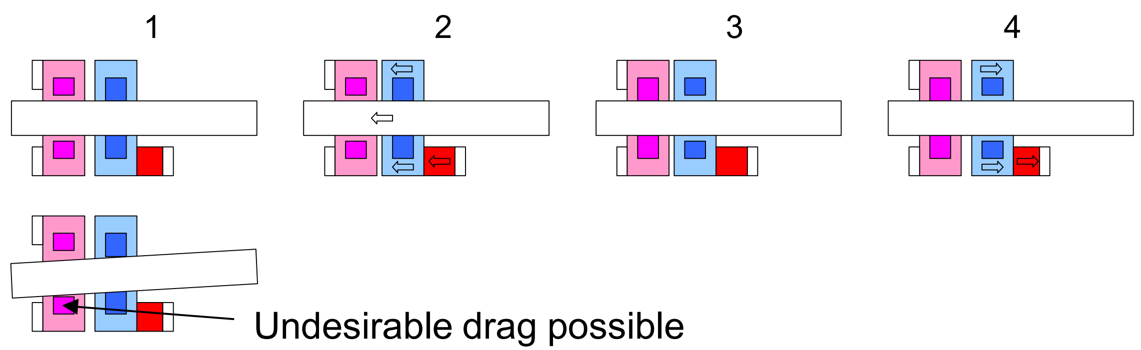
New Linear Microactuators



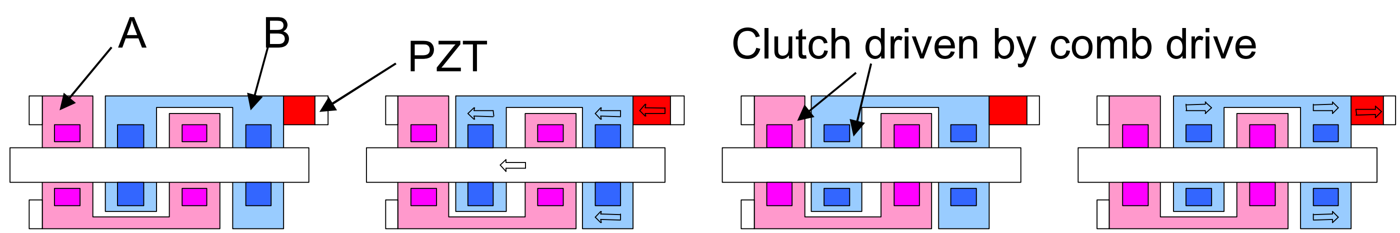
- R. Toda and **E. H. Yang**, “Development of Latching Type Large Vertical Travel Microactuator,” *ASME/Pacific Rim Technical Conference and Exhibition on Integration and Packaging of MEMS, NEMS and Electronic Systems (InterPACK ’05)*, San Francisco, USA, July 17-22, 2005.
- R. Toda and **E. H. Yang**, “Fabrication and Characterization of Vertical Inchworm Microactuator,” *Proceedings of 2004 ASME International Mechanical Engineering Congress and Exposition*, Anaheim, California, November 13-19, 2004.

2-Point Clamping to 4-Point Clamping

2-point clamp actuator is prone to slider tilt



4-point clamp actuator is more stable



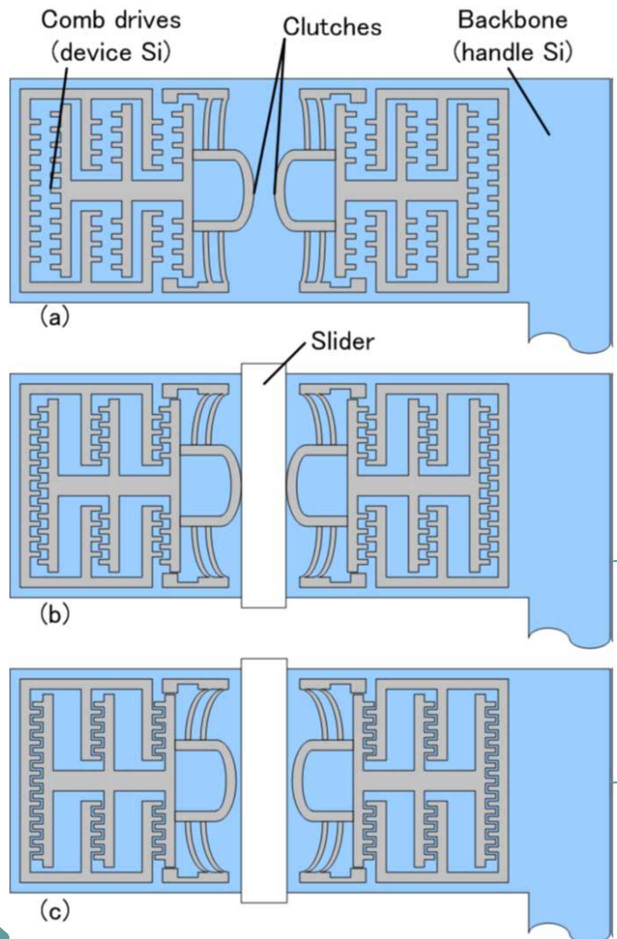
(a) Unit A released. Unit B clutched.

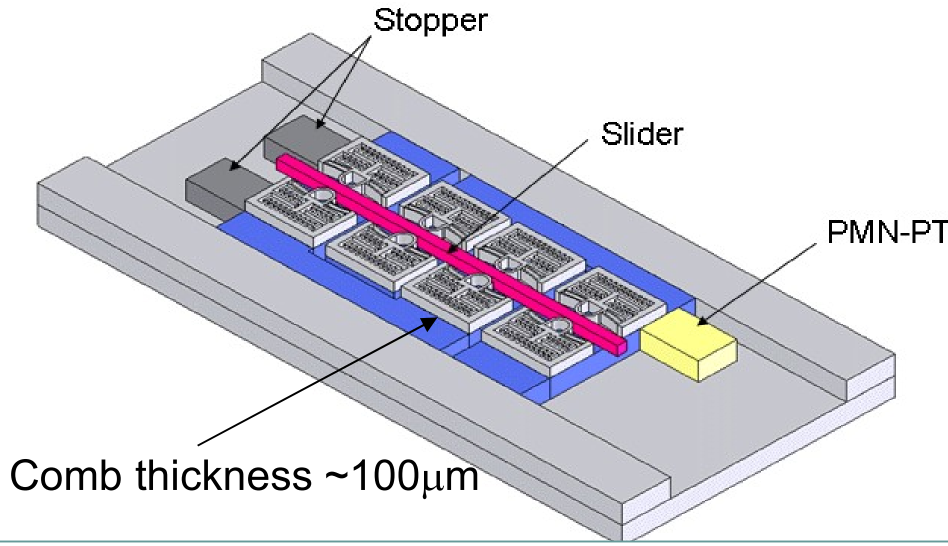
(b) Unit B laterally moved.

(c) Unit A clutched. Unit B released.

R. Toda and E. H Yang, “Four Point Latching Microactuator,” *(NPO-42041)*

Self-Latched Linear Microactuator

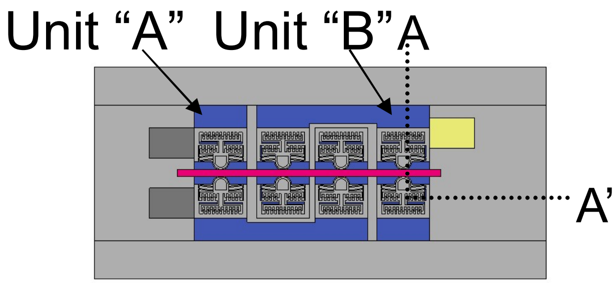




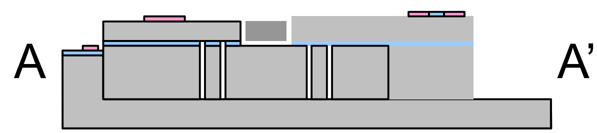
- **Increase electrostatic force / clamping force**
  - **Thick structures**
    - **➔ Post-engagement**
    - **➔ Pre-stressing tethers for self-latching**

R. Toda and **E. H. Yang**, "Normally-Latched, Large-Stroke, Inchworm Microactuator," *Journal of Micromechanics and Microengineering*, 2007. *in-press*

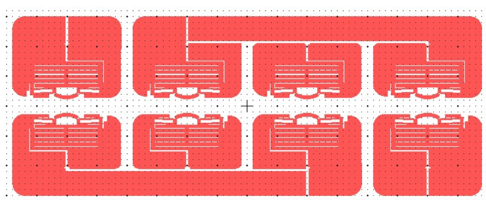
Schematics of Silicon Components



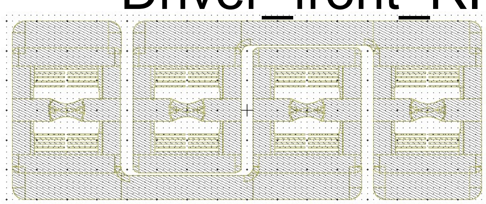
Top view



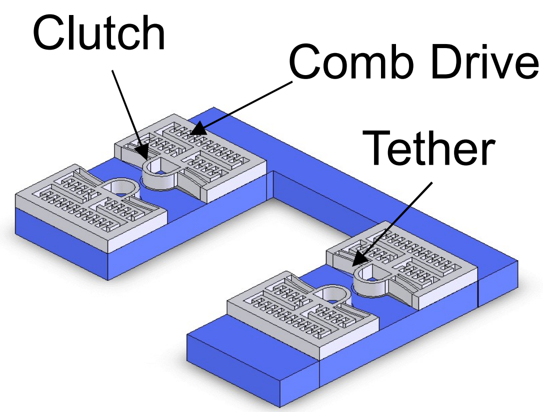
Cross-section



Driver_front_RIE



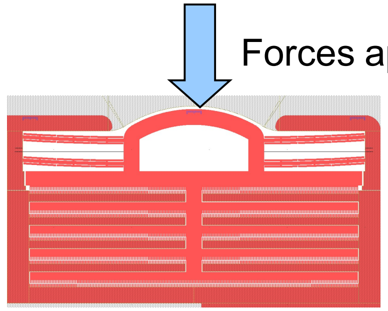
Driver_back_RIE

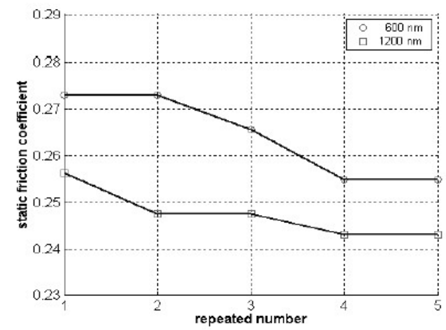


A Drive Unit

Modeling: Slider Force

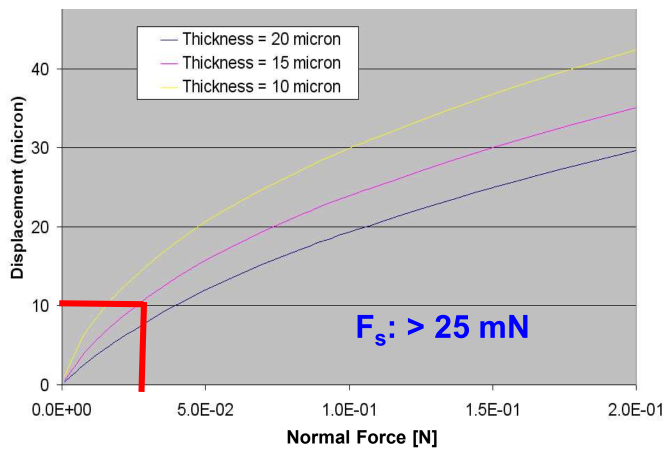
Forces applied by slider

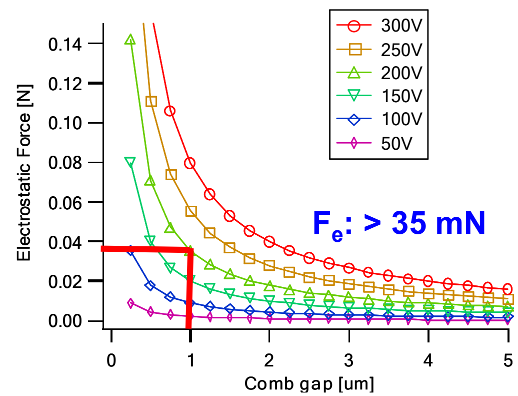




Hwang *et al.*, *IEEE MEMS 06*, Istanbul, Turkey, Jan. 2006, p.210.

Assuming the static friction coefficient is 0.24, the estimated push force when actuating is approximately 24 mN. **In power-off mode, the estimated clamping force is approximately 48 mN.**





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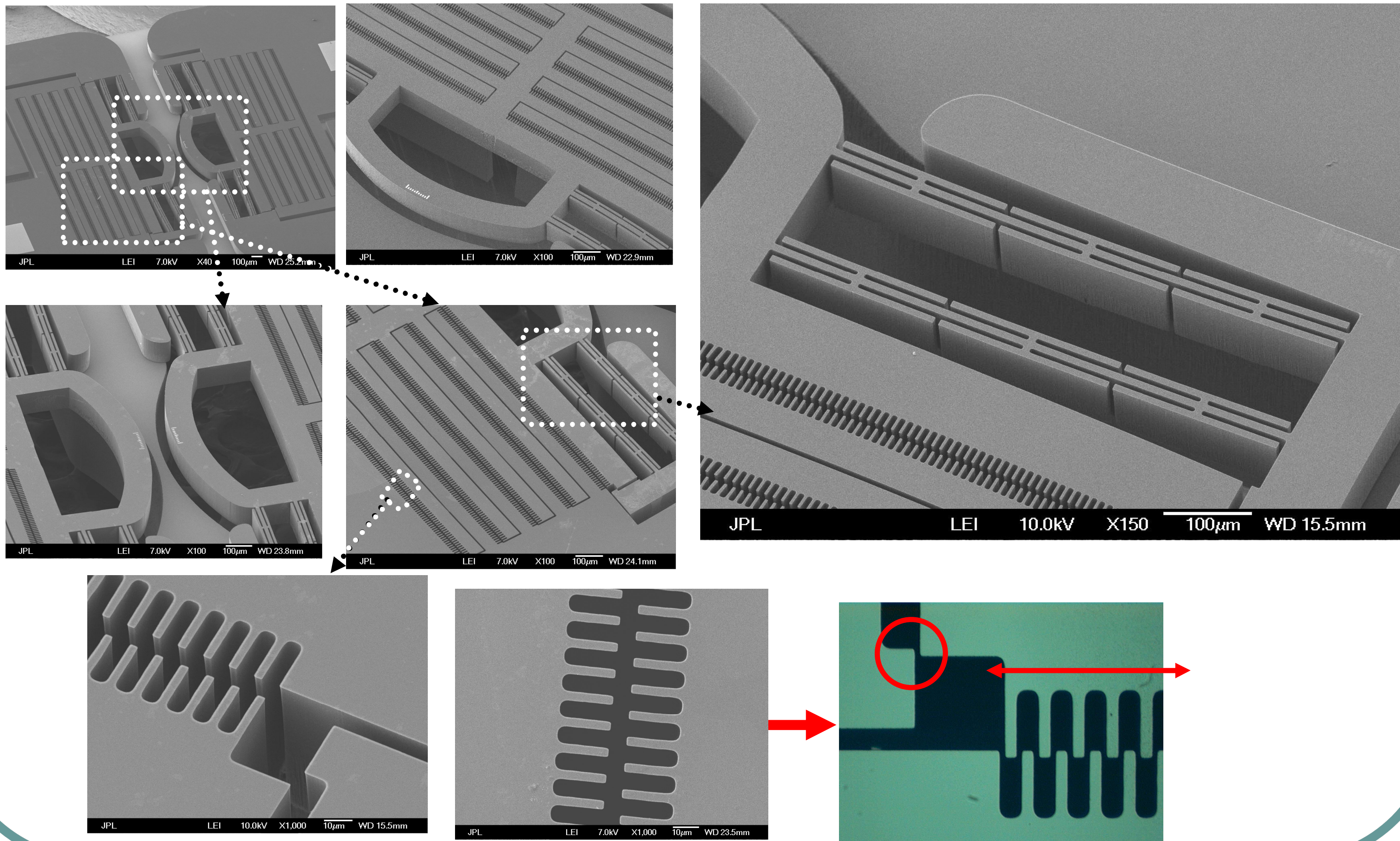
Fabricated Silicon Components



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Assembly Sequence

Driver fabrication | Rail fabrication | Slider fabrication

↓

Slider insertion

↓

Individual comb drive actuation test

↓

Epoxy attachment with PMN-PT

↓

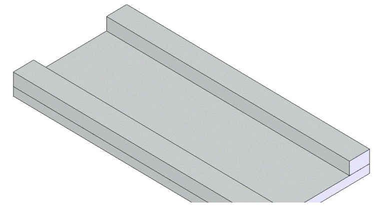
Wire bonding to Rail

↓

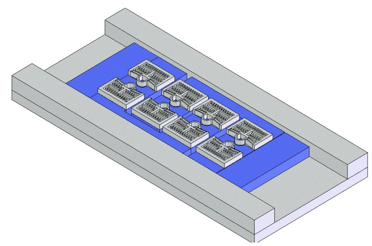
Mount on PCB, wiring with Ag-epoxy

↓

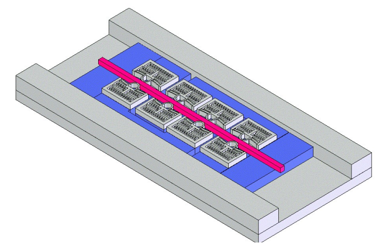
Actuation test



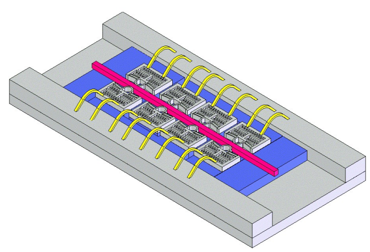
1. Fabricate rail guides.



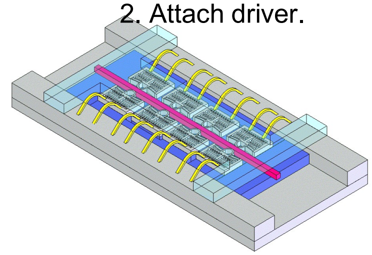
2. Attach driver.



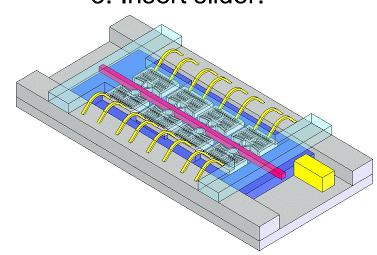
3. Insert slider.



4. Bond Au wires.

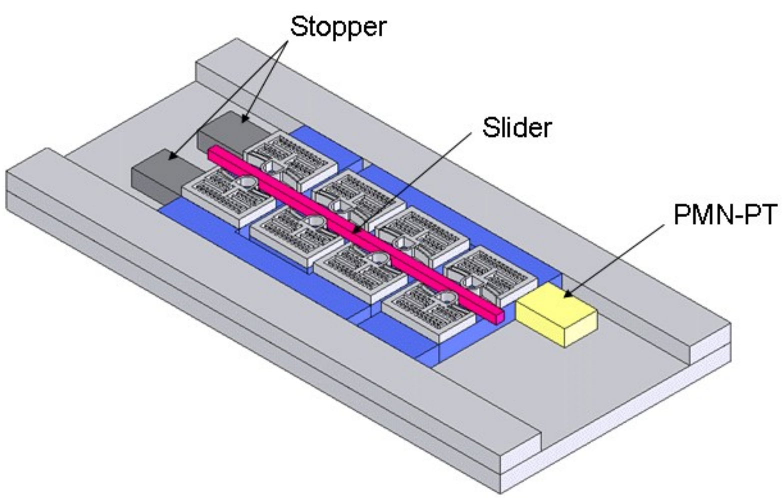


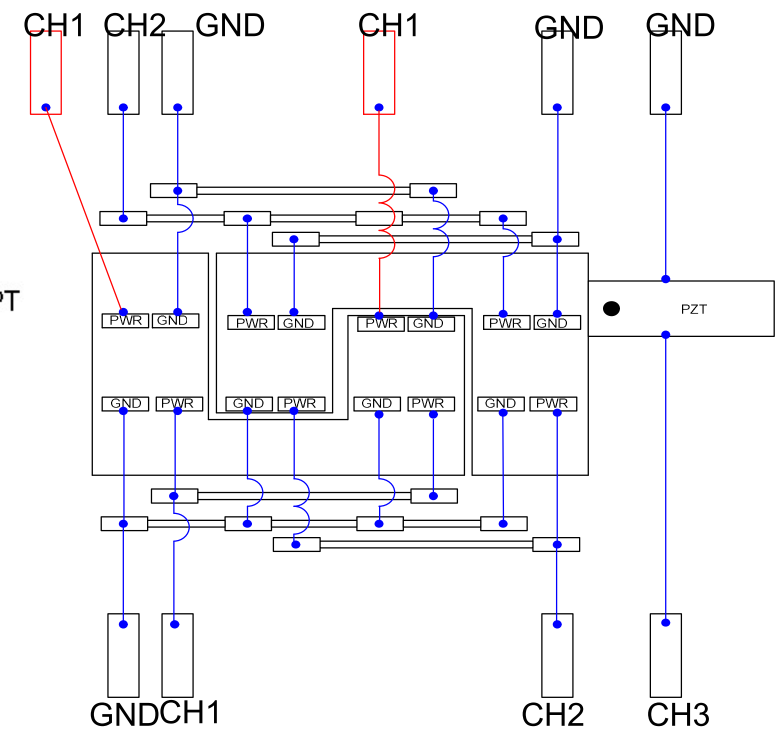
5. Attach the lid.



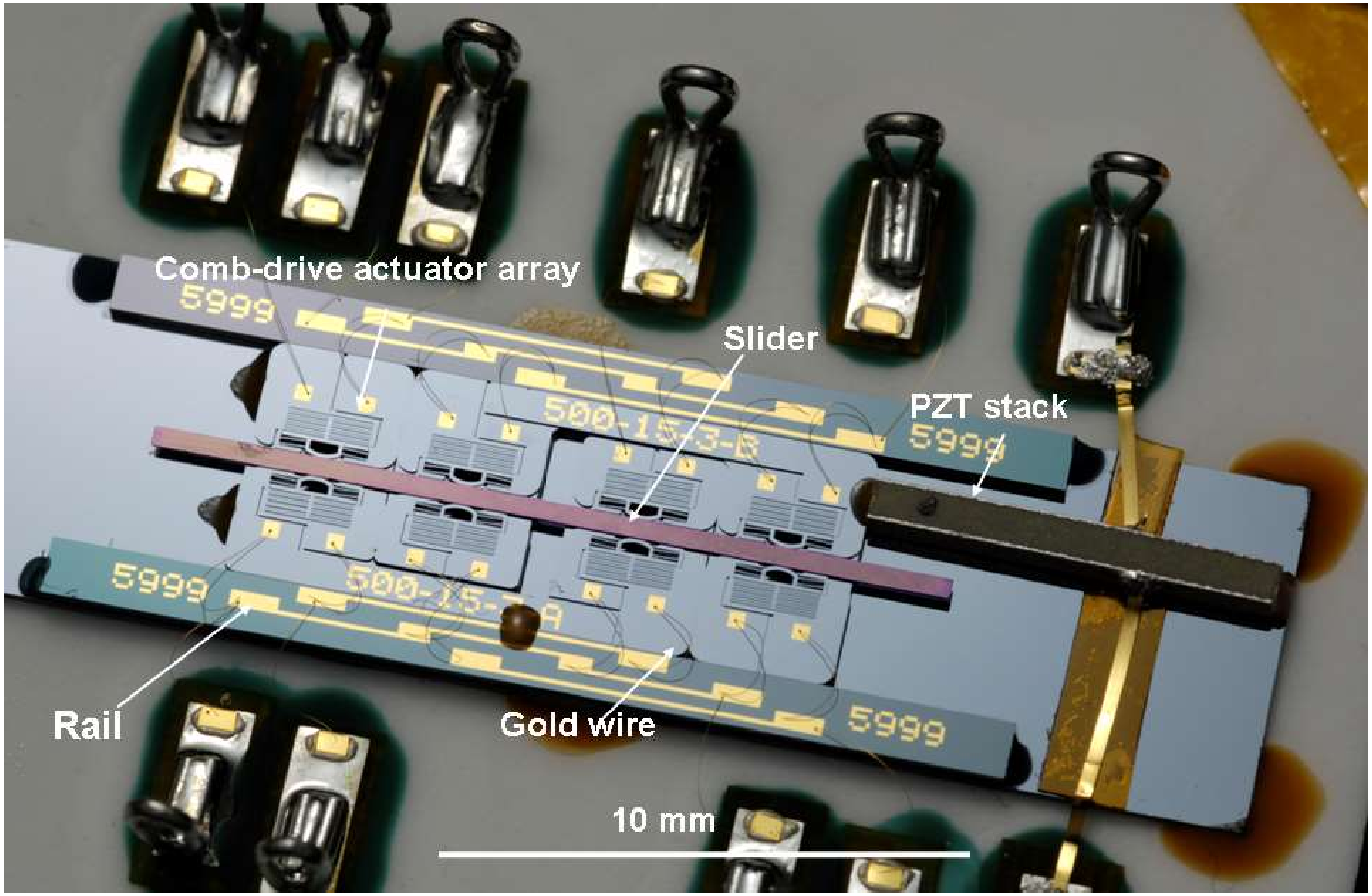
6. Attach the PMN-PT to driver and rail.

Wiring Scheme

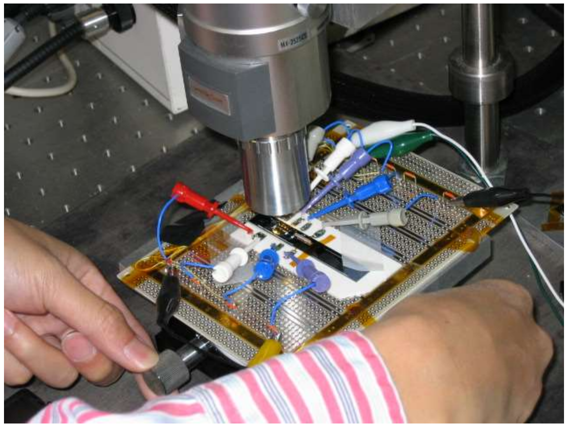


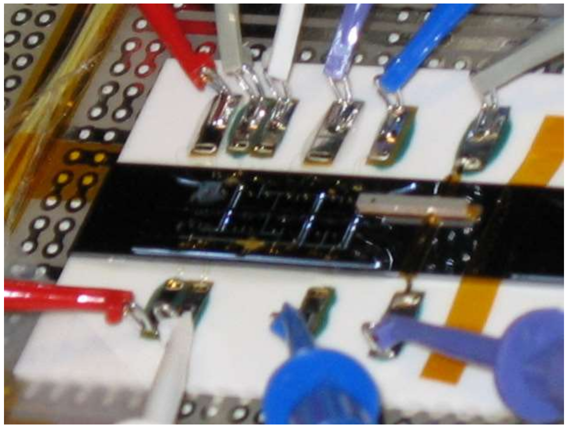


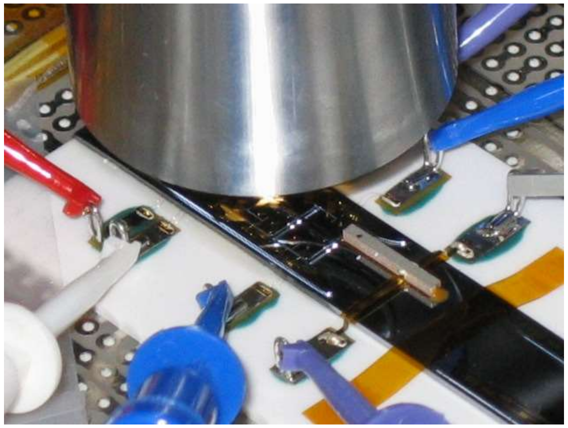
Fabricated and Assembled Actuator - 1st generation



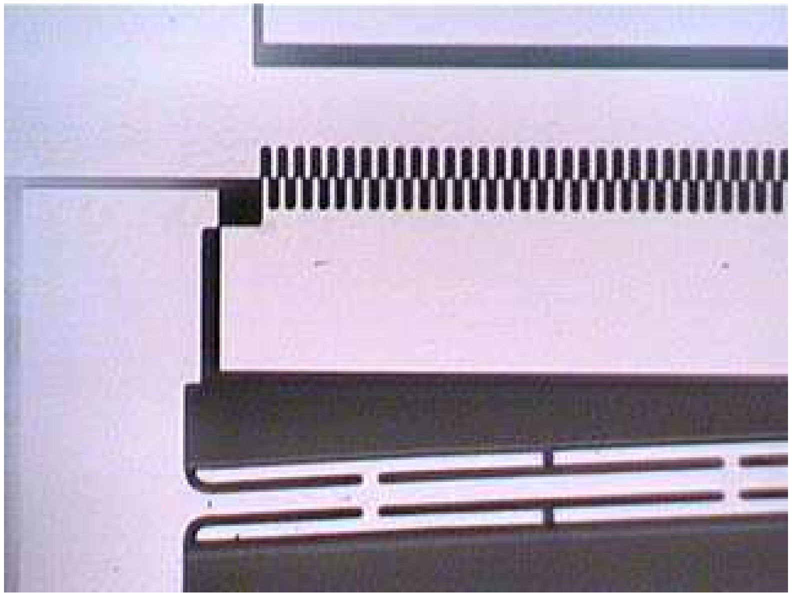
Actuator Test Setup



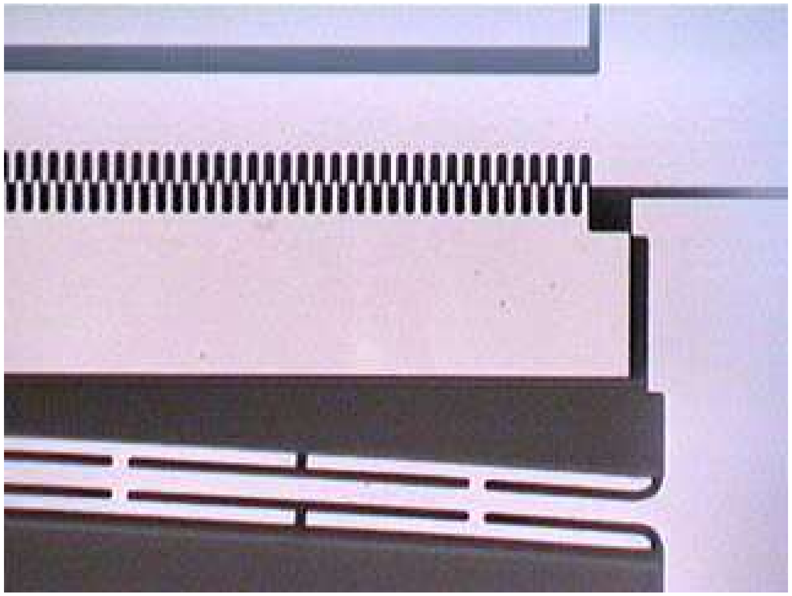




Comb-Drive Actuation

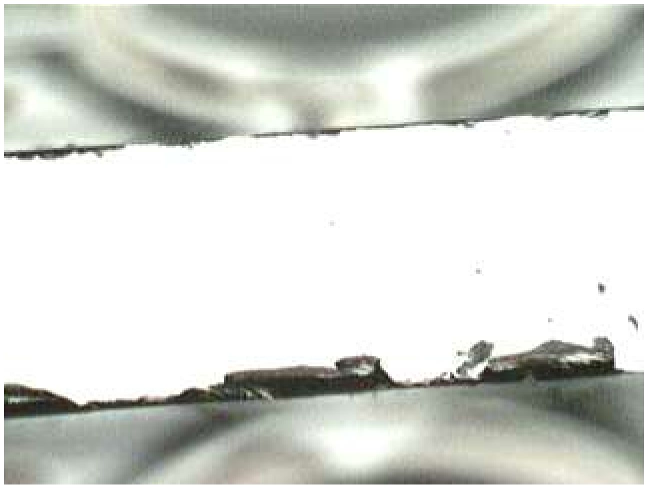


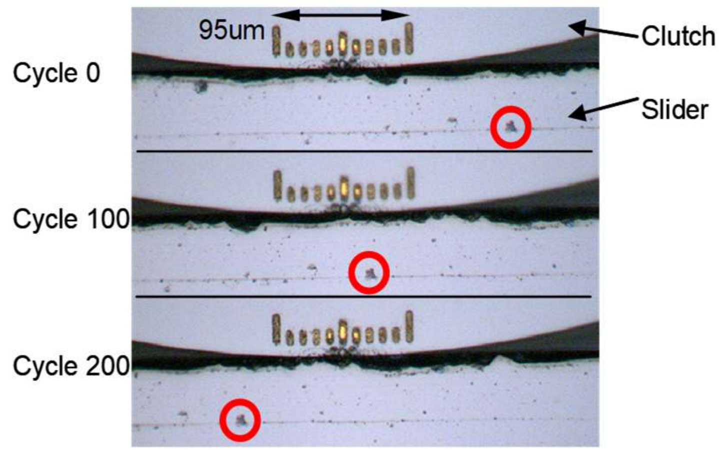
Unit A



Unit B

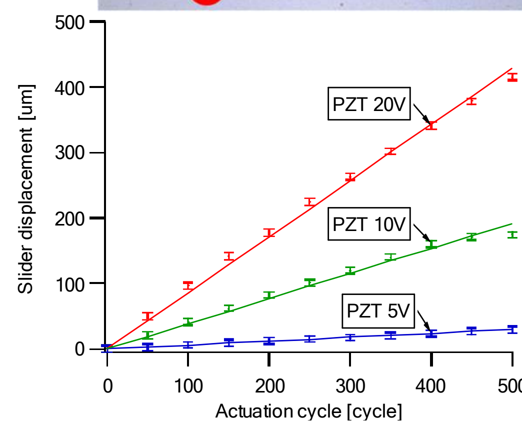
Actuation: Measured Stroke



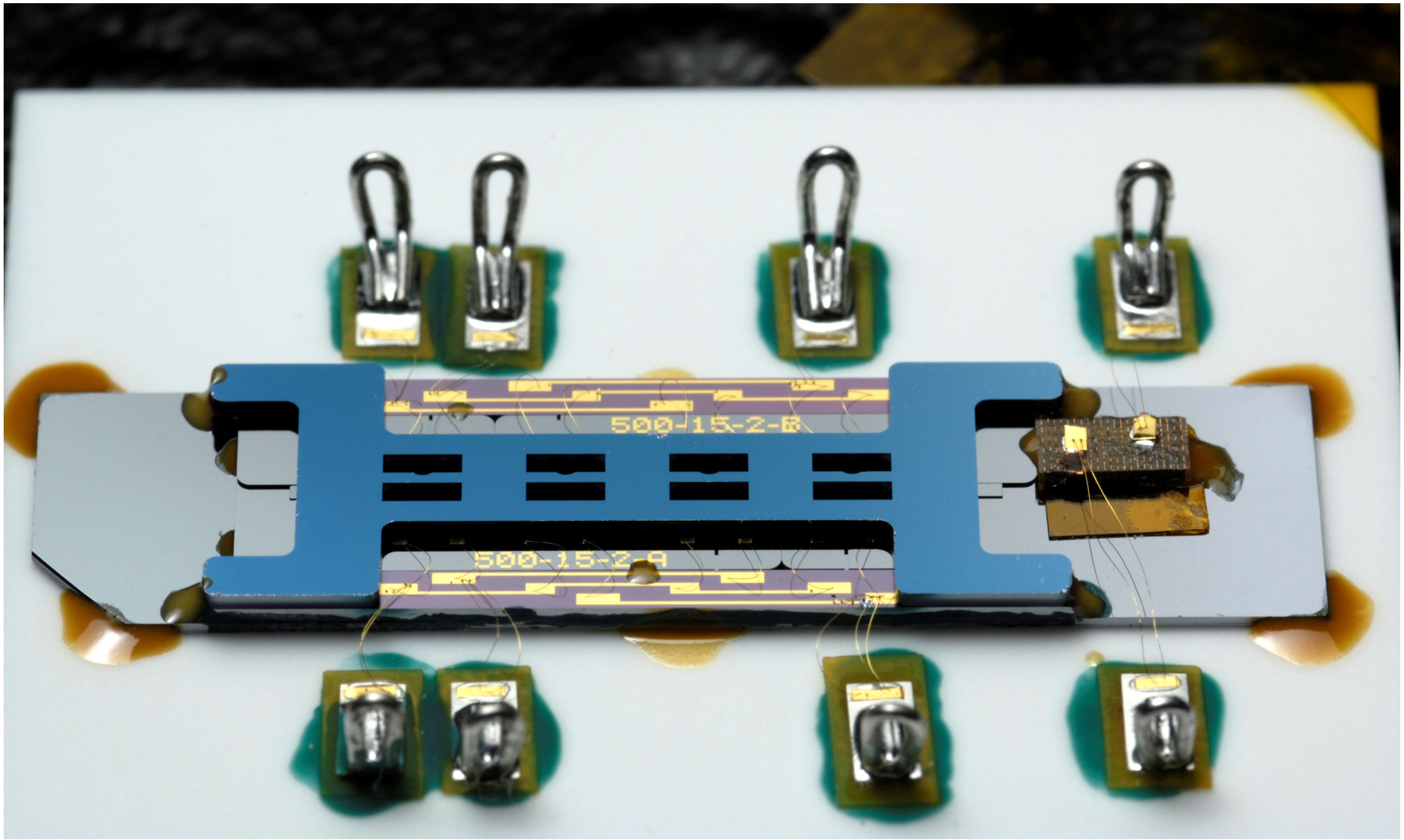


Actuation speed: 1 cycle / 2 second

After the 500-cycle actuation, the slider was moved by approximately 450 μm. PZT voltage was 20V. **There is no conceivable limit to the maximum stroke of our actuator other than constraints imposed by the slider length and external load.**

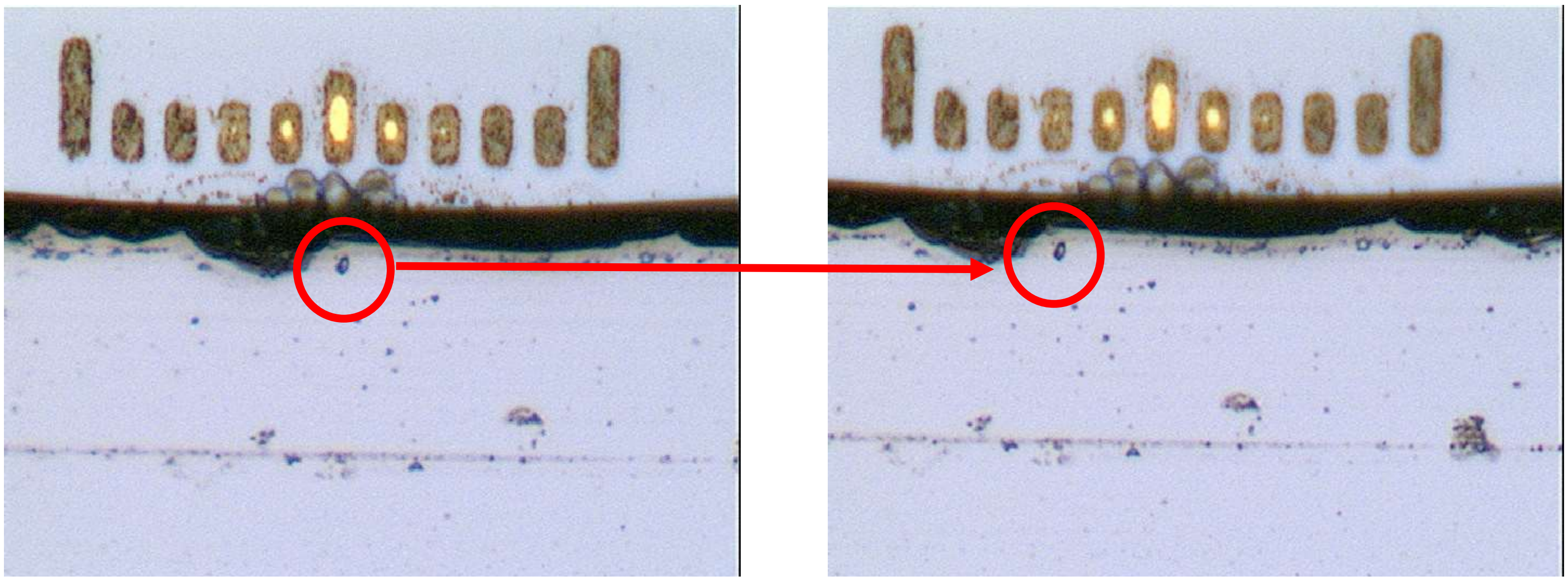


Fabricated and Assembled Actuator - 2nd generation



Slider Motion (2nd Batch Actuator)

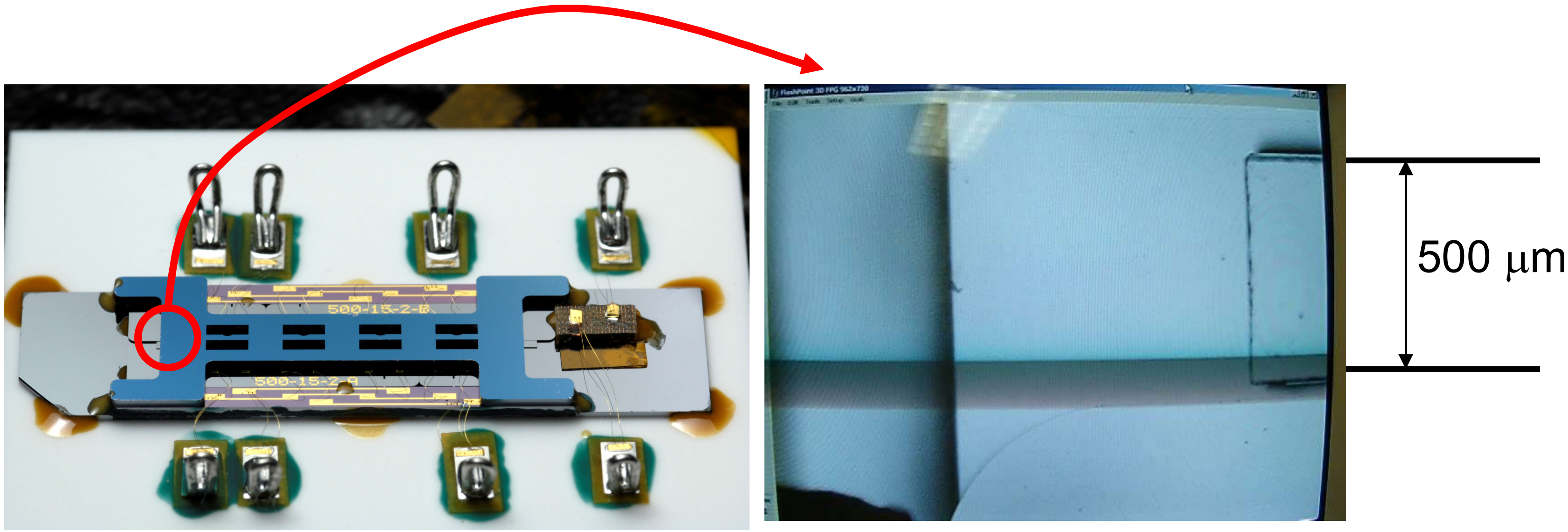
Image Processing Using Matlab



Actuator images taken before and after 100-cycle actuation:

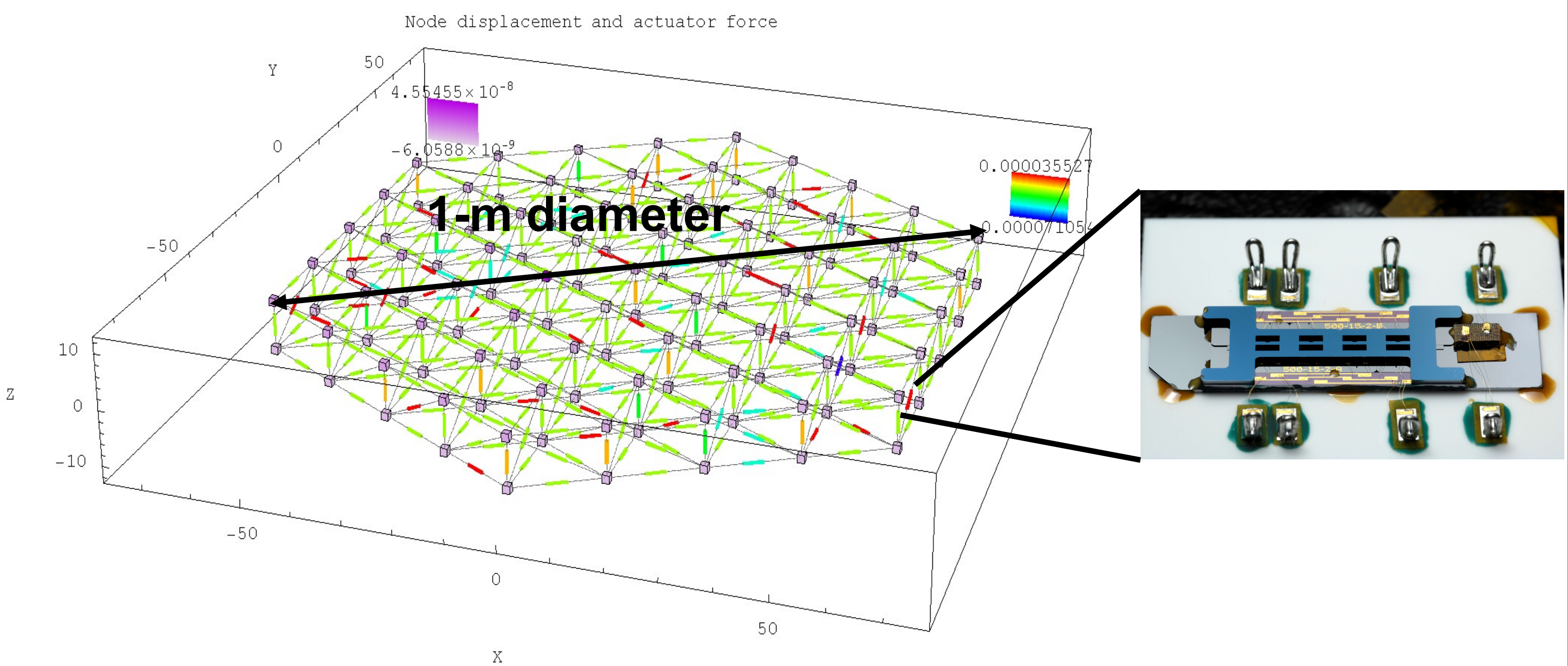
Image processing was performed to accurately calculate the slider movement, by comparing two different images taken before and after the actuation. The resolution from the calculation is approximately 50 nm.

Slider Motion



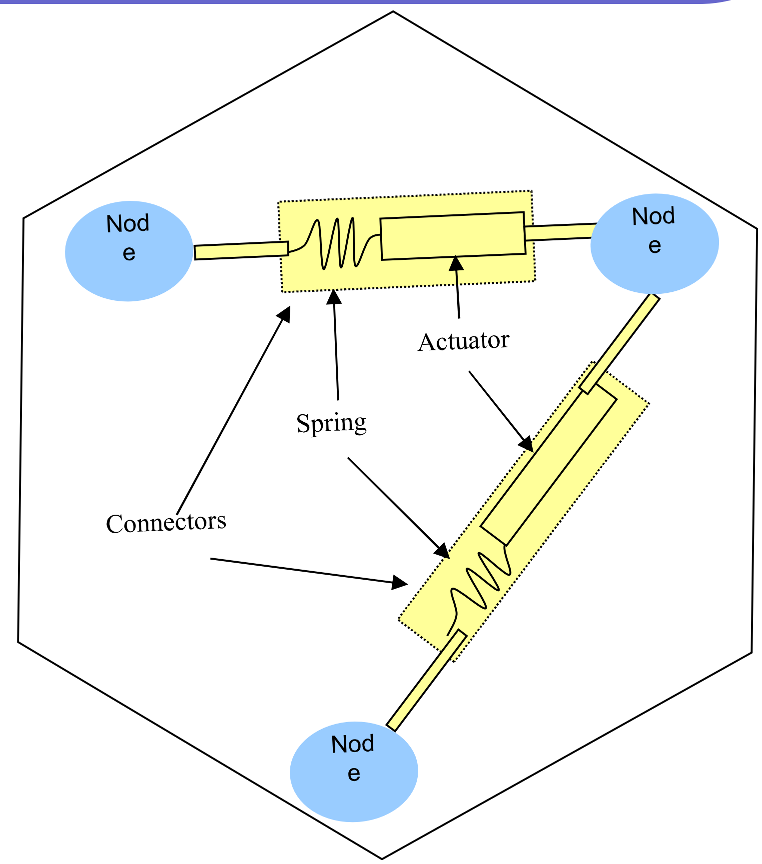
Actuated @ 20-cycle per
second with 100 V to PMN-PT

Pathfinder Mirror Modeling



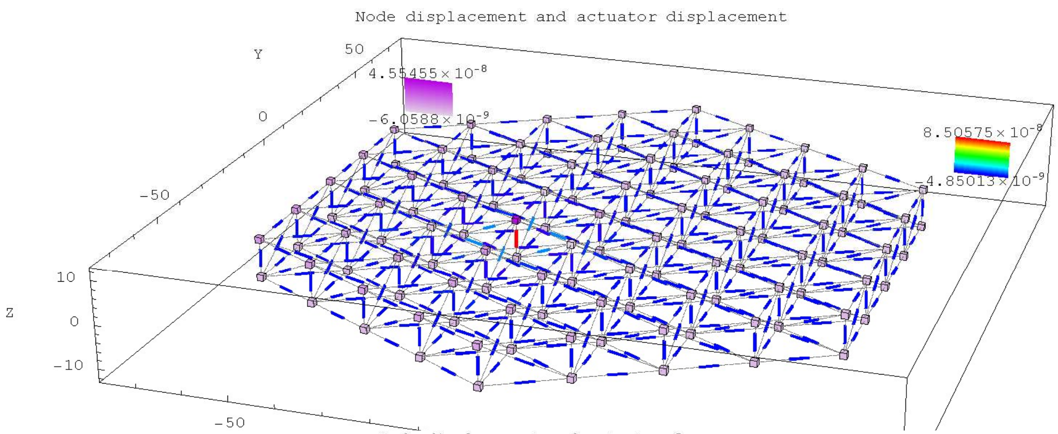
Pathfinder Mirror Modeling

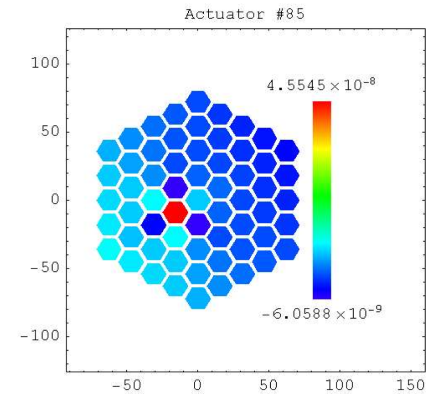
- The response of the structure to applied stimulus was calculated by minimizing the total structure energy with respect to the rest of the parameters.
- For a 1 μm step, the maximum required force on all actuators is around 1 mN (rod stiffness of 10^4 N/m).

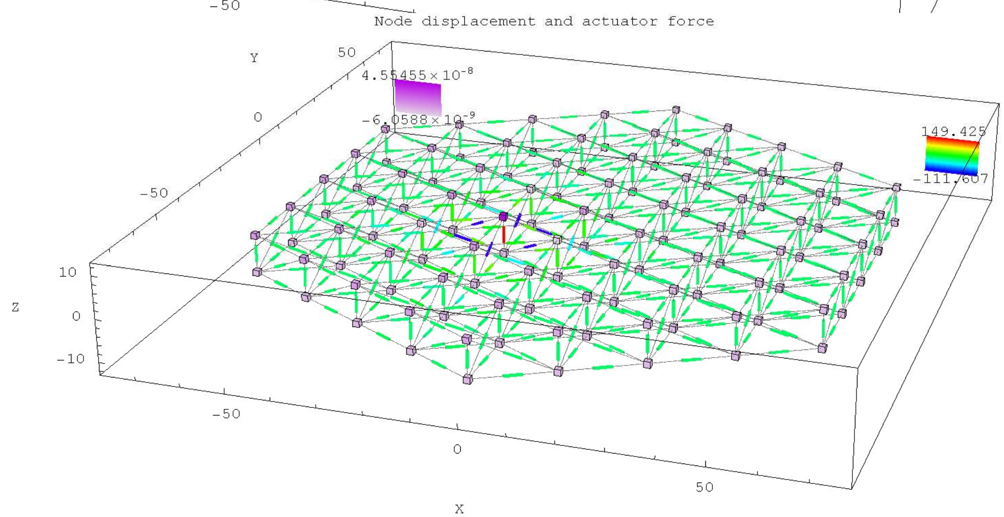


General "bulk element" model for an arbitrary actuated lattice structure

Pathfinder Mirror Modeling

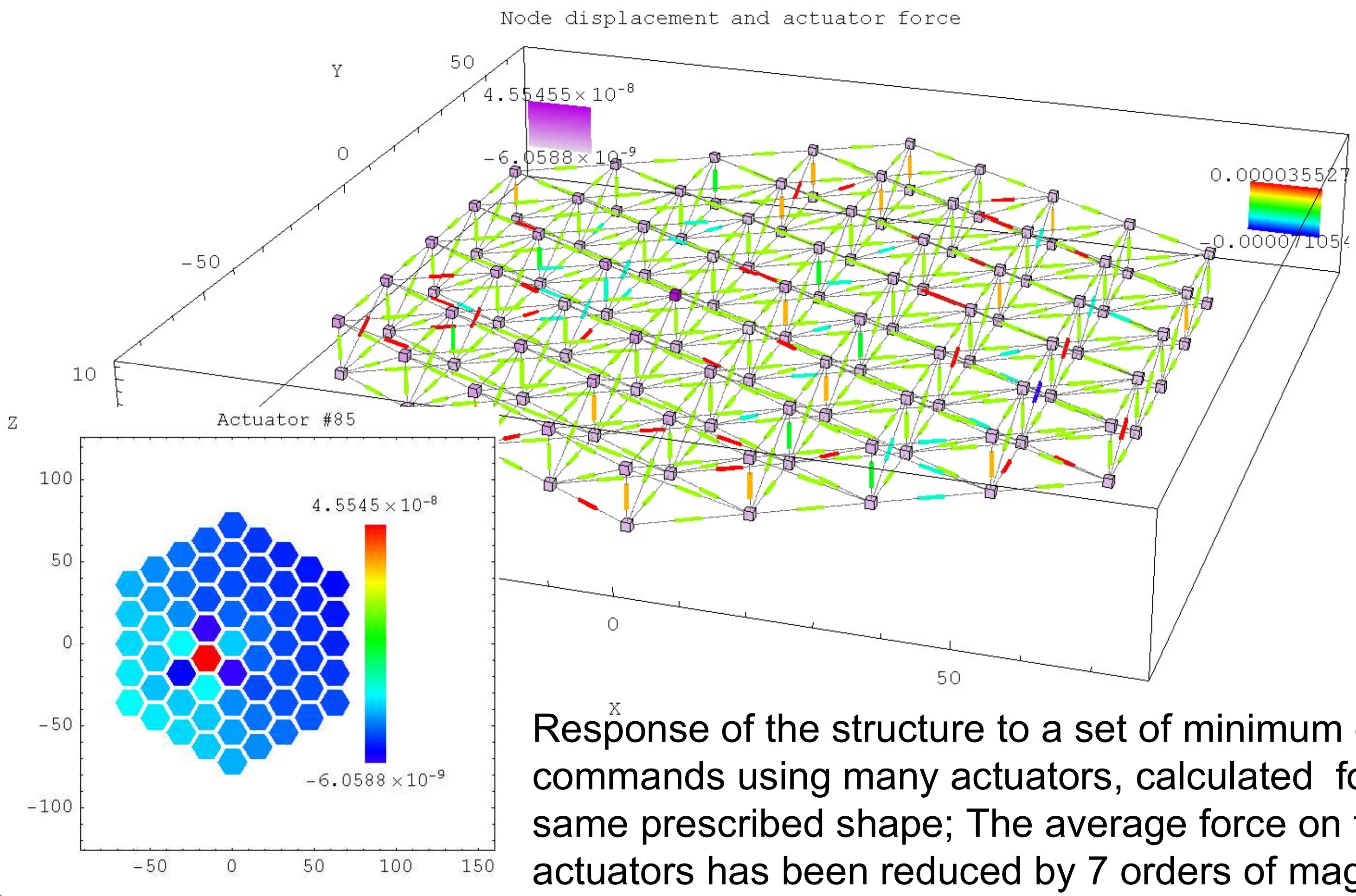






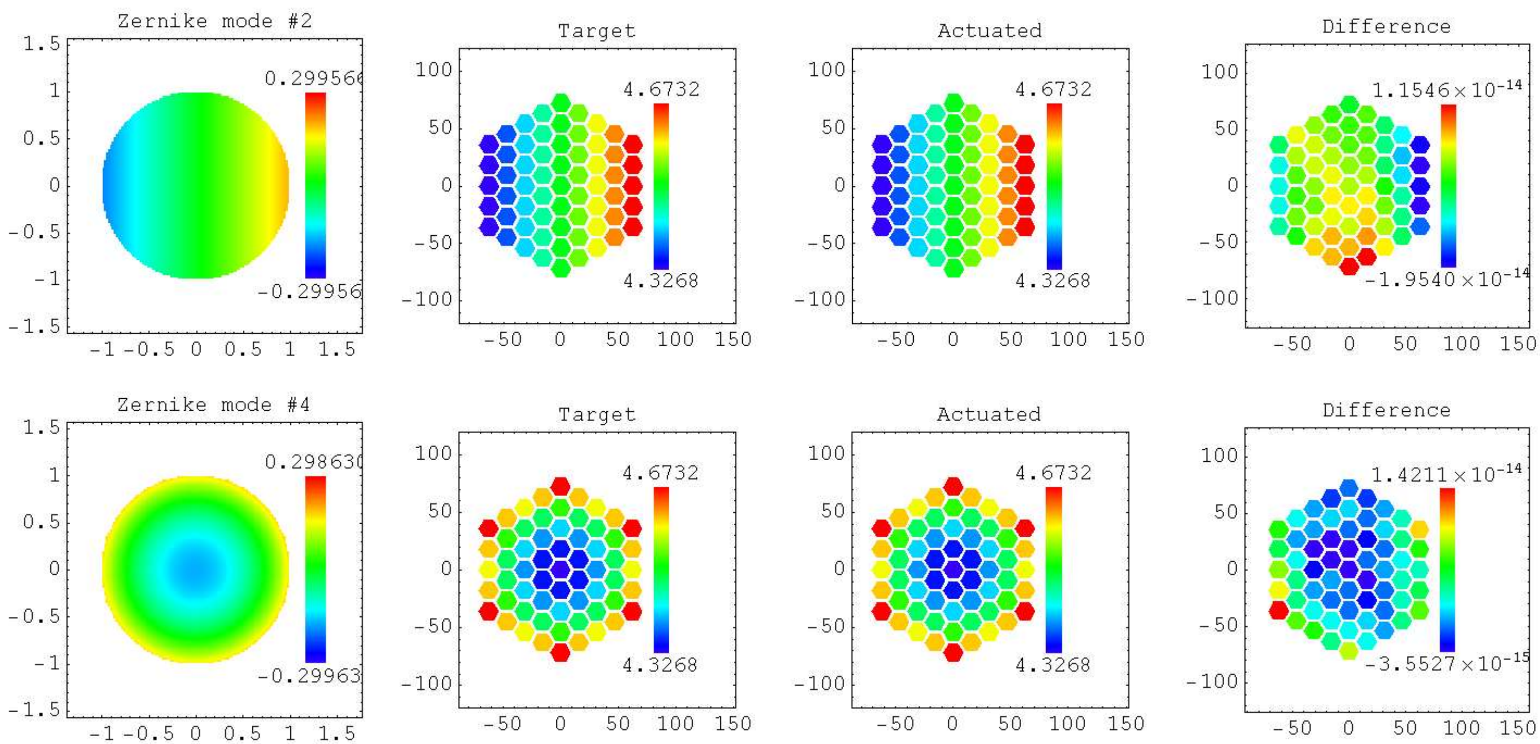
Effect of <u>one</u> actuator; A 1 nm node displacement and actuator displacement (top) and actuator force (bottom) in dynes.

Pathfinder Mirror Modeling



Response of the structure to a set of minimum energy commands using many actuators, calculated for the same prescribed shape; The average force on the actuators has been reduced by 7 orders of magnitude.

Pathfinder Mirror Modeling



Structure control to the Zernike* modes 2 and 4. Actuator displacement commands were calculated and were subsequently applied. The structure response to the commands was computed.

* In optics, the aberrations are often represented as a sum of special polynomials, called *Zernike polynomials*. Atmospheric random aberrations can be considered in the same way; however, the coefficients of these aberrations (defocus, astigmatism, etc.) are now random functions changing in time. A Zernike polynomial is defined in polar coordinates on a circle of unit radius.

Actuator Performance Summary

	Target	Demonstrated	
Max. Freq.	~1 kHz	20-cycle/s	(1)
Stroke	> 1 mm	0.5 mm @ 130-cycle	(2)
Resolution	<30 nm	50 nm	(3)
Force	> 30 mN	48 mN	(4)
Power	100 μW	0 W when latched	
Size	~ 10 mm^3	14x7x0.6	
Mass		100 mg	

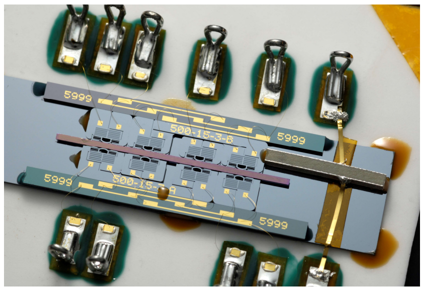
(1) *The higher-speed actuation (>20Hz/cycle) could not be demonstrated due to the frequency limit of the mechanical relay used for supplying electrical AC signal to actuators. In principle, the actuator structure with PZT and comb units can move at frequencies exceeding 1kHz.*

(2) *The stroke of our actuator is limited only by the slier length and imposed force.*

(3) *The measured resolution was limited by the image quality for image processing. Actual resolution (minimum step size) is expected to be better.*

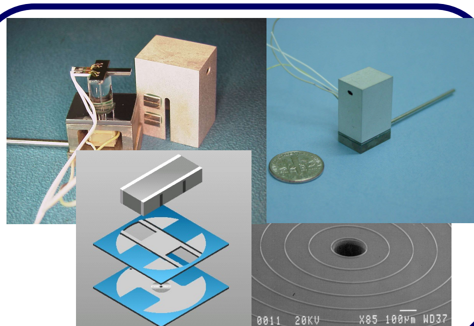
(4) *The clamping force was modeled using ANSYS.*

Topics that are covered in this talk



- Linear Microactuator

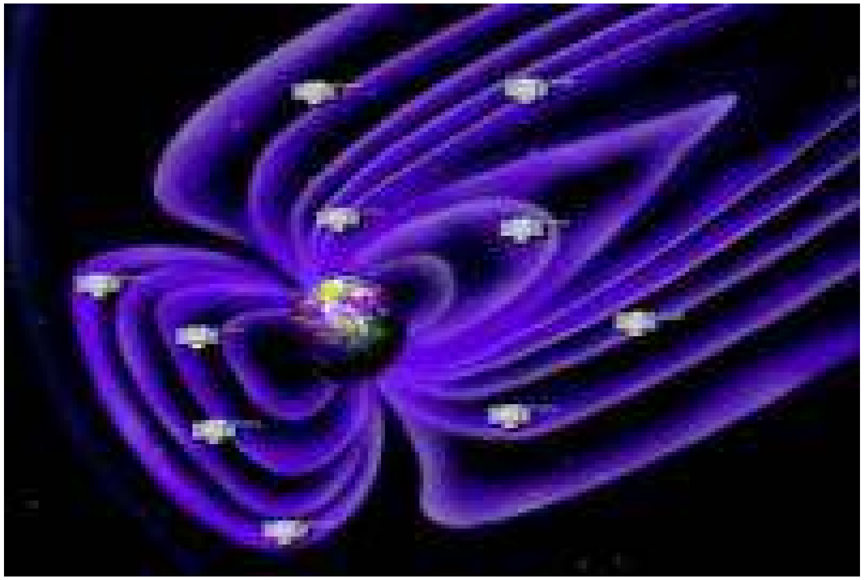
For active wavefront correction for space telescopes



- **Piezoelectric Microvalve**

For micropropulsion for microspacecrafts

Small Spacecrafts Requiring Microvalves



NASA's future Earth Science Mission
10s - 100s of S/C

Microspacecraft typical envelope:

1~ 10 kg mass, ~10 cm^3 volume, ~1 W power

➔ Requiring microvalves capable of fast-actuation, low-leak, high-pressure and low-power operation

For Xenon-based Micropropulsion (High pressure)

Generic Microvalve Requirements

- **Leak Rate** - 0.005 sccm He

Generic Microvalve Requirements

- <u>Leak Rate</u> - 0.005 sccm He
- <u>Inlet Pressure</u> - ~ 1000 psi

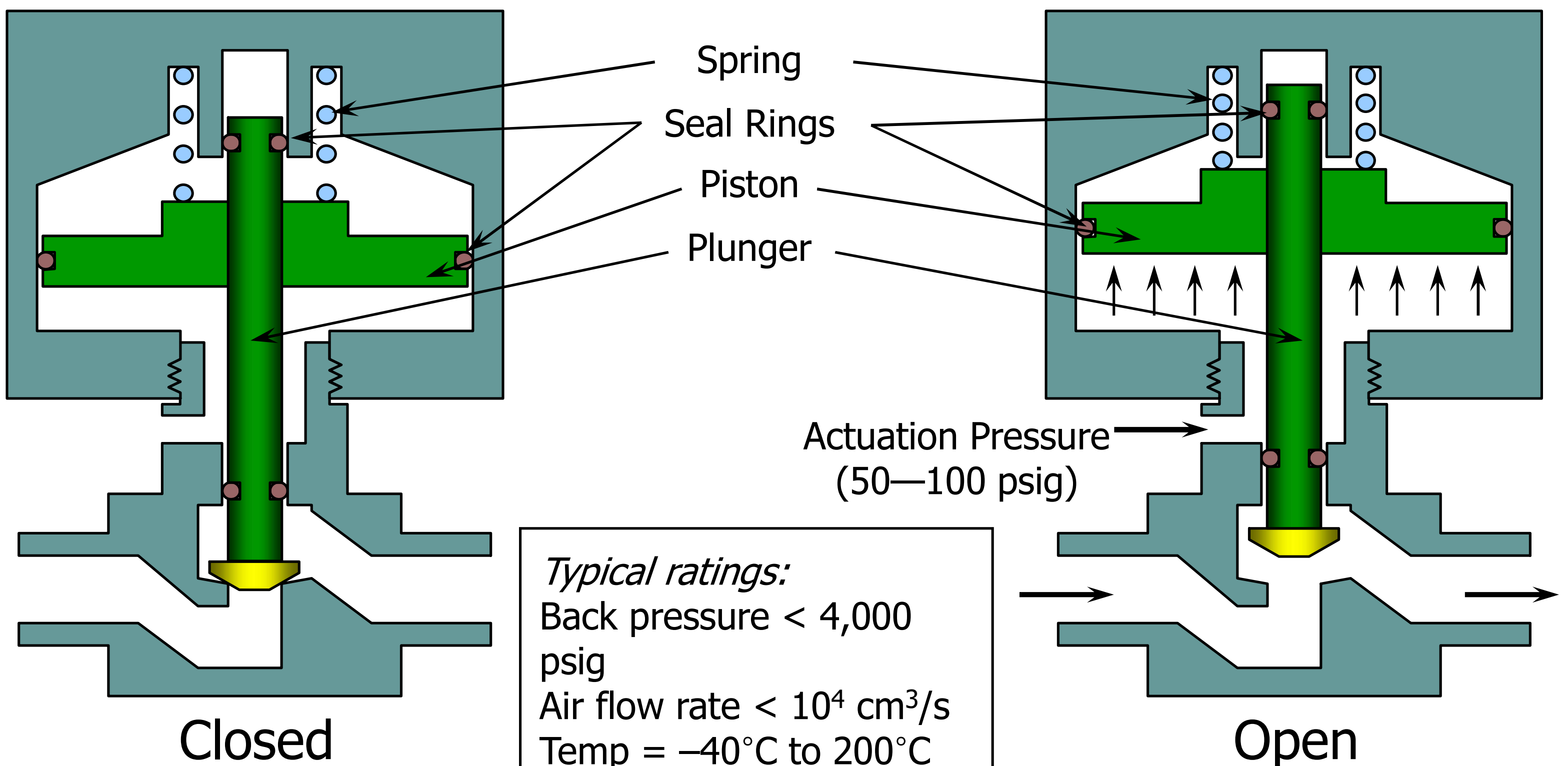
Generic Microvalve Requirements

- **<u>Leak Rate</u>** - 0.005 sccm He
- **<u>Inlet Pressure</u>** - ~ 1000 psi
- **<u>Actuation Speed</u>** - << 1 ms

Generic Microvalve Requirements

- <u>Leak Rate</u> - 0.005 sccm He
- <u>Inlet Pressure</u> - ~ 1000 psi
- <u>Actuation Speed</u> - << 1 ms
- <u>Power</u> - << 1 W
- <u>Package Weight</u> - < 10 g
- <u>Temperature</u> - 0 ~ 75 °C

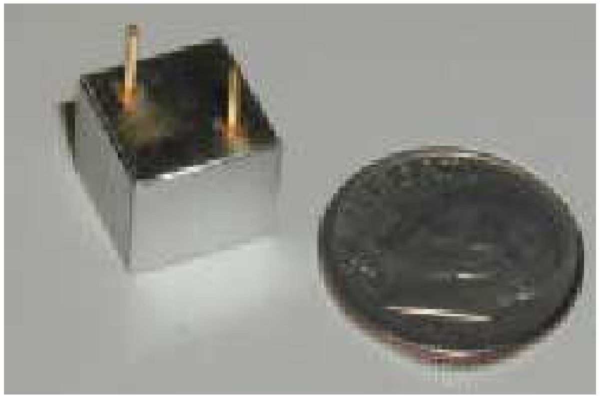
Typical Normally-Closed Valves



Typical ratings:
Back pressure < 4,000 psig
Air flow rate < 10^4 cm^3/s
Temp = –40°C to 200°C
Leak = 10^{-2} — 10^{-9} cm^3/s

Mass, size, power

Solenoid-based Microvalve for Micropropulsion



Moog Micro Valve prototype

Table 2: Performance Parameters of the MMV Prototype

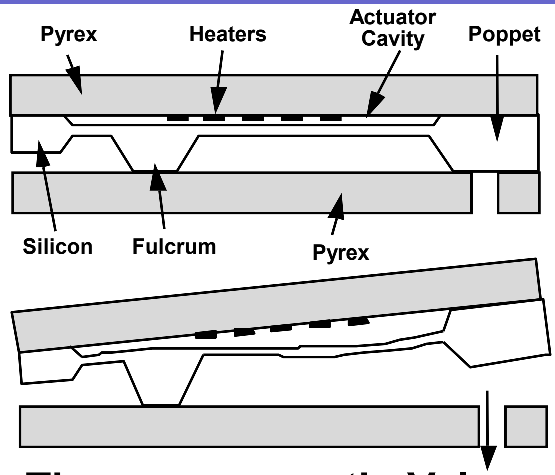
Parameter	MMV Performance
Mass (gram)	7
Size (cm^3)	1 (approx. 1 x 1 x 1 cm)
Power (W)	0.7 (continuous) **4 W (open)**
Voltages (Vdc)	5
Response (ms)	1.5 (open), 0.5 (close)
Pressure (psi)	300 (nom), 1000 (max)
Operating Temp(°C)	0-70
Life	1,000,000 cycles*
Leakage	$< 10^{-4}$ sccs GN_2 (after 1M cycles)

*Test terminated voluntarily

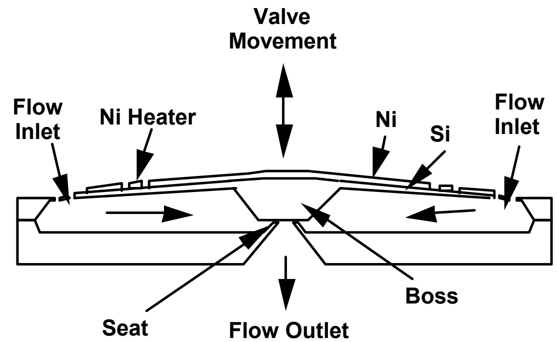
Ref: Juergen Mueller, et. al., "An overwiew of MEMS-based micropropulsion developments at JPL", IAA 2001, B3-1004

S/C Power - 1 W

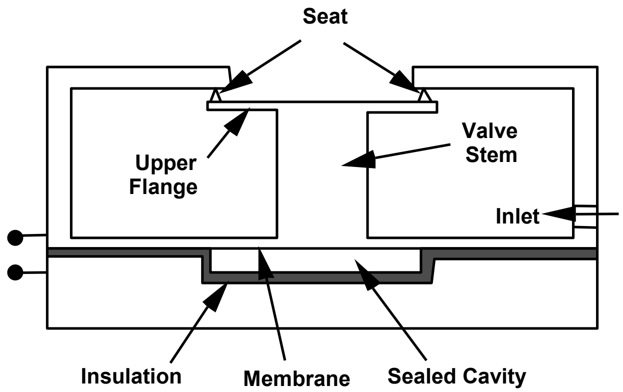
MEMS-based Valves



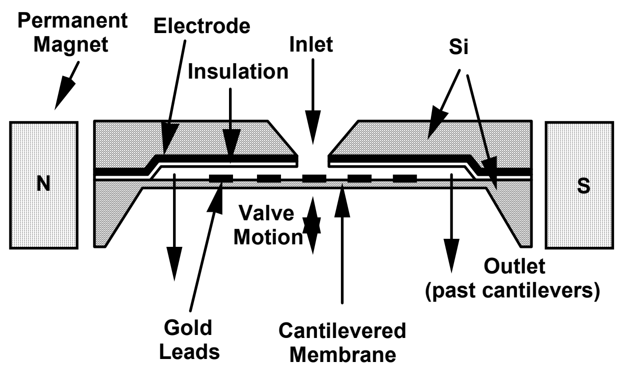
Thermopneumatic Valve



Bimorph Valve



Electrostatic Valve



Electromagnetic Valve

Limitations of Existing Microvalves

• Conventional microvalve technologies: mass/volume, power consumption

➔*e.g. 3-8 W to operate*

• Typical MEMS-based valves: leak and/or narrow pressure range

➔ *e.g. 400 ms, 0.2 sccm (20 psi), 2 W*

Microvalve Actuation Choices

	Thermo-pneumatic	Bi-metalic	SMA	Electrostatic (w/spring)	Piezoelectric
Governing Equations	$F = A\ P_2\ (T_1 / T_2)$ P = pressure A = area T = temperature	$F = w\,t^3\,(\Sigma E)\,d / l^3$ w = beam width t = beam thickness ΣE = sum of moduli l = beam length d = deflection	$F = K\,A\,\delta$ A = actuator area δ = strain K = constant, based on Flexinol ™ data	$F = \varepsilon_0 A V^2 / 2g^2$ g = gap, V = voltage, A = area	$F = E_P\,A\,\delta$ E_P = piezo modulus A = area, δ = strain
Geometry	Gas Capsule 10 mm diameter 5 mm high	8 2mm × 2 mm Beams 100 µm thick, (50/50 Ni, Si)	SMA disk 10 mm diameter 5 mm high	Capacitor disk 10 mm diameter w/ spring	Piezo disk 10 mm diameter 5 mm high
Force	~ 1N	~ 2 mN	~ 14 kN	~ 2 µN	~ 5 kN
Max Deflection	-	10 µm	20 µm	5 µm	5 µm
Power	high	high	high	low	low
Actuation Time	long	long	long	short	short

National Aeronautics and Space Administration
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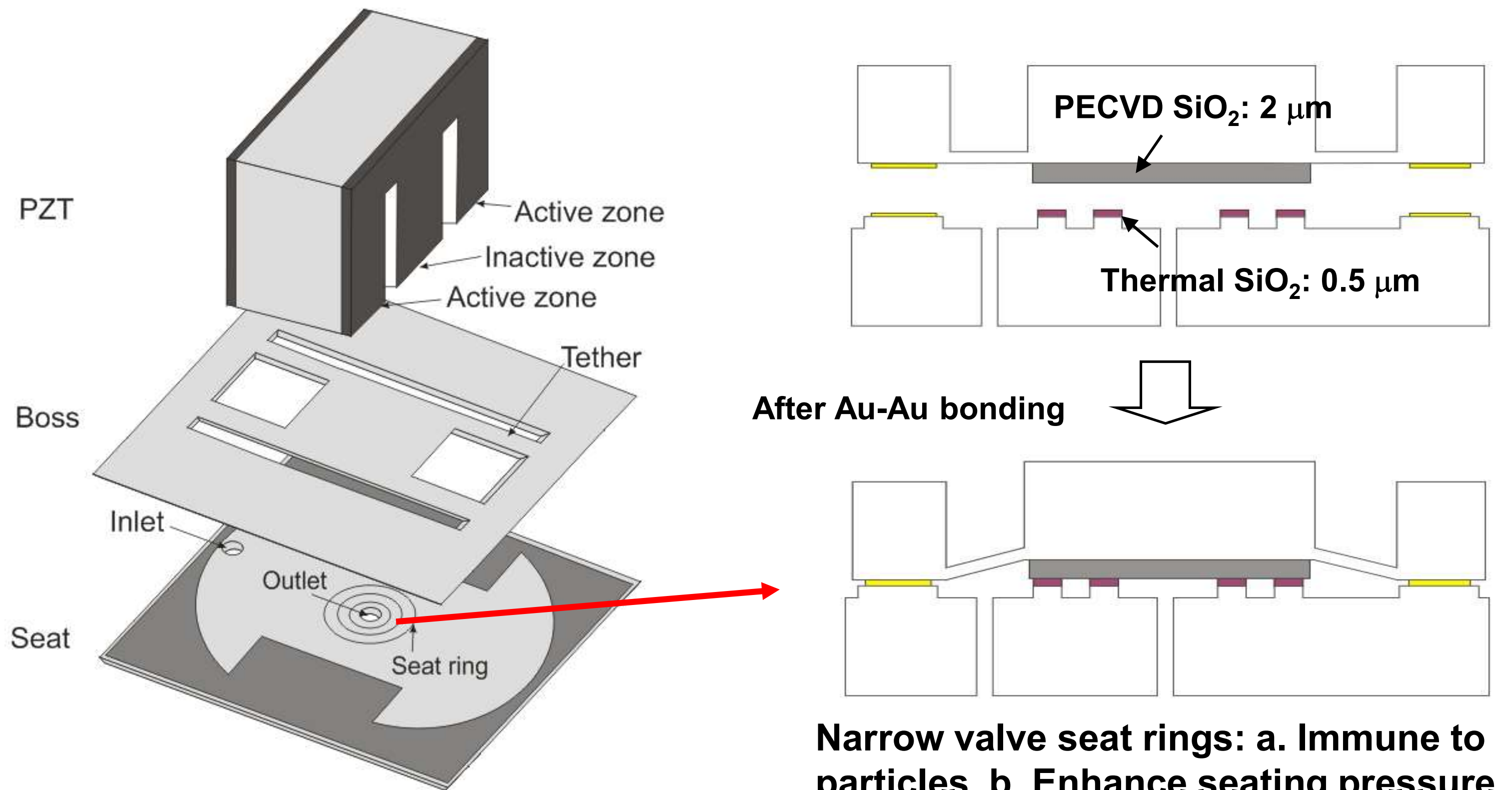
Microvalve Design



Narrow valve seat rings: a. Immune to particles, b. Enhance seating pressure

•Estimated maximum stresses in the tethers (ANSYS): 80 MPa (on-state).
•Seating pressure from pre-stressed PZT: 50 GPa (reducing leak rates)

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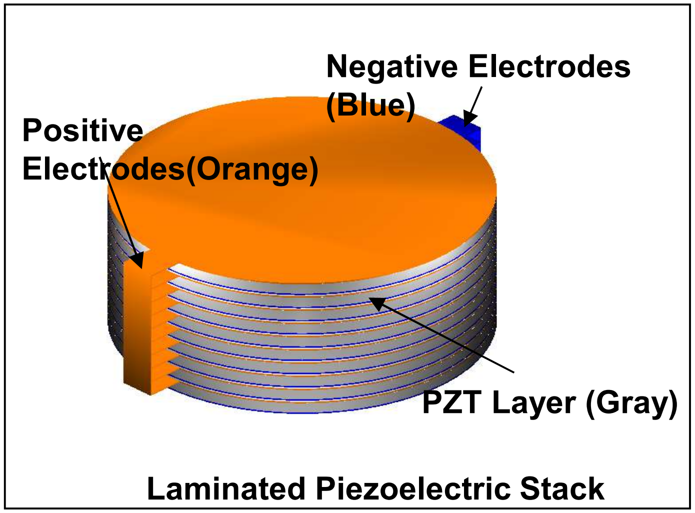
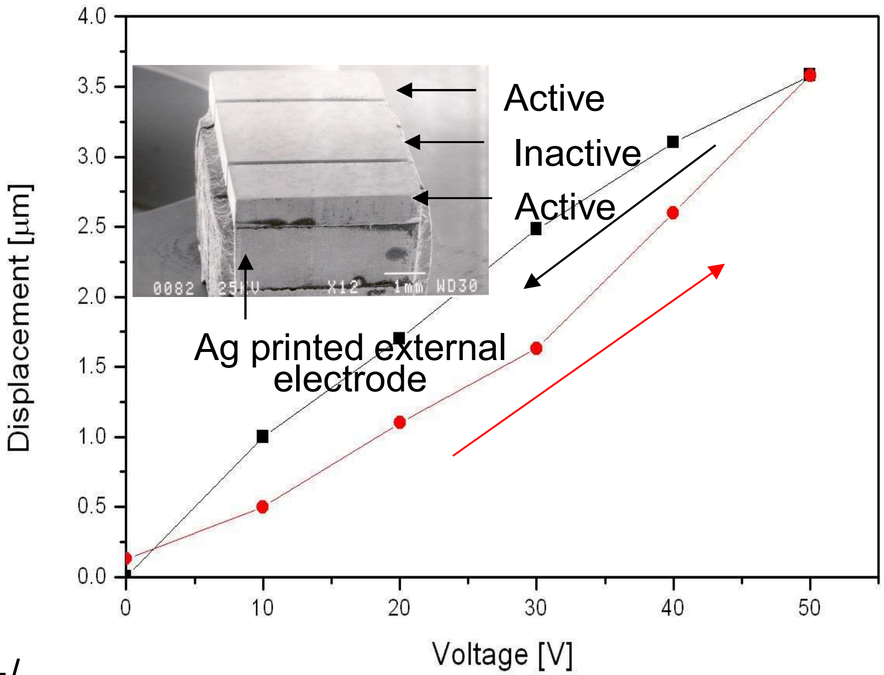
Custom-Designed PZT-Stack

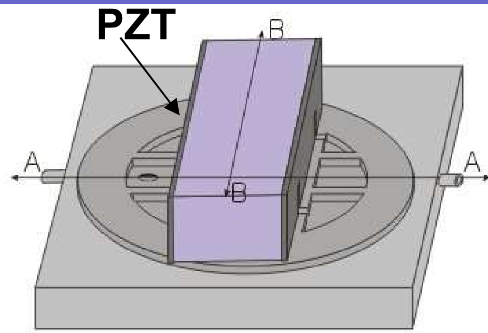


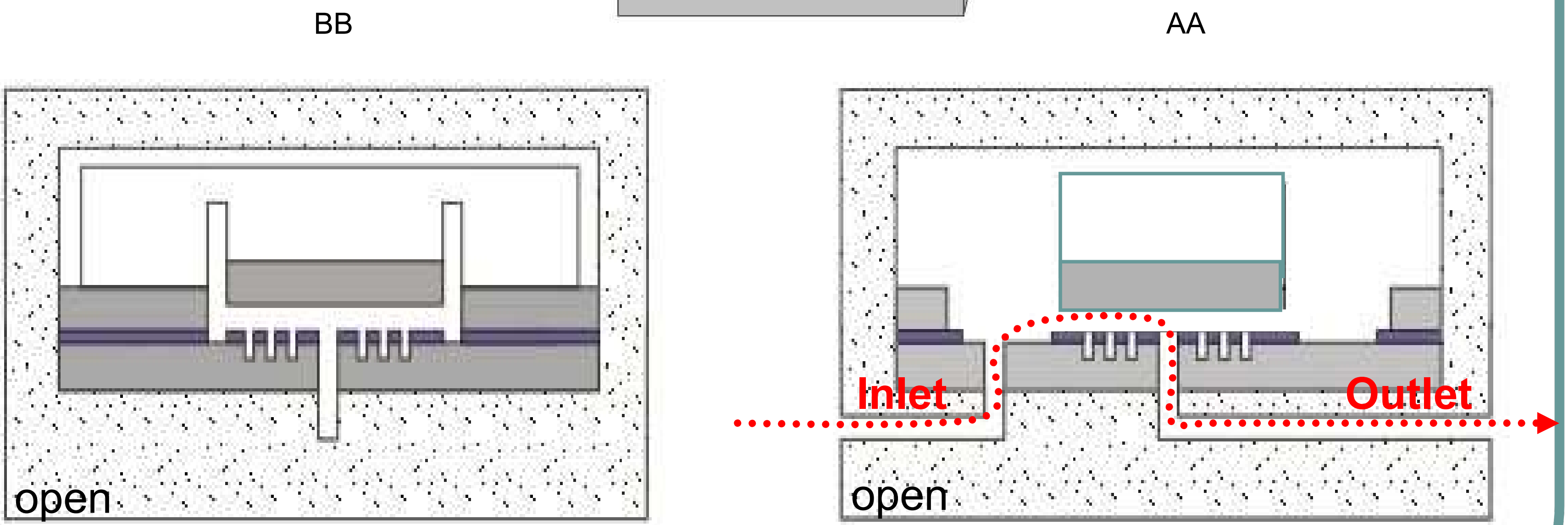


- Thin layers of PZT (100 µm),
- Each layer sandwiched between +/- electrodes
- d33 mode actuation

Seating pressure from pre-stressed PZT: 50 GPa

Microvalve Operation

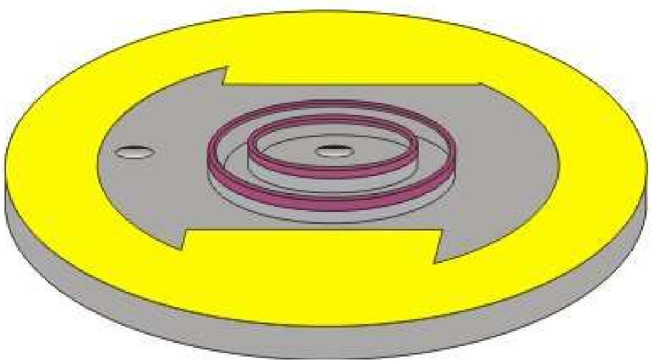




E.H. Yang, L. Wild, N. Rohatgi and D. Bame, “A Piezoelectric Microvalve under Ultra-High Upstream Pressure for Integrated Micropropulsion and Method for Operating the Same”, CIT-3889, US Patent Pending, 10/853,072.

Fabrication Process

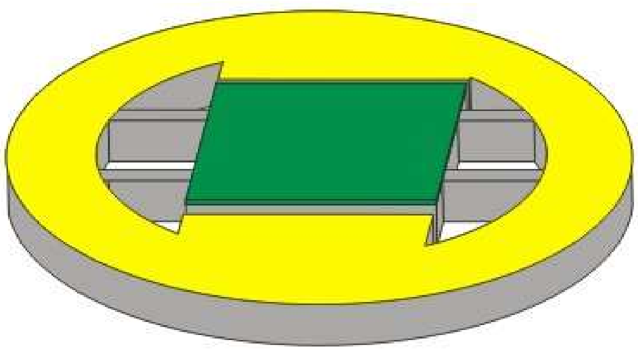
- Seat process



Etching: inlet & outlet holes

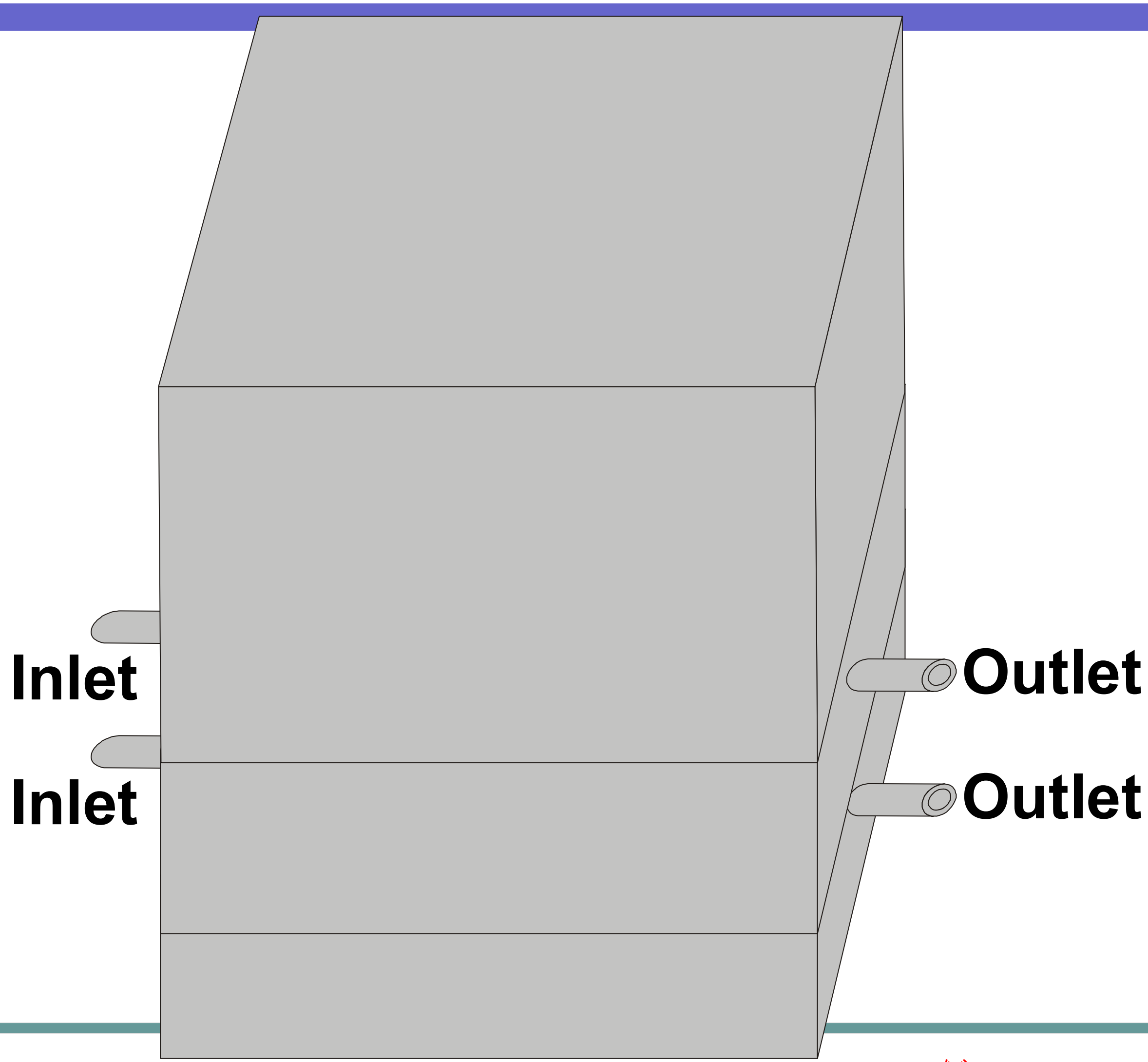
Fabrication Process

- Boss process

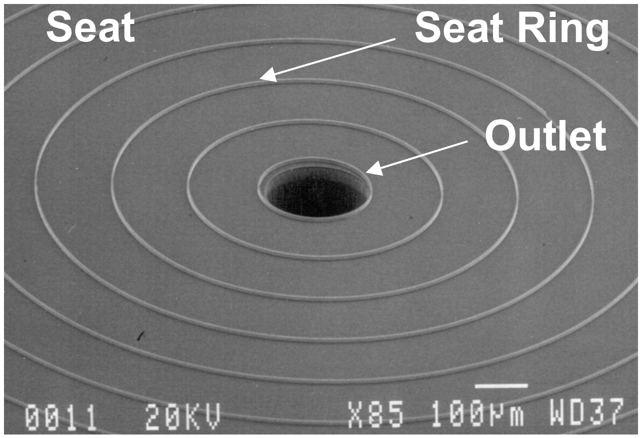


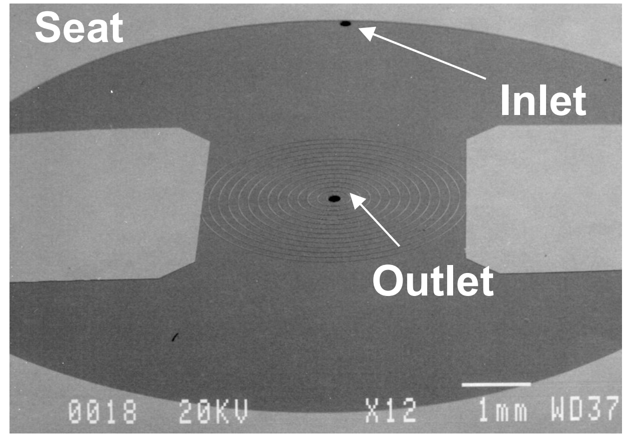
Etching: boss & tethers

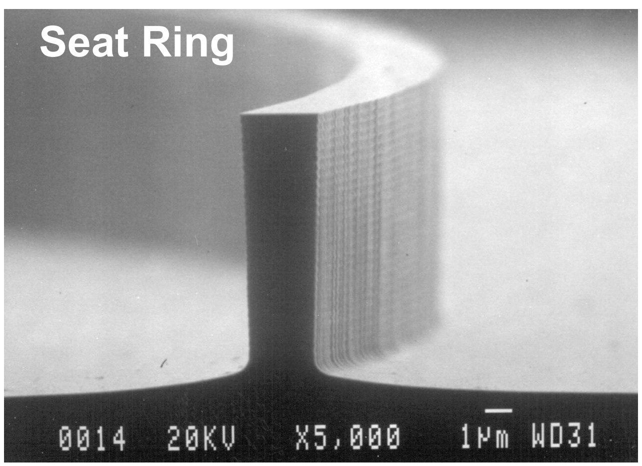
Assembly Sequence

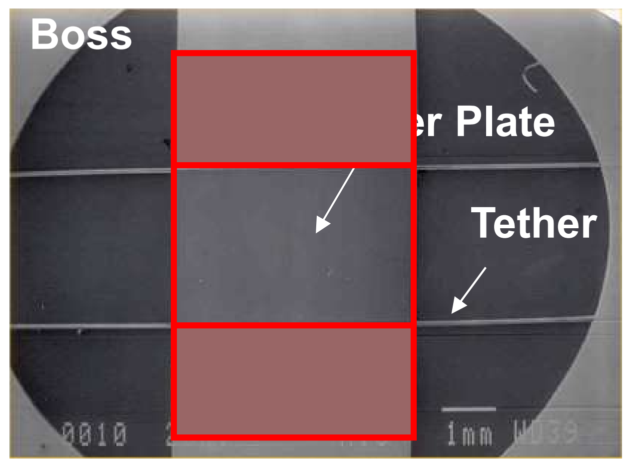


Fabricated Microvalve

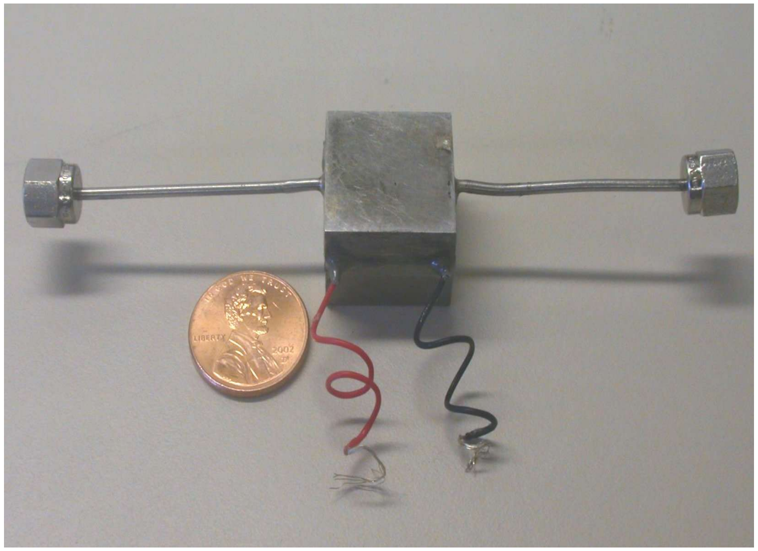


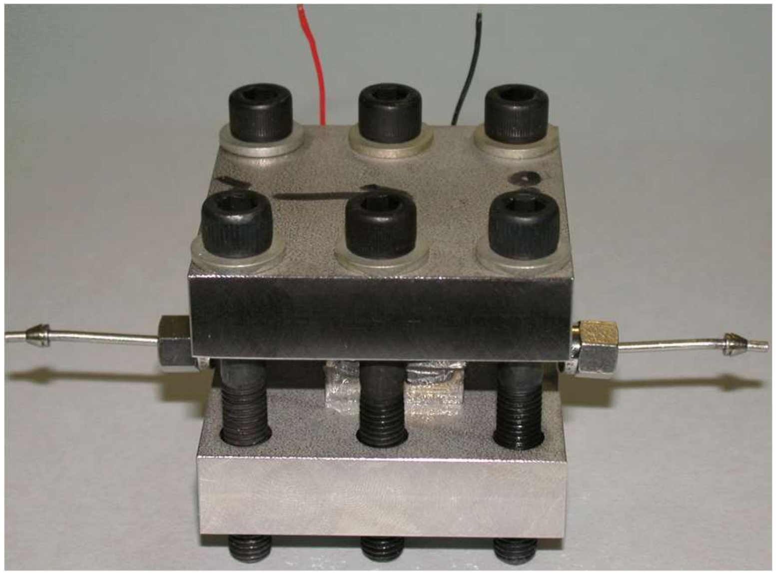






Fabricated Microvalve

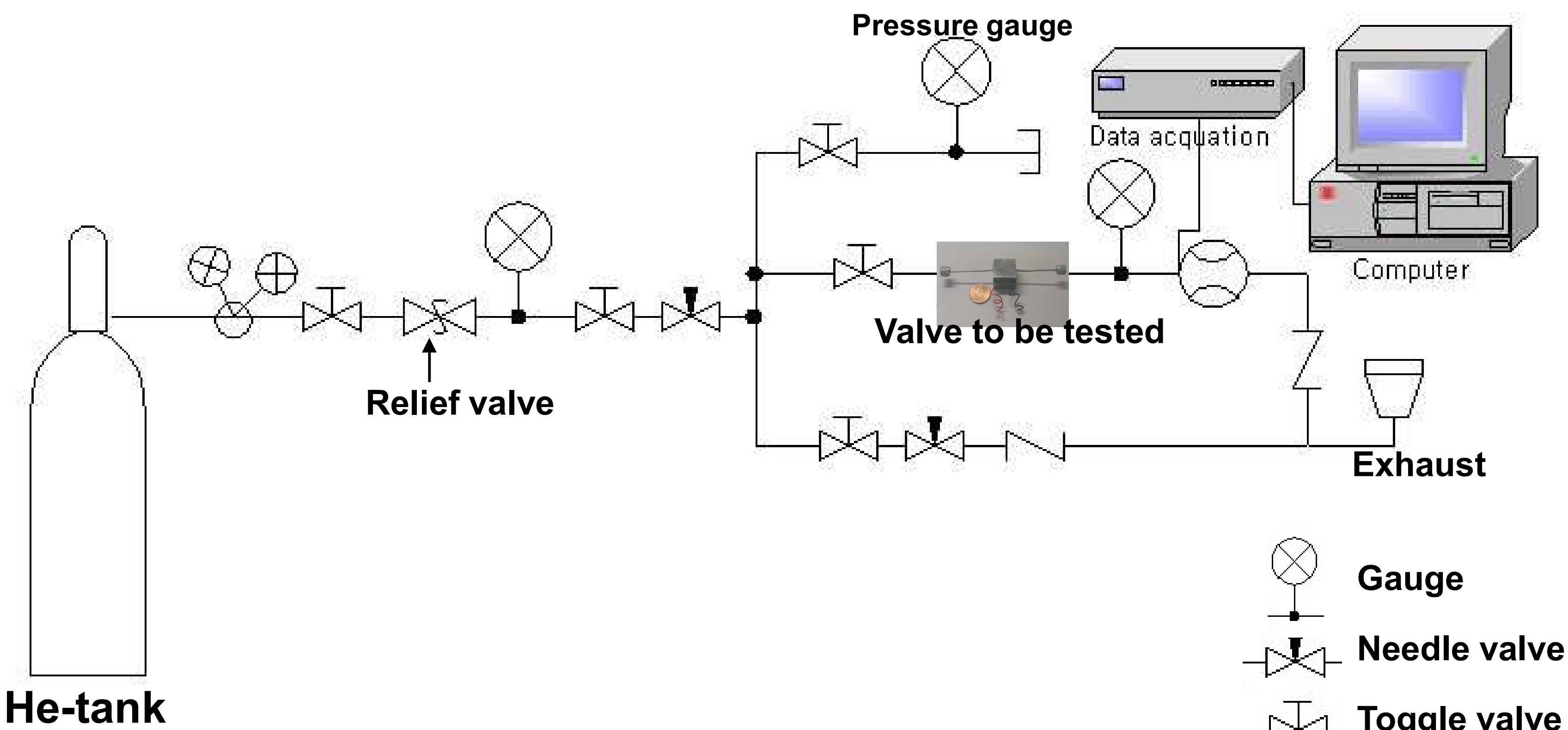




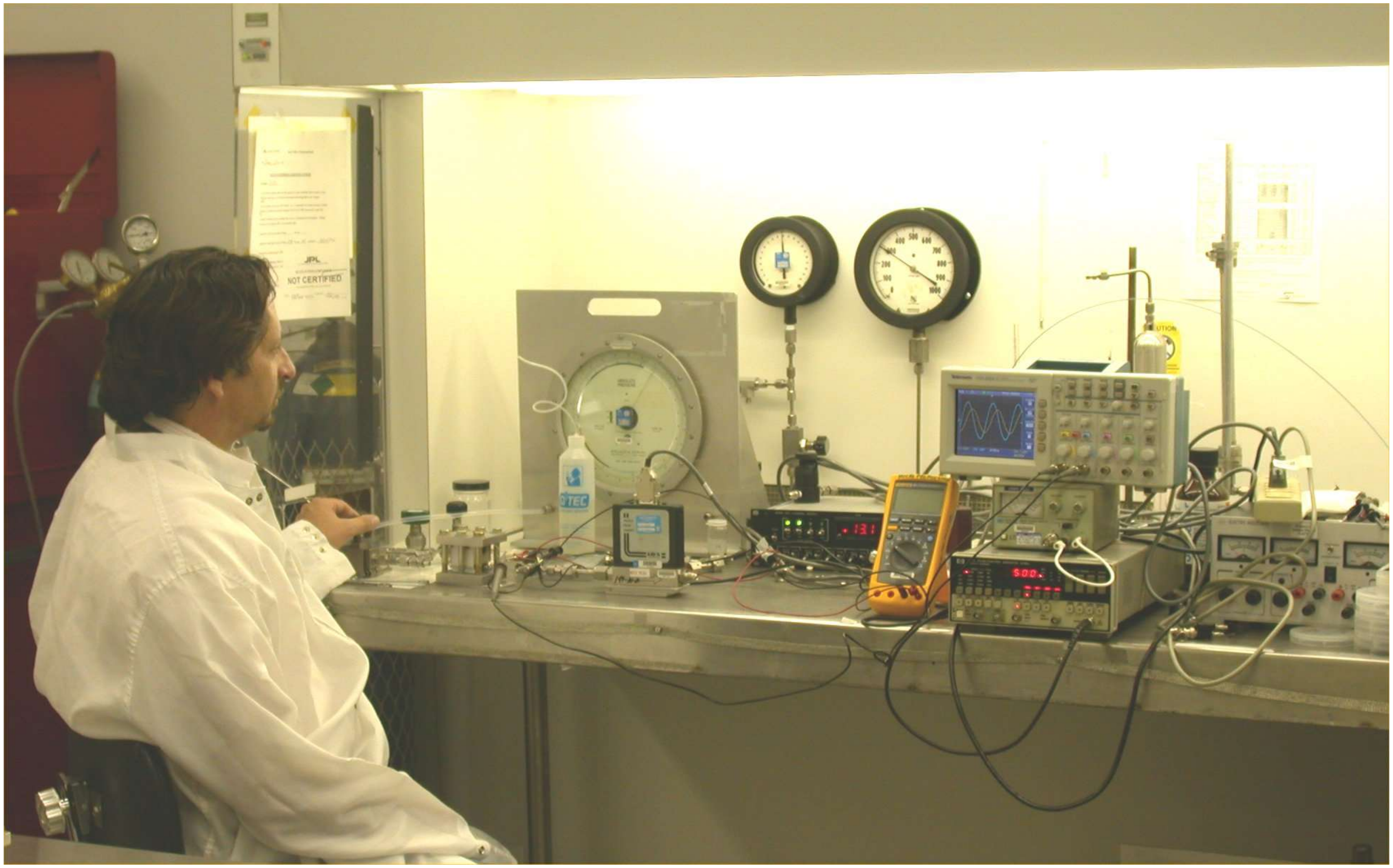
Microvalve Housing for High-Pressure Test

E. H. Yang, C. S. Lee, J. Mueller and T. George, "Leak-Tight Piezoelectric Microvalve for High-Pressure Gas Micropropulsion," *IEEE/ASME Journal of Microelectromechanical Systems, Vol. 13, No. 5,* pp. 799-807, Oct. 2004.

Test Bench


Pressure gauge
Data acquation
Computer
Valve to be tested
Relief valve
Exhaust
He-tank
Gauge
Needle valve
Toggle valve

Test Bench



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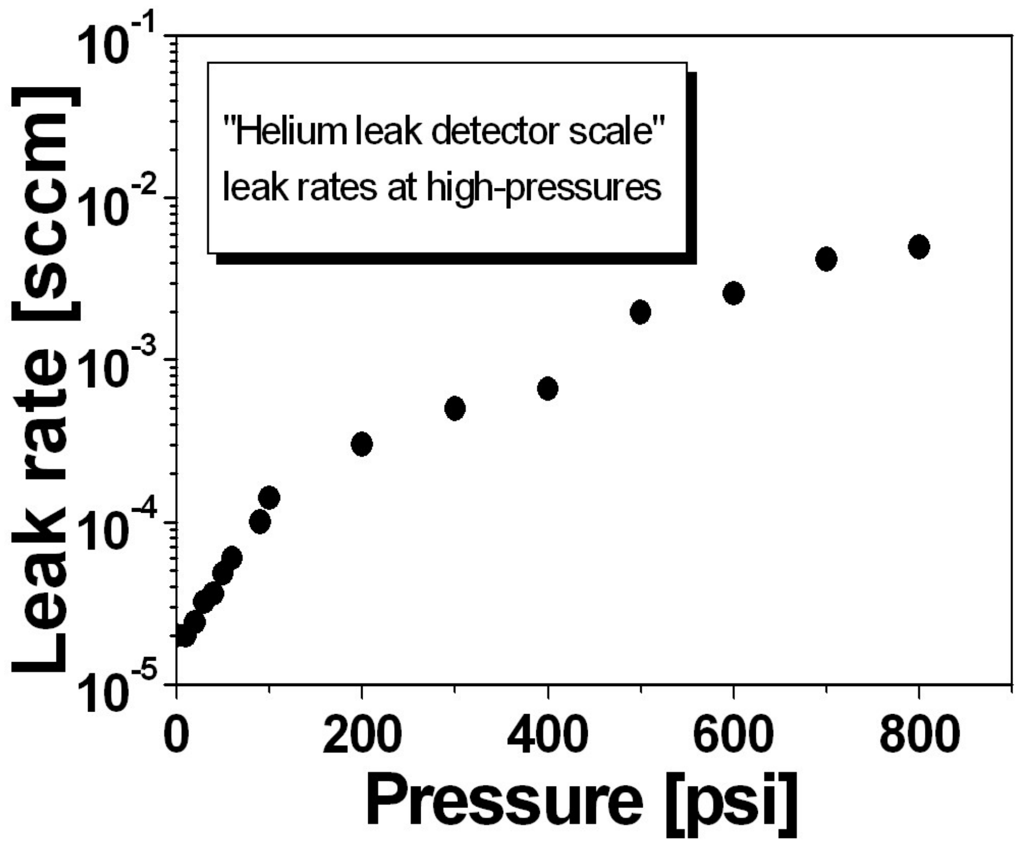
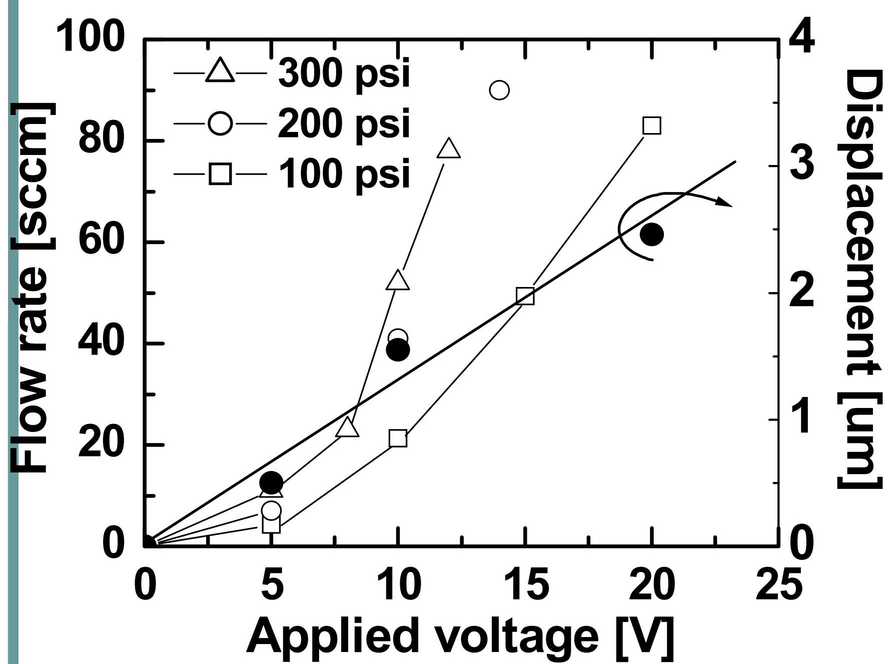
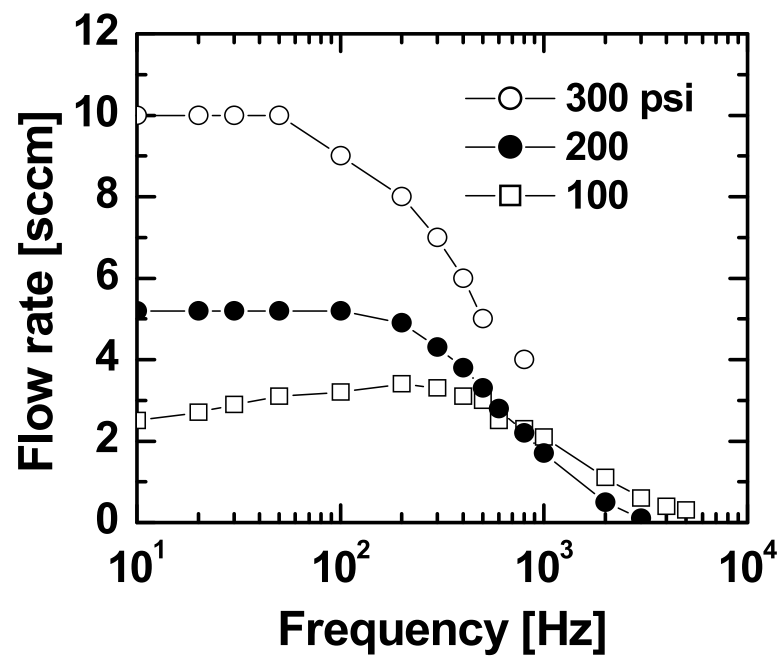
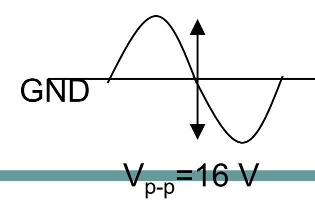
Leak Performance



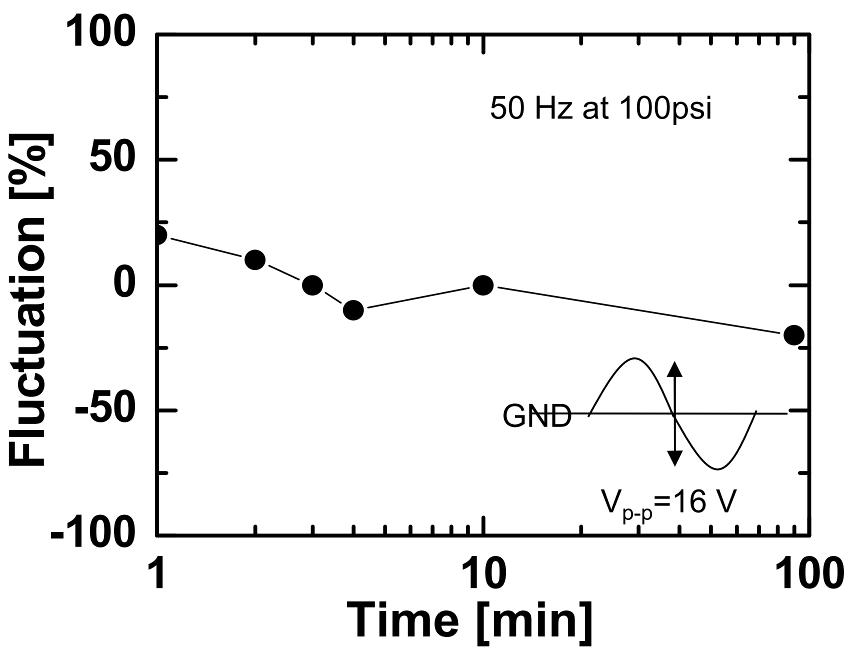
Flow Characteristics

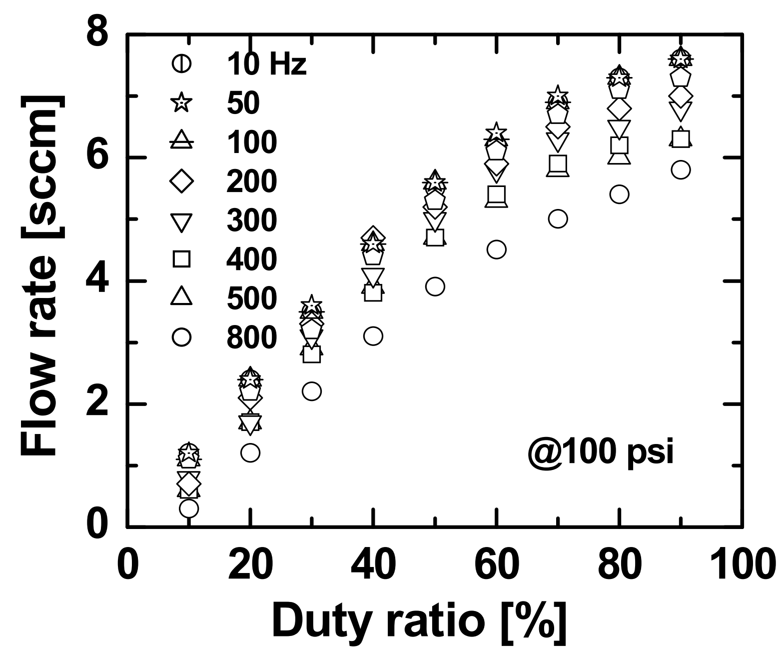


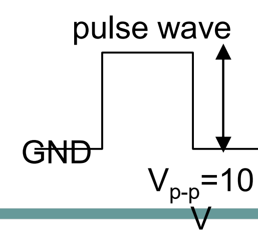




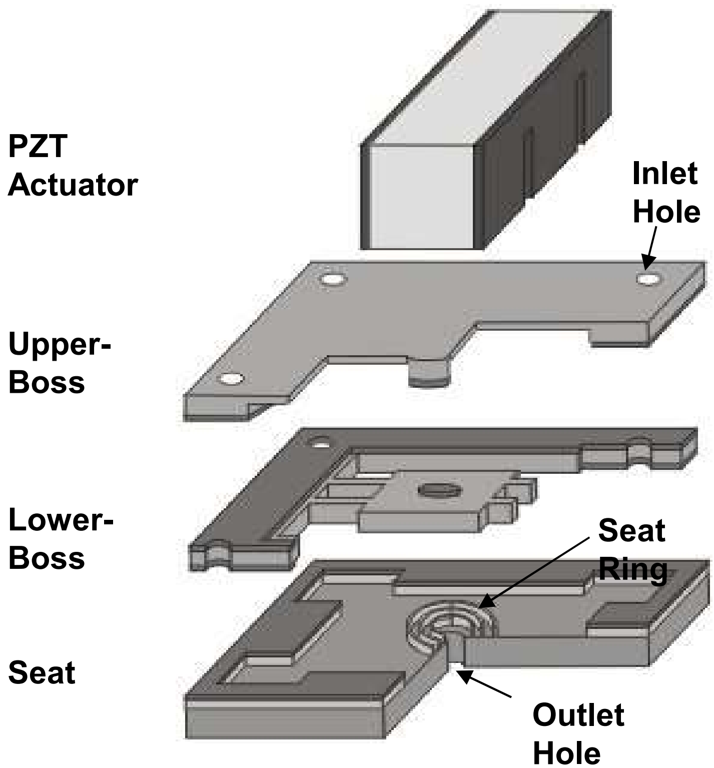
Flow Characteristics

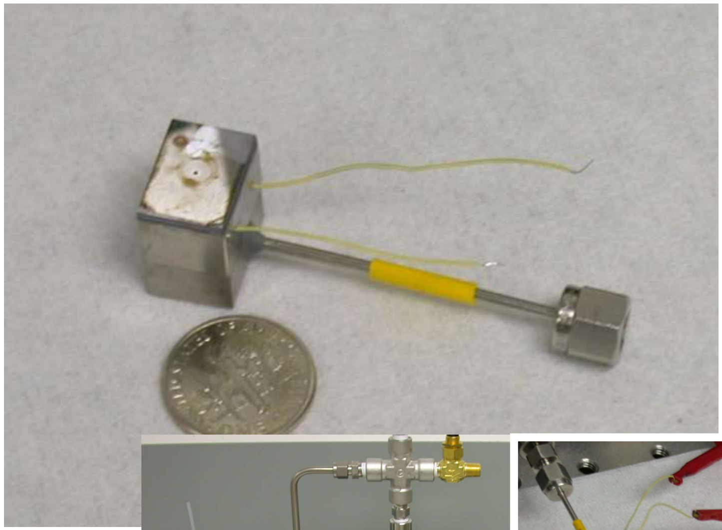


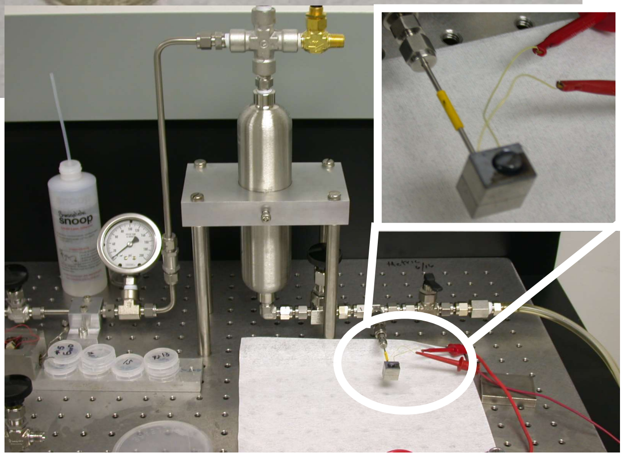




Microvalve for Liquid Flow Control

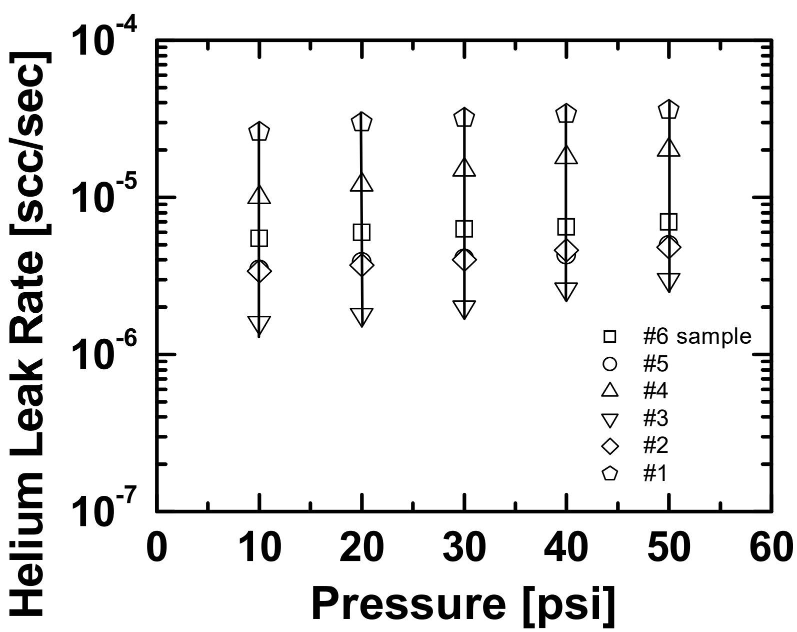


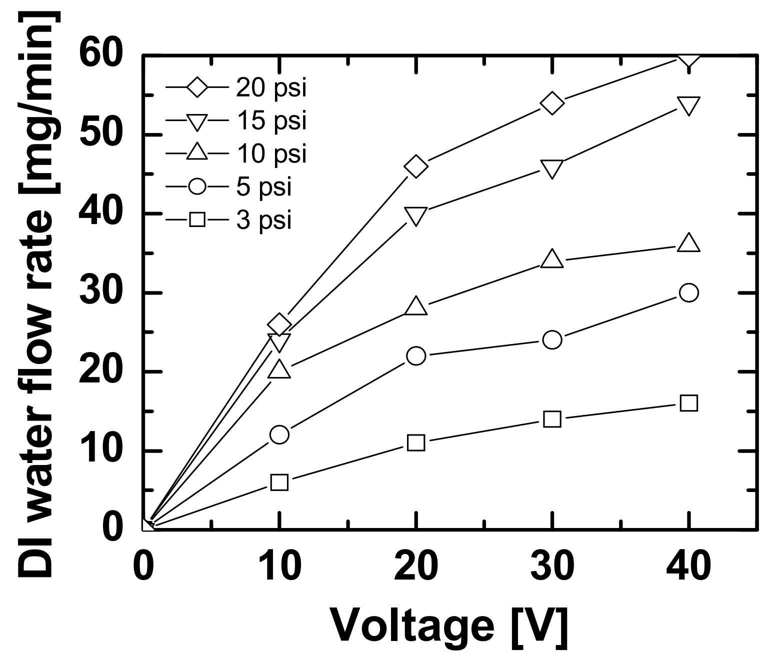




For Butane-based Micropropulsion (Medium pressure)

Leak Flow Characteristics





C. Lee, **E. H. Yang**, S. M. Saeidi and J. Khodadadi, "Fabrication, Characterization and Computational Modeling of a Piezoelectrically Actuated Microvalve for Liquid Flow Control," *IEEE/ASME Journal of Microelectromechanical Systems, Vol. 15, No. 3, June 2006.*

Valve Performance Summary

	Generic Micro-propulsion requirements	Commercially available MEMS valves		Miniaturized Solenoid valve	Our Piezoelectric Microvalve (Demonstrated)
		Company A (Fluistor™ Microvalve)	Company B (High Pressure Shuttle, .187" Spring Biased)	Moog MMV	
Leak Rate	< 5x10^{-3} sccm He	50*μl/min* @ 100 psi, 30 *°C*	5 drops/hr	6x10^{-3} sccm N_2 (after 1 M cycles)	5x10^{-3} sccm/He @ 800 psi (after 1 M cycles)
Inlet Pressure Tolerance	~ 1000 psi	100 psi max	-	1000 psi max	0 ~ 1000 psi
Actuation Speed	< 1 ms	1 s	-	2 ms	**30 μs** (calculation)
Power (on-state)	<< 1 W	1.5 W	-	4 W to open	**3 mW @ DC**
Life Time	> 10^6 cycles	-	-	10^6 cycles (Test terminated voluntarily)	10^6 cycles (Test terminated voluntarily)

Summary

- MEMS/NEMS is ideally suited for Space applications since it offers the possibility of having highly capable devices with low mass, size and power consumption.

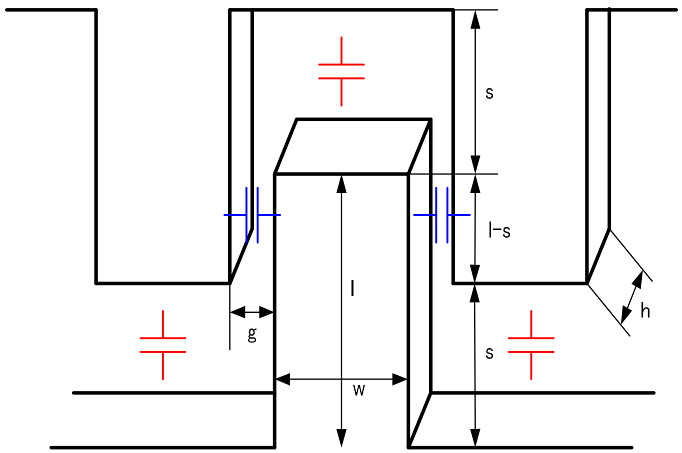
- Microactuator technologies have been developed for future space applications.
  - Linear microactuator technology: demonstrated the slider motion and modeled a pathfinder mirror structure.
  - Piezoelectric microvalves for high-pressure flow control: demonstrated fast, low power, leak-tight operation under high-upstream pressure.

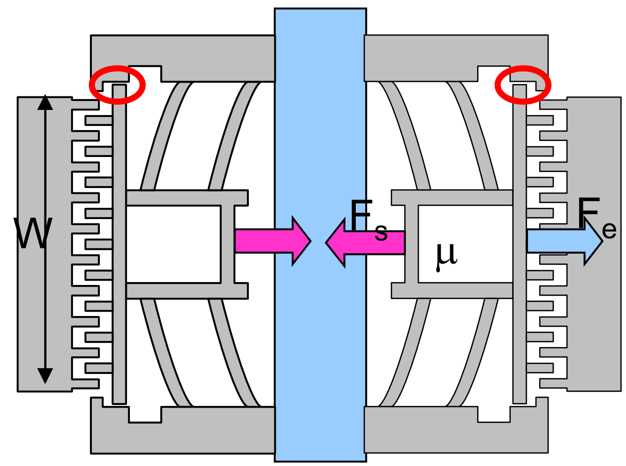
Acknowledgments

Collaborators and Team Members: Kirill Shcheglov, Risaku Toda, Zensheu Chang, B. M. Levine, R. M. Morgan, Y. Bar-Cohen (NASA/JPL); J. Su (NASA/LaRC); J. Khodadadi (Auburn); S. Trolier-McKinstry (PSU); X. Jiang (TRS);

Sponsors: NASA Code R Micro/Nano Sciencecraft, NASA Gossamer S/T NRA, JPL RTD05-06, JPL DRDF02-05, NRO, NRO-DII04-05

Comb Drive Design





Capacitance at comb drive:

$$C = (C_{tip} + C_{side})\frac{W}{2(w+g)} = \varepsilon_0\left(\frac{w}{s-x} + \frac{l-s+x}{g}\right)\frac{hW}{w+g} \cong \varepsilon_0 \frac{(l-s+x)hW}{g(w+g)}$$

Electrostatic force at comb drive F_e:

$$F_e = \frac{1}{2}\frac{\partial C}{\partial x}V^2 = \frac{1}{2}V^2\frac{\varepsilon_0 hW}{g(w+g)}$$

F_s: Tether beam restoring force
μ: friction coefficient
F_e: Electrostatic force

For unclamping, $F_e > F_s$
Maximum clamp load=μF_s