MEMS Technologies for Optical Applications

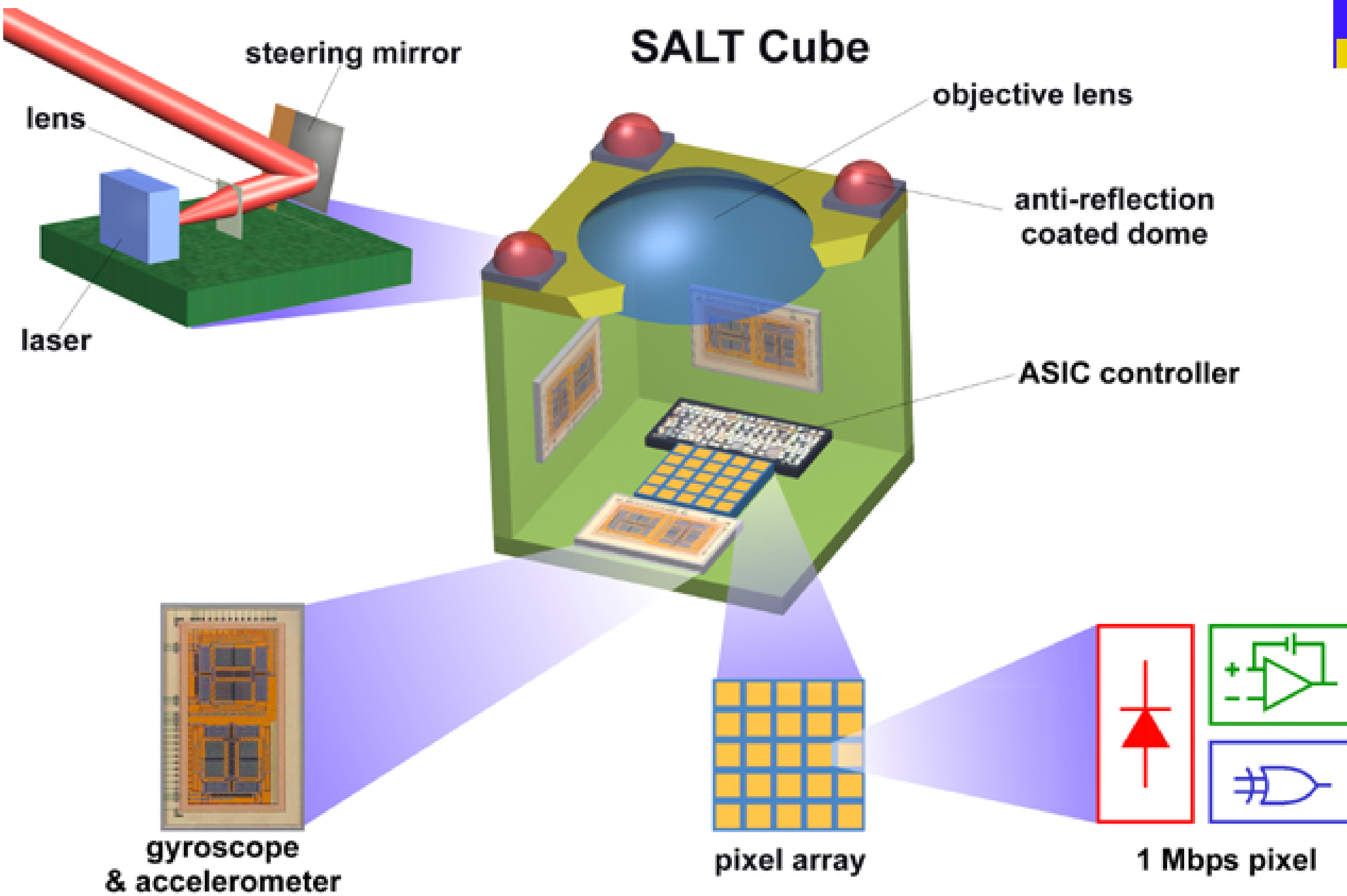
Dr. Veljko Milanović
Adriatic Research Institute
2131 University Ave Suite 322
Berkeley, CA 94704-1079
http://www.adriaticresearch.org

Adriatic Research Institute

Outline

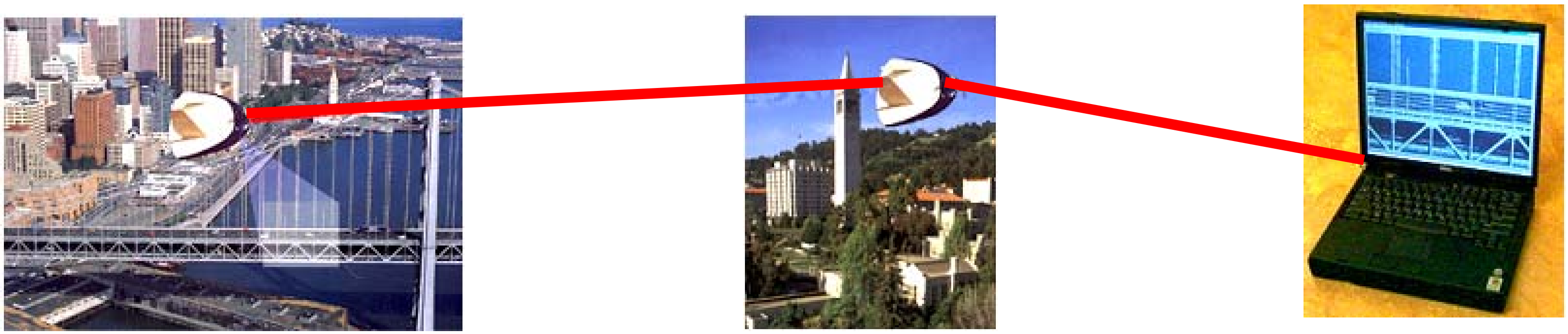
- Motivations and Background
  - Application Examples
  - Electrostatic actuators overview
  - Some micromirror examples
- High aspect ratio MEMS
  - Silicon on Insulator MEMS (SOI-MEMS)
  - Micromirrors in SOI-MEMS
- ARI Approach: Multilevel Beam SOI-MEMS
  - Fabrication and Results
  - Device examples
- Latest results with collaborators at UC Berkeley, demos
- Gimbal-less 2D Optical Scanner – *Kyoto* device

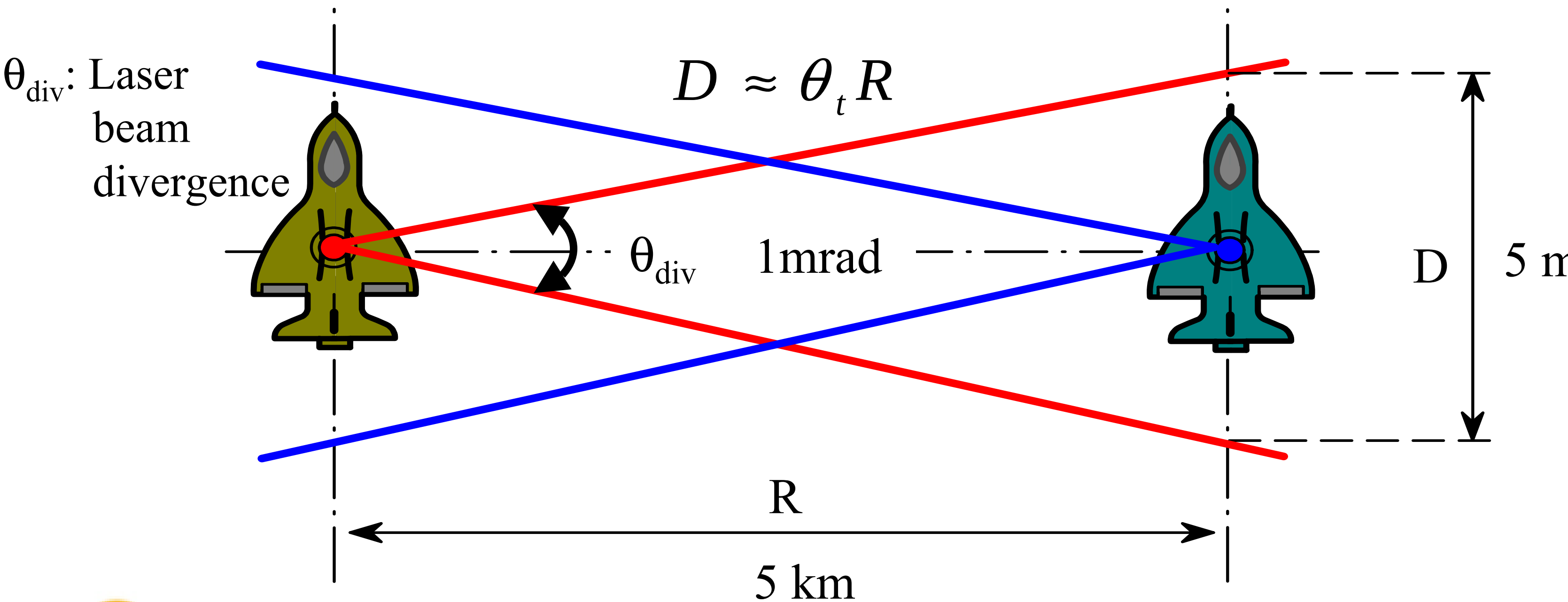
BSAC Motivation: cm^3 Multisensor Optical Transceiver



Latest SALT Objectives

Free-space laser communication between mobile nodes using MEMS transceivers

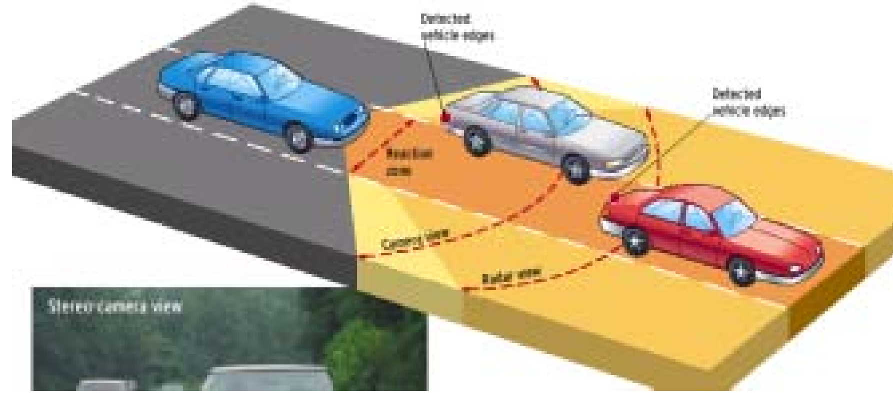




Applications: Automotive

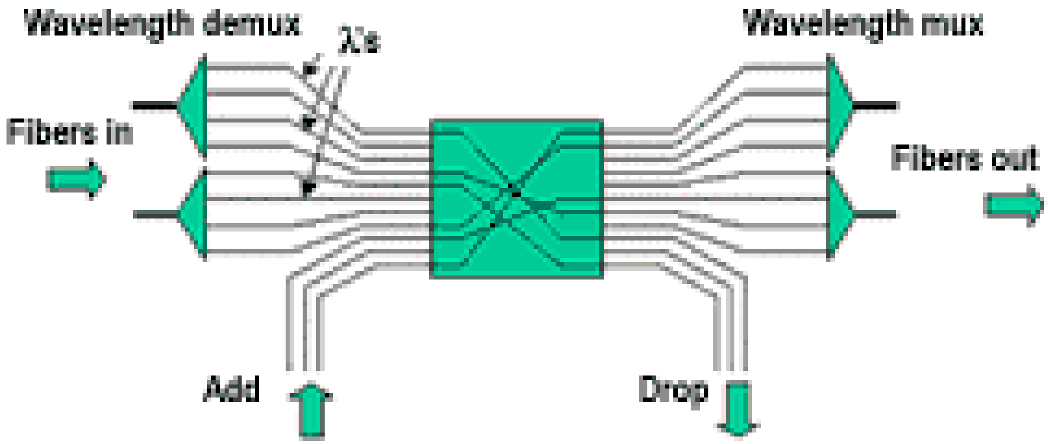
HUD – head-up display

Collision Avoidance



- Demand for miniature and low-cost laser beam-steering systems
- High speed scanning/refresh rate
- Large deflection angles desirable

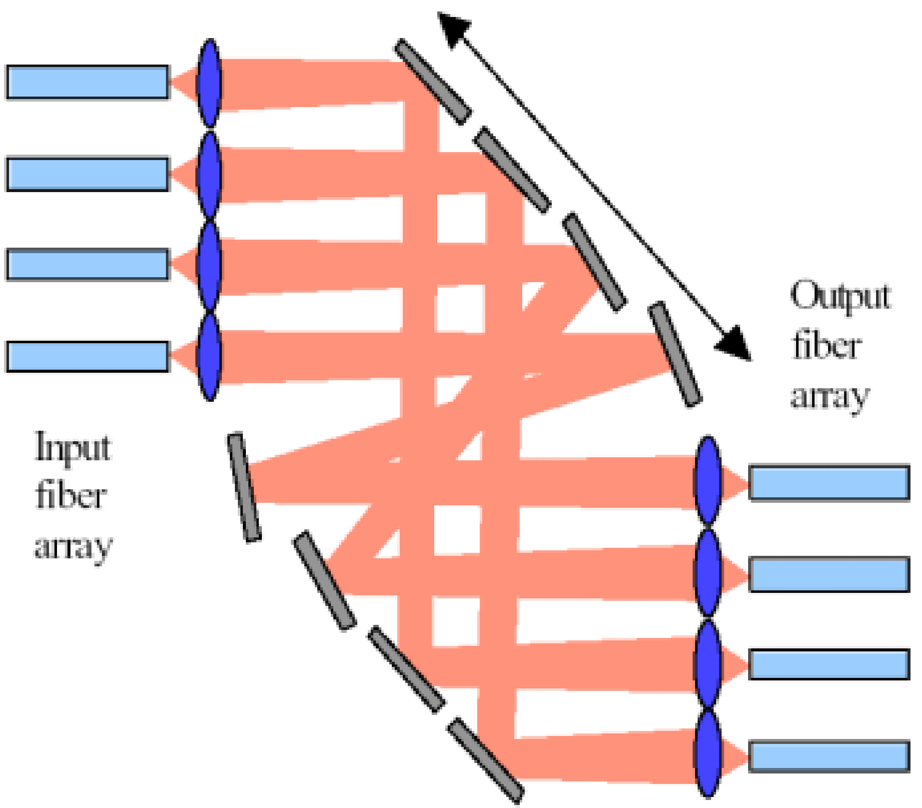
Fiber-optic switches
Optical cross-connects (OXC)



Reconfigurable OADM
port counts: 10-100

- Optical switches
  - 1xN and NxN switch arrays for network restoration/protection (OADMs)
  - NxN large port-count optical cross-connects (OXC)
    - Above e.g. 32x32 count beam-steering mirrors with 1DoF or 2DoF

Beam-steering OXC



- Analog mirrors – more complex implementation
  - 1DoF or 2DoF
- 2N Scaling – easier to achieve larger N
- Lucent, C-speed, Xros, …

Motivation: Adaptive Optical Arrays

- Array of micromirrors
  - High fill factor
  - High reflectivity
  - Analog Tip and tilt rotation
  - Analog piston (vertical) actuation
- Universal optical element
  - Beam steering
  - Reflective lenses
  - Gratings, etc.
  - Yield breaks!

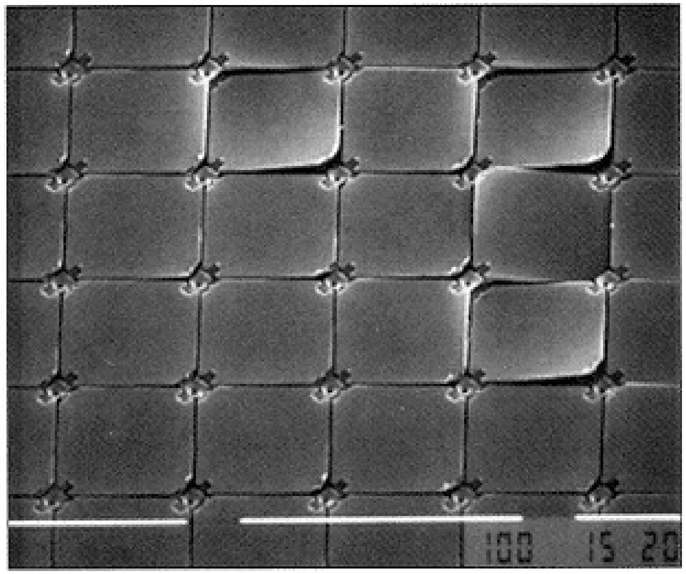


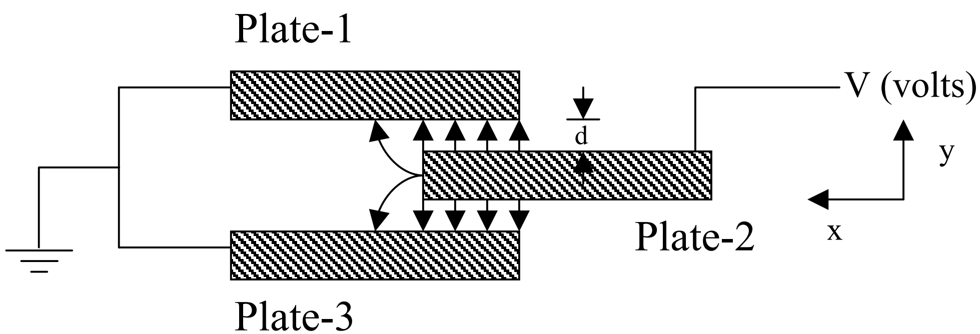
Figure 3. A portion of a DMD array showing selected mirror elements deflected.

Digital micromirrors – TI
No tip/tilt, nor piston
Not analog

Outline

- Motivations and Background
  - Application Examples
  - Electrostatic actuators overview
  - Some micromirror examples
- High aspect ratio MEMS
  - Silicon on Insulator MEMS (SOI-MEMS)
  - Micromirrors in SOI-MEMS
- ARI Approach: Multilevel Beam SOI-MEMS
  - Fabrication and Results
  - Device examples
- Latest results with collaborators at UC Berkeley, demos
- Gimbal-less 2D Optical Scanner – *Kyoto* device

Electrostatic Actuators



Consider parallel plate 1 & 2

Force of attraction (along y direction)

$$F_p = (\tfrac{1}{2}\, \varepsilon\, V^2)(A/g^2)$$

1nN@15V

dimensionless

Consider plate 2 inserted between plate 1 and 3
(Popularly known as a COMB DRIVE)

Force of attraction (along x direction)

$$F_c = (\tfrac{1}{2}\, \varepsilon\, V^2)(2t/g)$$

Constant with x-directional translation

Parallel-Plate Electrostatic Actuator Pull-in

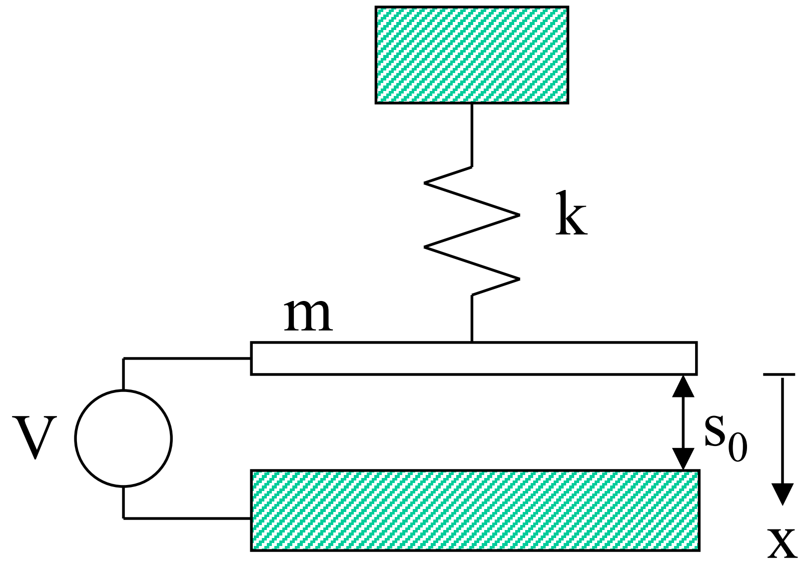
Electrostatic instability

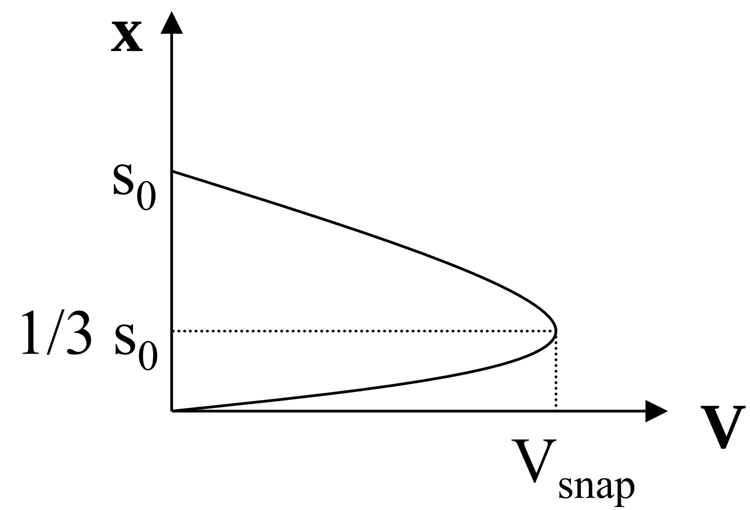
$$F = \frac{\varepsilon_0 V^2}{2(s_0 - x)^2} = kx \Rightarrow$$

$$V = \sqrt{\frac{2kx}{\varepsilon_0}}(s_0 - x)$$

$$\frac{\partial V}{\partial x} = 0 \Rightarrow x_{snap} = \frac{s_0}{3}$$

$$V_{snap} = \sqrt{\frac{8ks_0^3}{27\varepsilon_0}}$$





Outline

- Motivations and Background
  - Application Examples
  - Electrostatic actuators overview
  - Some micromirror examples
- High aspect ratio MEMS
  - Silicon on Insulator MEMS (SOI-MEMS)
  - Micromirrors in SOI-MEMS
- ARI Approach: Multilevel Beam SOI-MEMS
  - Fabrication and Results
  - Device examples
- Latest results with collaborators at UC Berkeley, demos
- Gimbal-less 2D Optical Scanner – *Kyoto* device

2x2 MEMS Fiber Optic Switches

2x2 MEMS Fiber Optic Switches with Silicon Sub-Mount for Low-Cost Packaging

Shi-Sheng Lee, Long-Sun Huang, Chang-Jin "CJ" Kim and Ming C. Wu
Electrical Engineering Department, UCLA
63-128, engineering IV Building, Los Angeles, California 90095-1594
Mechanical and Aerospace Engineering Department

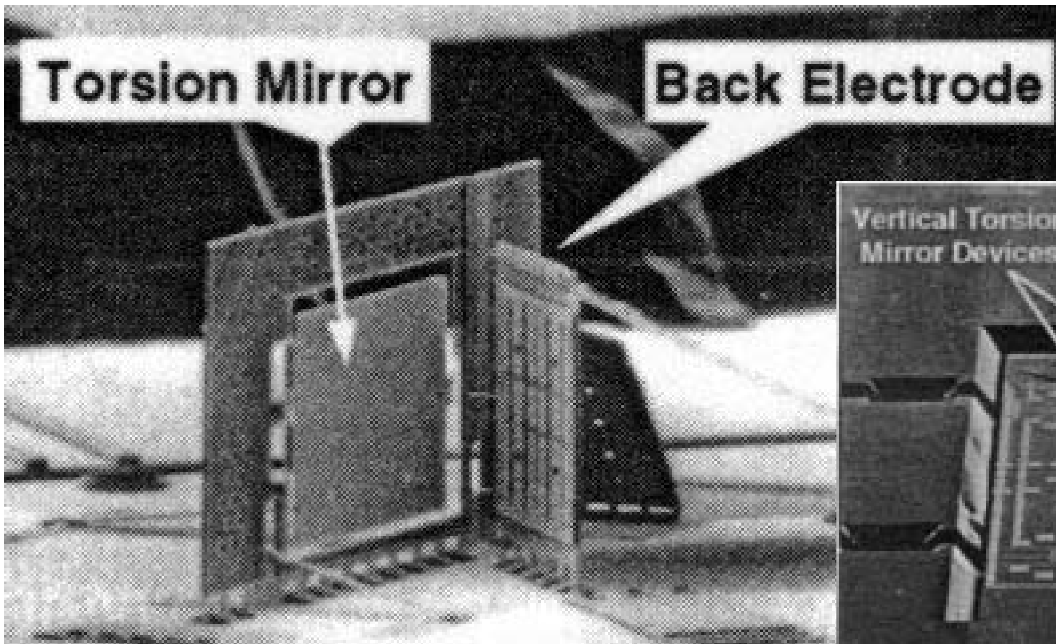


Figure 3. SEM of the torsion mirror device.

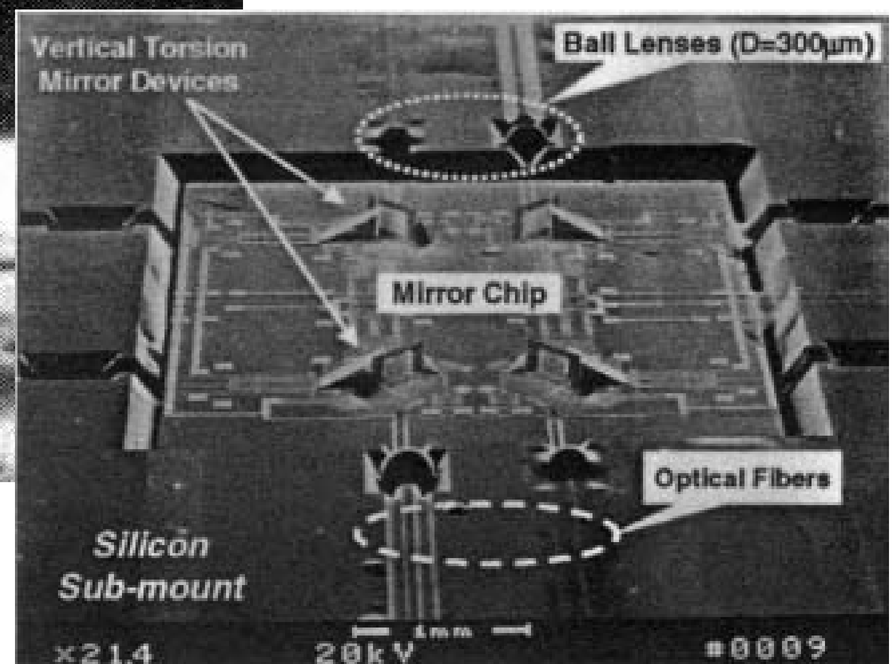
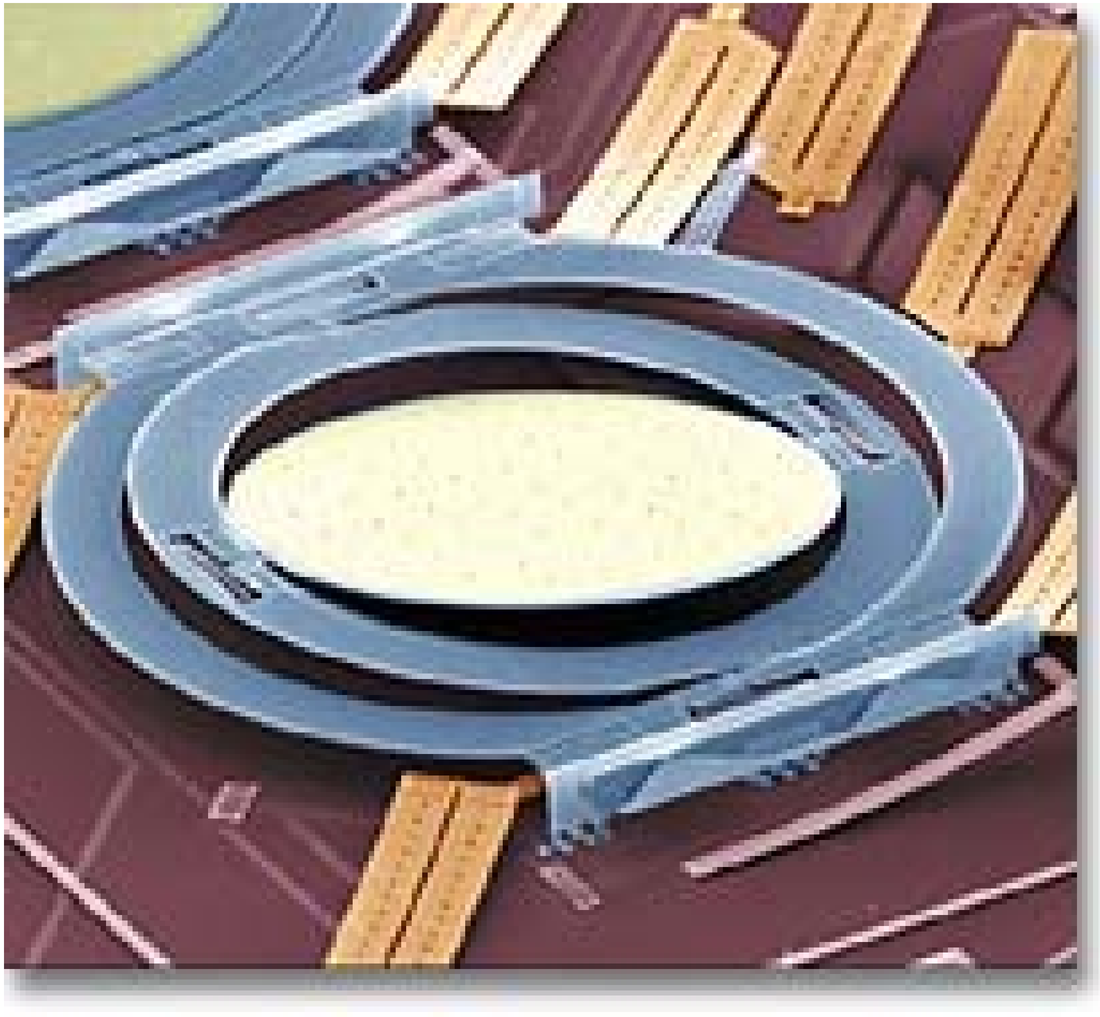
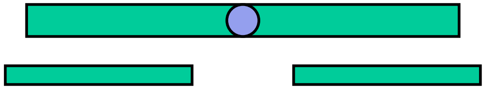


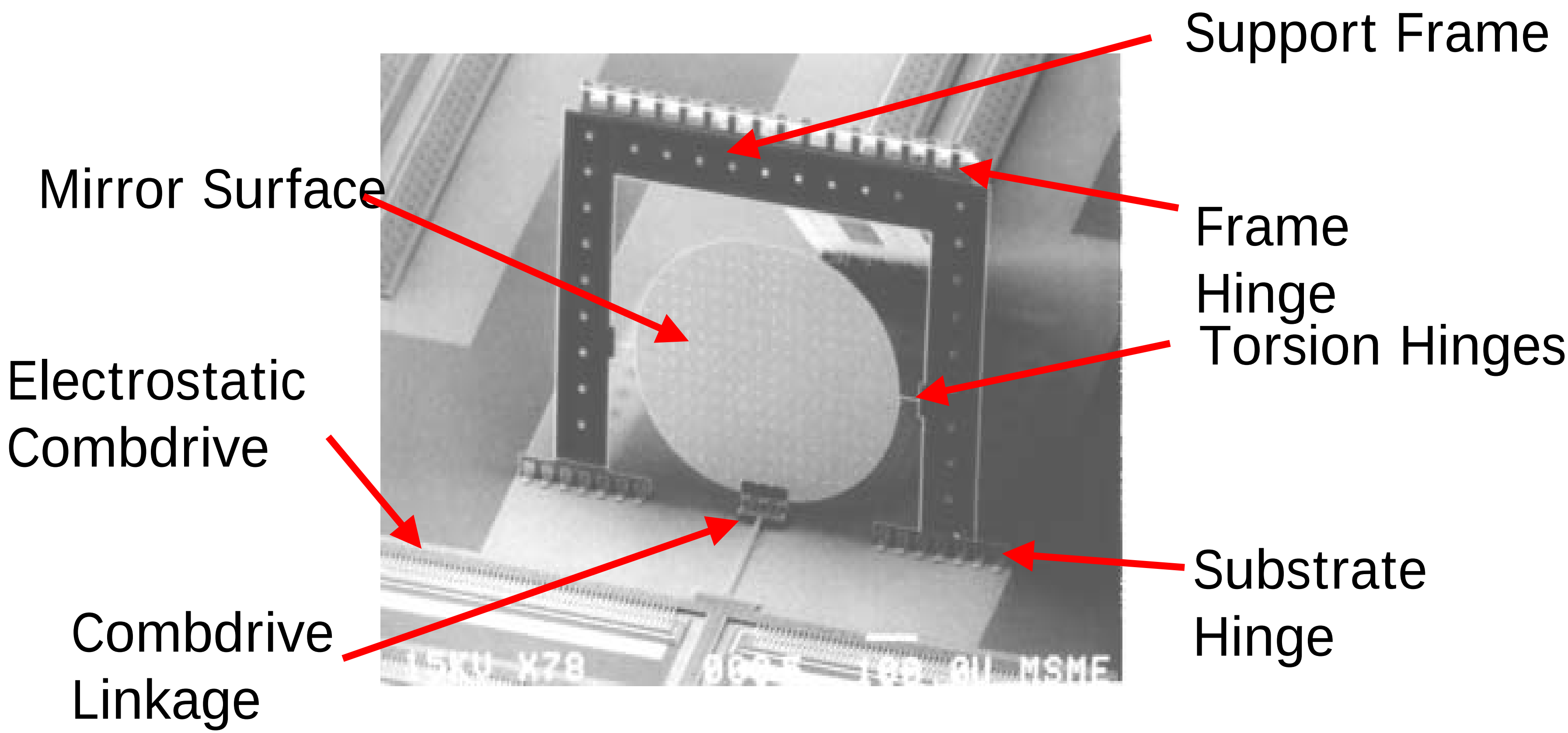
Figure 1. SEM of the 2x2 MEMS fiber optic switch.

Lucent 2DoF Micromirror





Surface MEMS Micromirror Structure

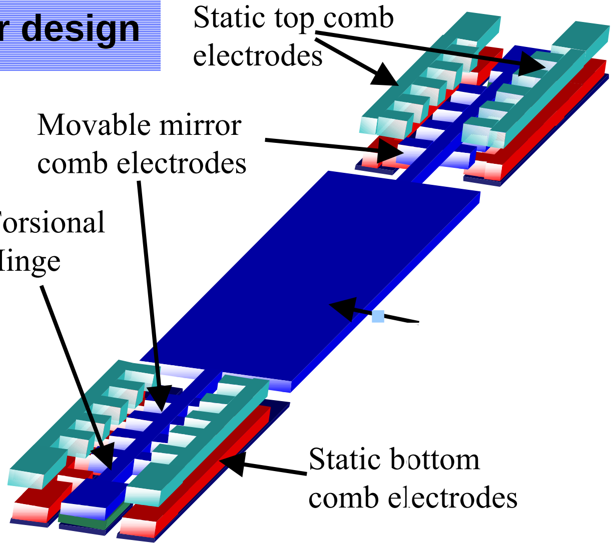


Conant et al, MOEMS99

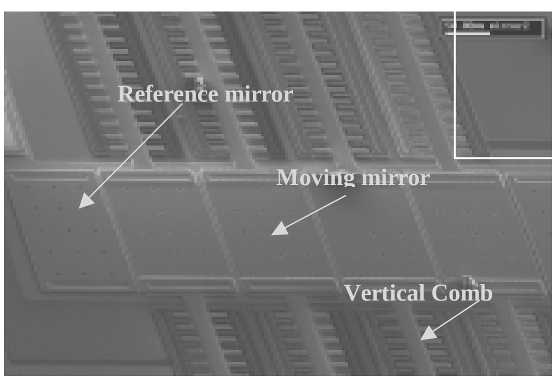
Optical Phased Arrays Of Micromirrors

Courtesy of O. Solgaard

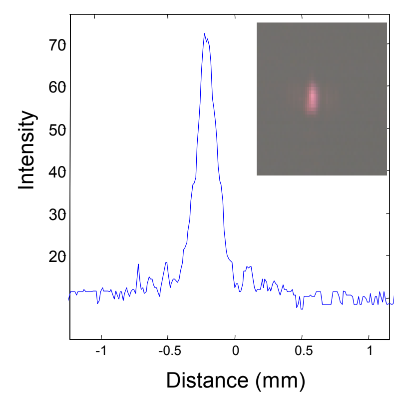
Dual mode μmirror design



- Phased arrays of micromirrors allow directional control and optical phase correction for precision optical spatial and spectral scanning
- Applications:
  - Spectroscopy
  - Fiber optics
  - Free space optical communication

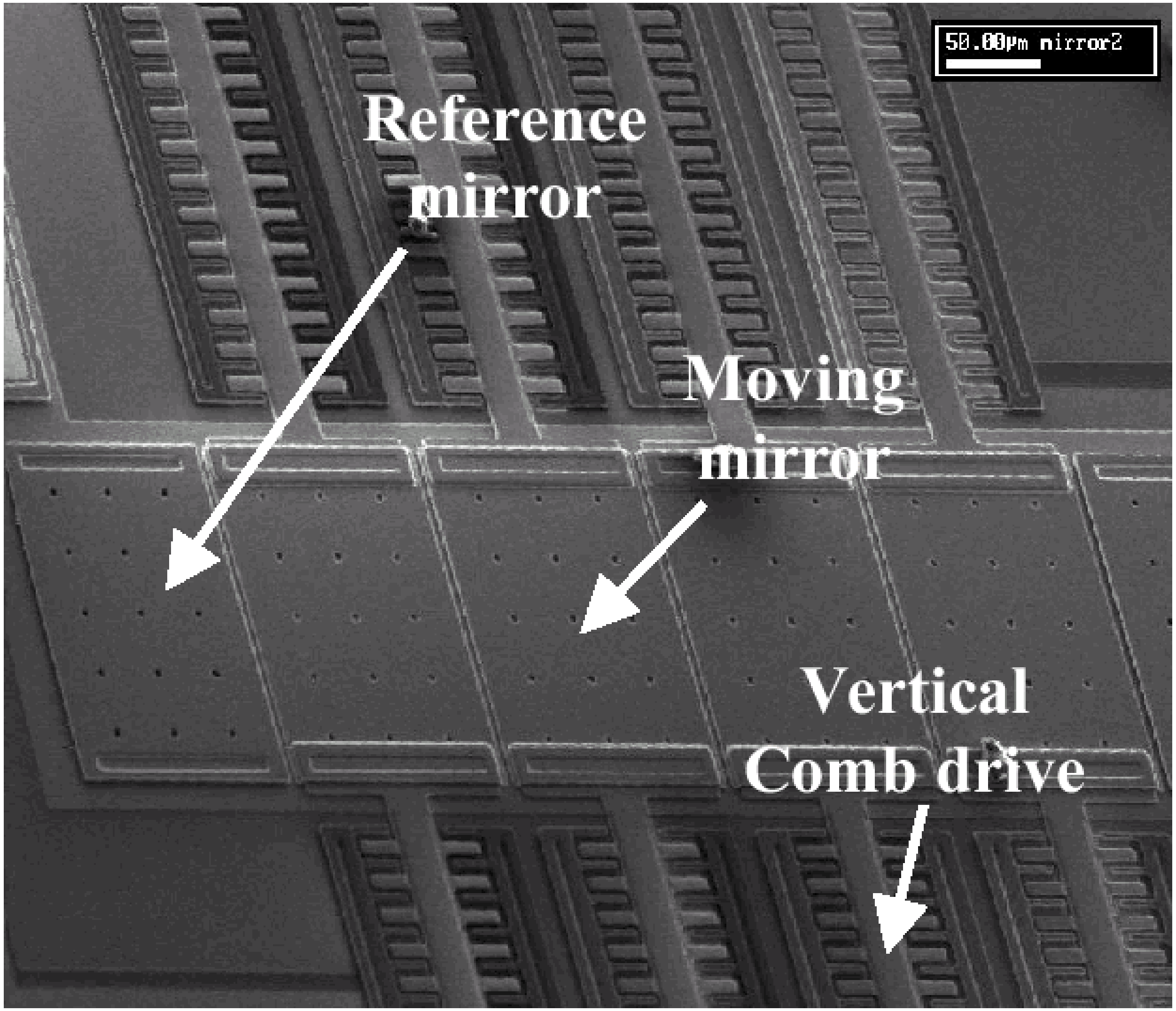


SEM of phased array for spatial switching.



Far-field pattern of scanning mirror array with phase correction

1D Phased Array with Tilt and Piston motion



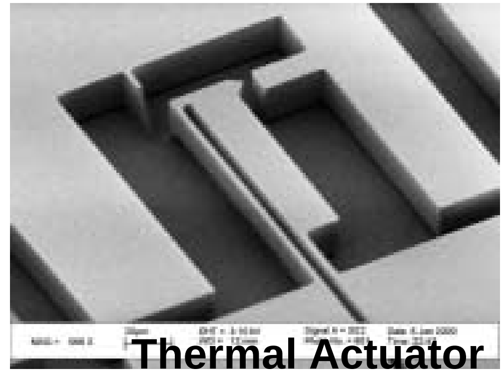
Krishnamoorthy et al, Transducers 01, Munich, Germany

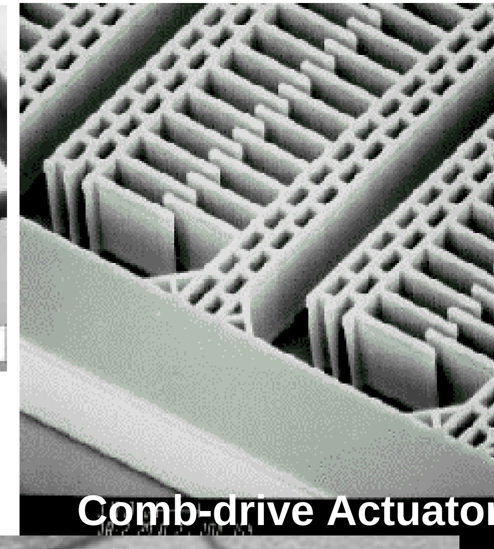
Outline

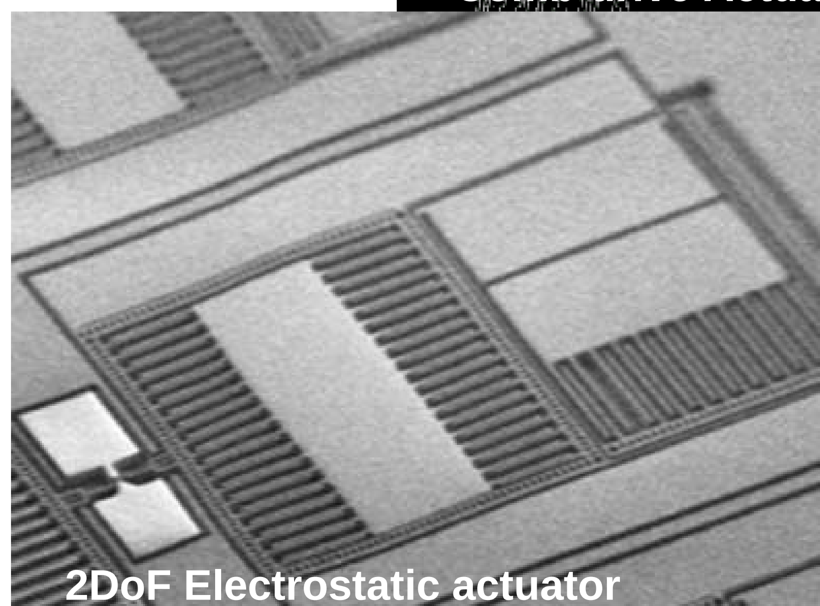
- Motivations and Background
  - Application Examples
  - Electrostatic actuators overview
  - Some micromirror examples
- High aspect ratio MEMS
  - Silicon on Insulator MEMS (SOI-MEMS)
  - Micromirrors in SOI-MEMS
- ARI Approach: Multilevel Beam SOI-MEMS
  - Fabrication and Results
  - Device examples
- Latest results with collaborators at UC Berkeley, demos
- Gimbal-less 2D Optical Scanner – *Kyoto* device

High Aspect Ratio MEMS (HARM)
SOI-MEMS

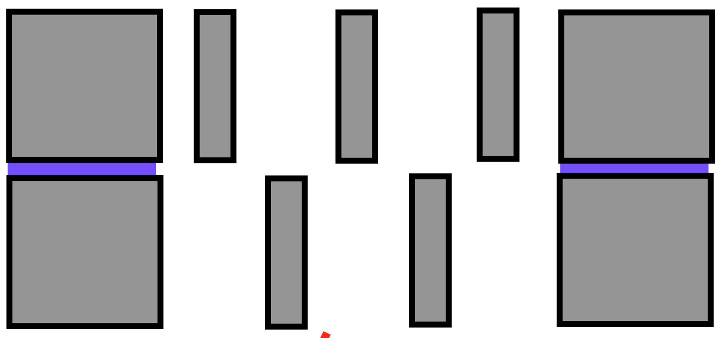
- Height/width > ~3:1
- Height/space > ~3:1
- Increased capacitance for actuation and sensing
- Low-stress structures
  - single-crystal Si only structural material
- Highly stiff in vertical direction
  - isolation of motion to wafer plane
  - flat, robust structures

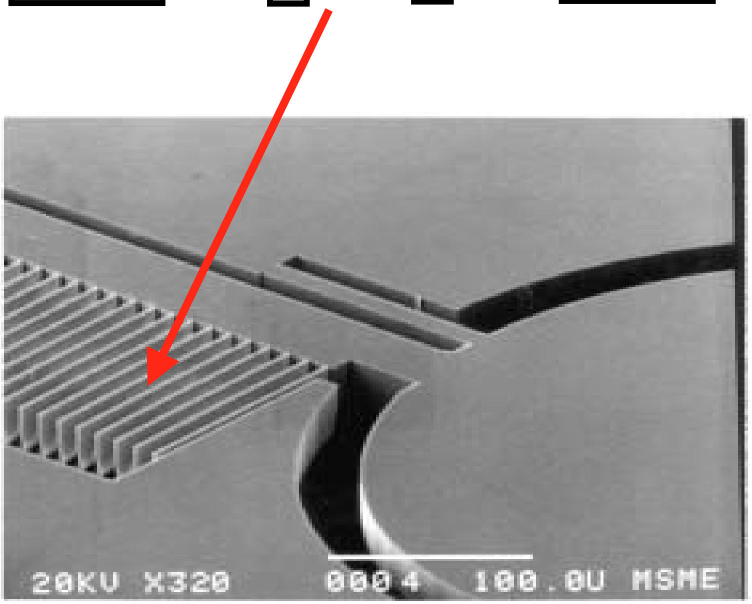






MEMS Mirrors in SOI



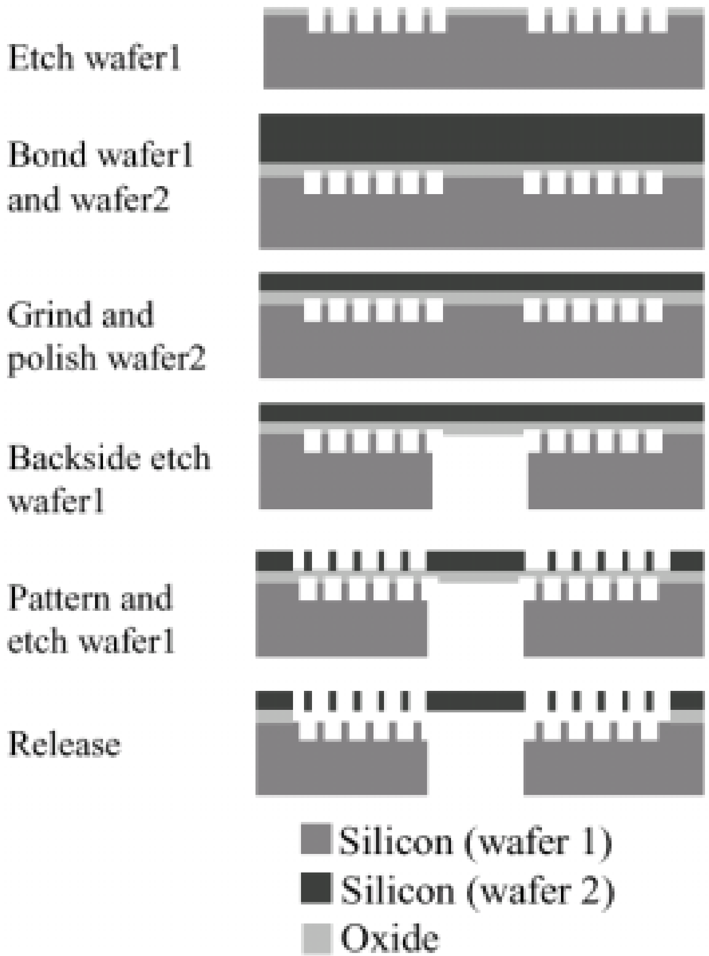


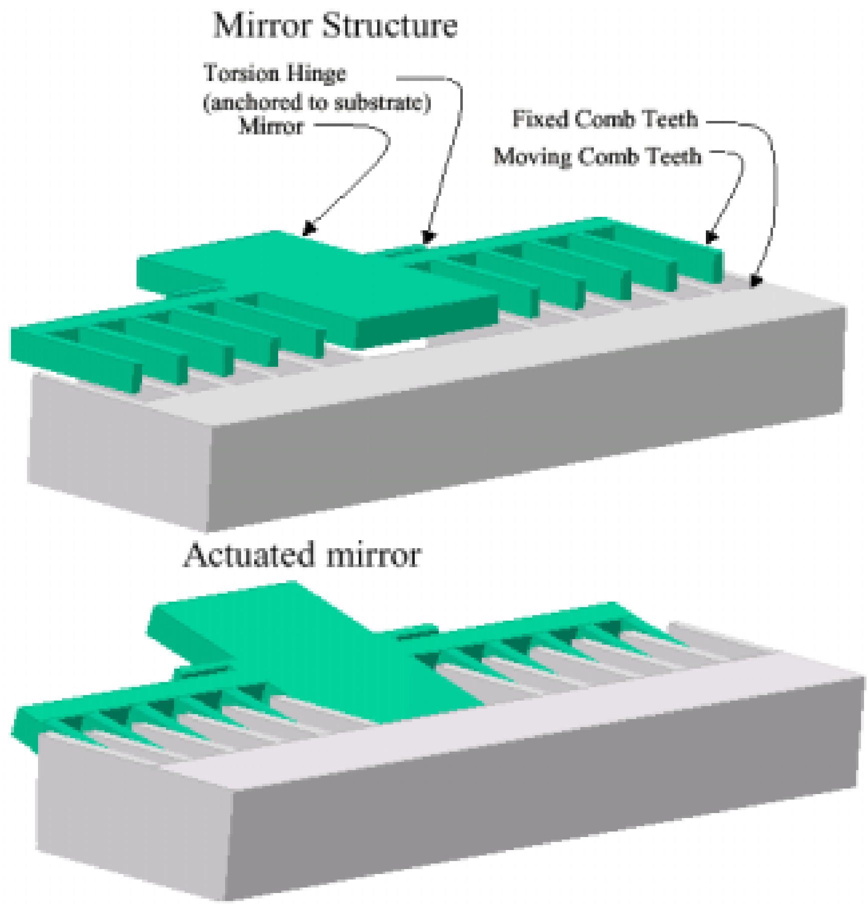
Courtesy Robert A. Conant, BSAC

- DRIE etching of SOI materials
- High-quality, flat, and stiff mirrors
- High-speed deflection
- Electrostatic actuators
  - High force, Dual-mode and two-sided possible, All-conductive structure
- Flexible Process
  - Phased arrays, 2-D arrays, Through-the-wafer interconnects
- Combs require accurate alignment
  - Yield, Reliability, Maximum deflection
- Front-side processing
  - Improved reliability and yield, controlled damping, standard wafers, integration

STEC Micromirror – Vertical Comb-drives

Conant *et al*, HH2000

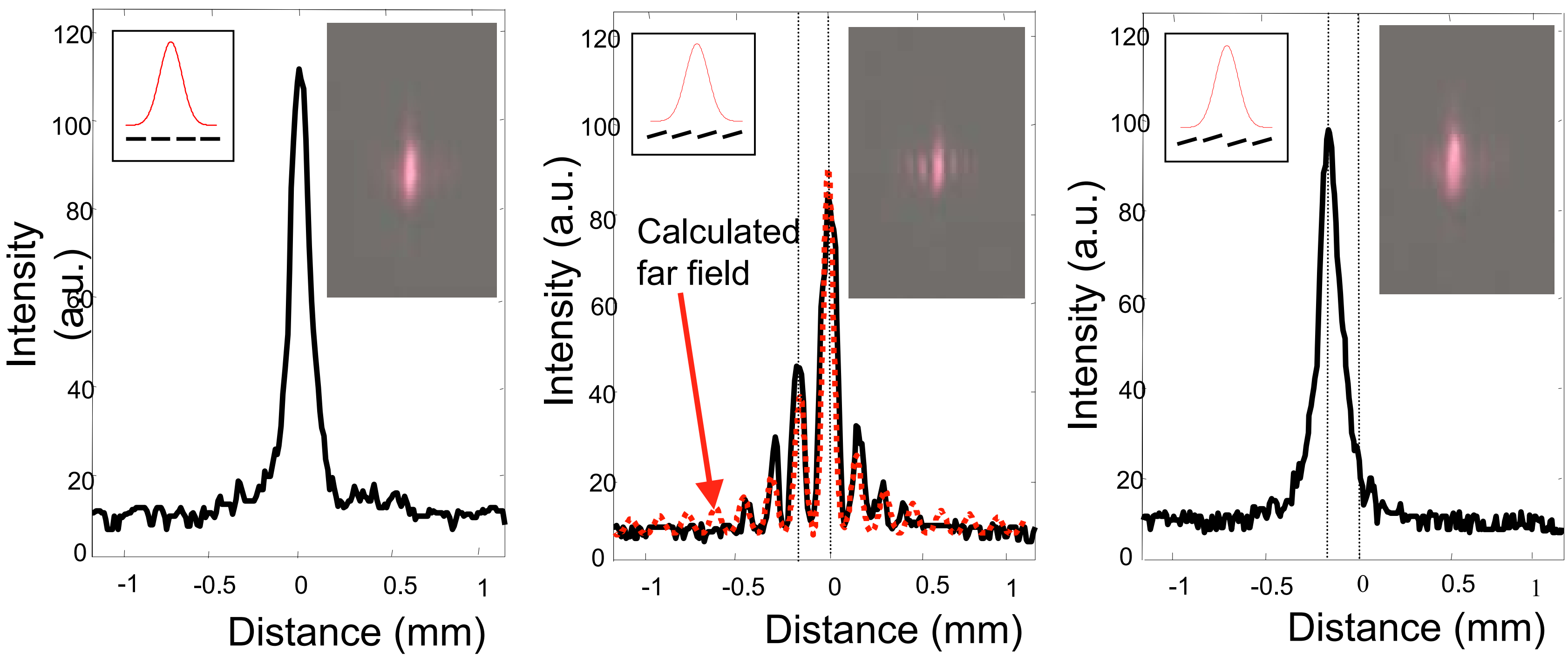




Conant *et al*, HH2000

Coherent phased array
Far-field diffraction patterns

O.Solgaard
Stanford



K. Li, U. Krishnamoorthy, J.P. Heritage, O. Solgaard “Micromirror Array Phase Modulator for Ultrashort Optical Pulse Shaping”, Proceedings of the Solid-State Sensor and Actuator Workshop, pp. 15-18, Hilton Head, South Carolina, June 2-6, 2002.

U. Krishnamoorthy, K. Li, K. Yu, D. Lee, J.P. Heritage, O. Solgaard, "Dual mode micromirrors for optical phased array applications", Sensors and Actuators: A. Physical, Vol. 97-98C, May 2002, pp 22-26.

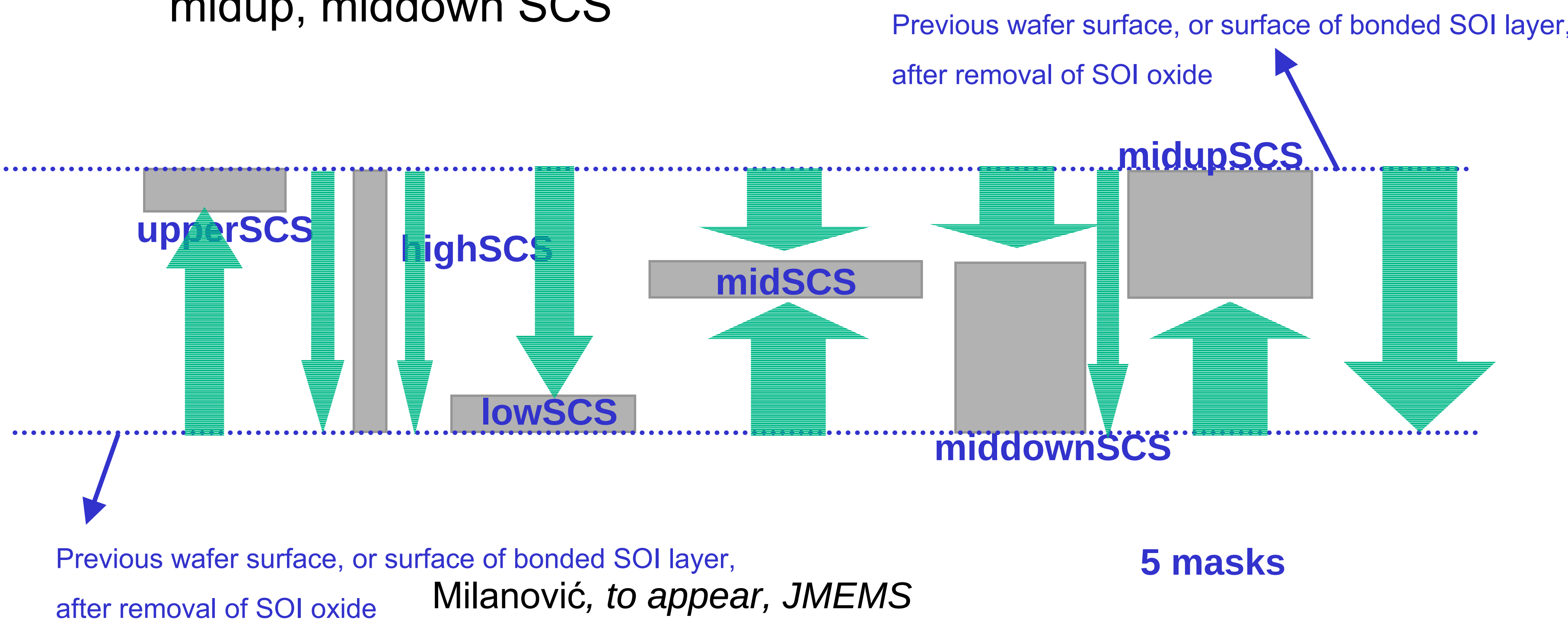
K. Li, U. Krishnamoorthy, J.P. Heritage, O. Solgaard “Coherent micromirror arrays”, Optics Letters Vol. 27, No. 5, March 1, 2002 p.366-368.

Outline

- Motivations and Background
  - Application Examples
  - Electrostatic actuators overview
  - Some micromirror examples
- High aspect ratio MEMS
  - Silicon on Insulator MEMS (SOI-MEMS)
  - Micromirrors in SOI-MEMS
- ARI Approach: Multilevel Beam SOI-MEMS
  - Fabrication and Results
  - Device examples
- Latest results with collaborators at UC Berkeley, demos
- Gimbal-less 2D Optical Scanner – *Kyoto* device

New methodology and devices: Multilevel Beam SOI-MEMS – ARI-MEMS

- Front- and Back-side multilevel etching for advanced HARM
- 2 front masks gives lowSCS, highSCS
- 2 front + 1 back mask gives lowSCS, highSCS, upperSCS
- 3 front + 2 back (or other combos) gives low, mid, upper, high, midup, middown SCS

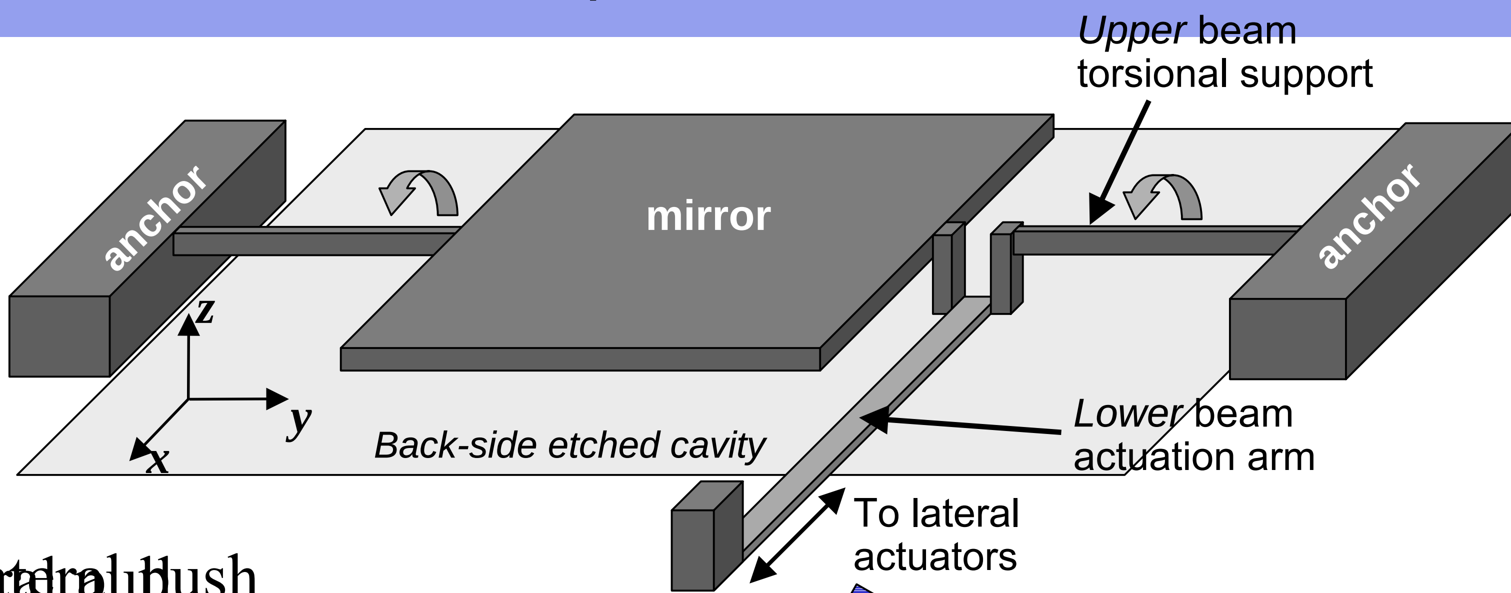


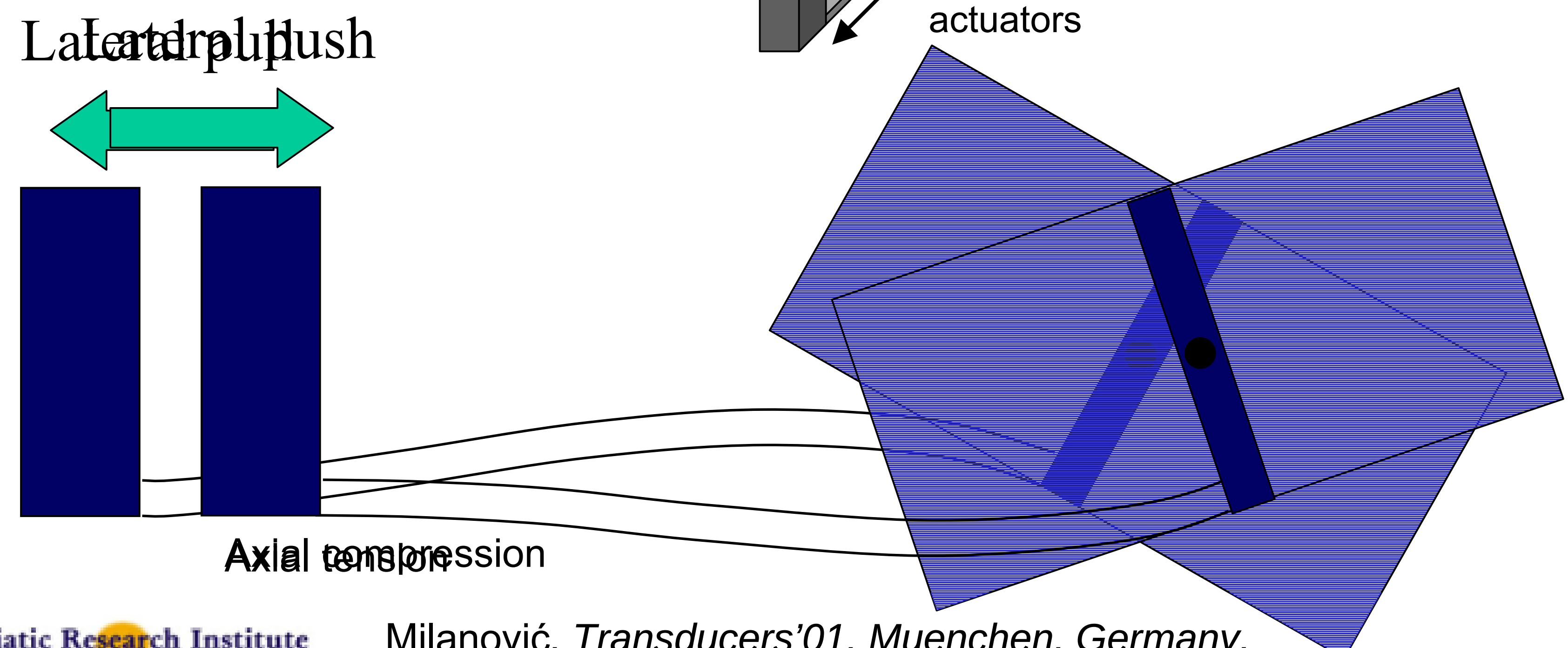
Milanović*, to appear, JMEMS*

Milanović*, ICECS'02, Dubrovnik, Croatia, Sep. 02*

Adriatic Research Institute

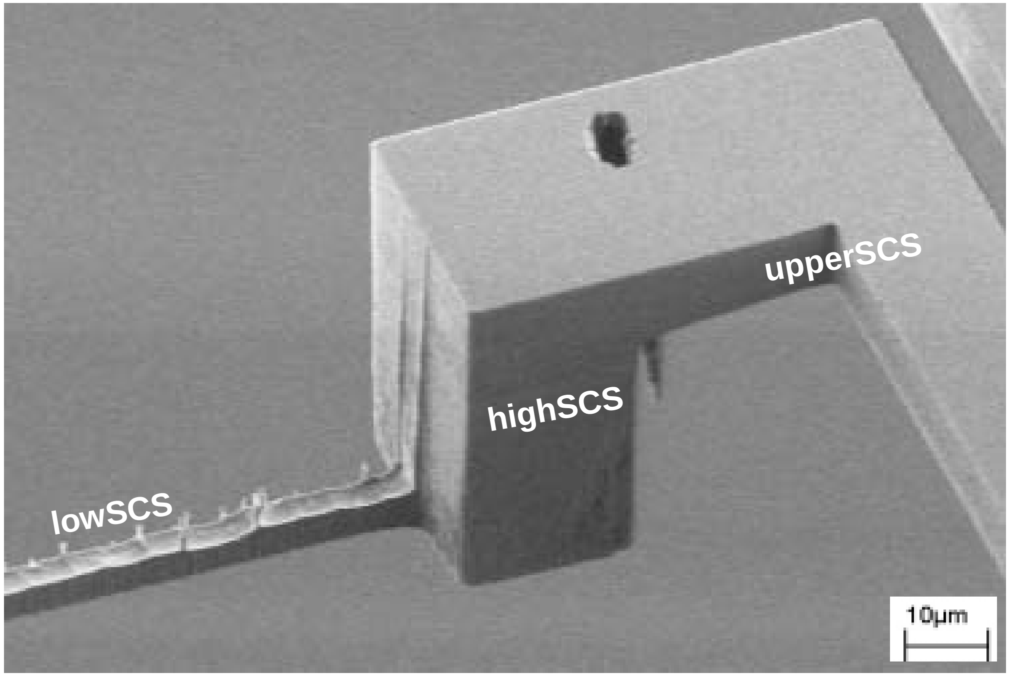
Conversion of in-plane motion to rotation - I

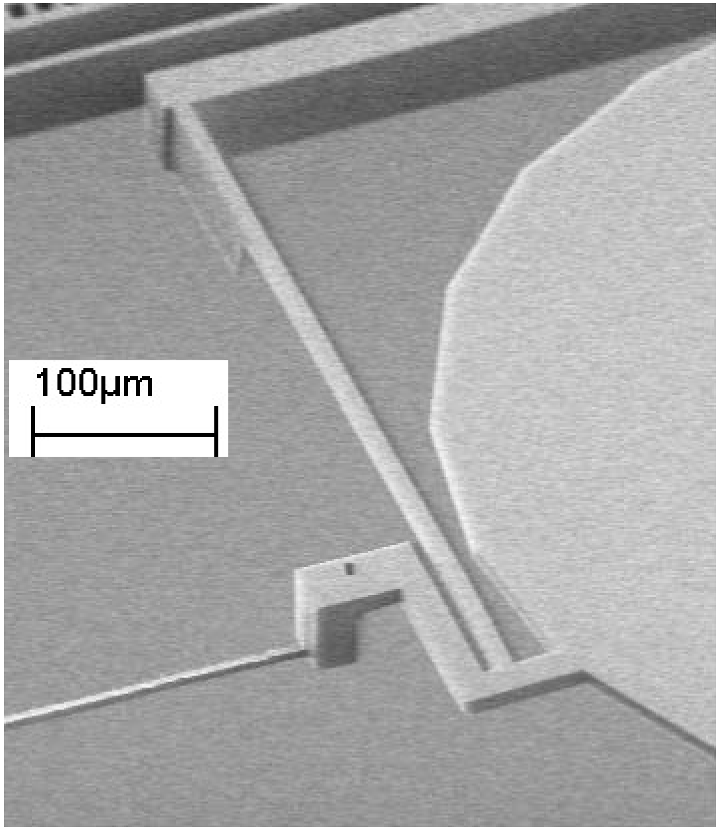




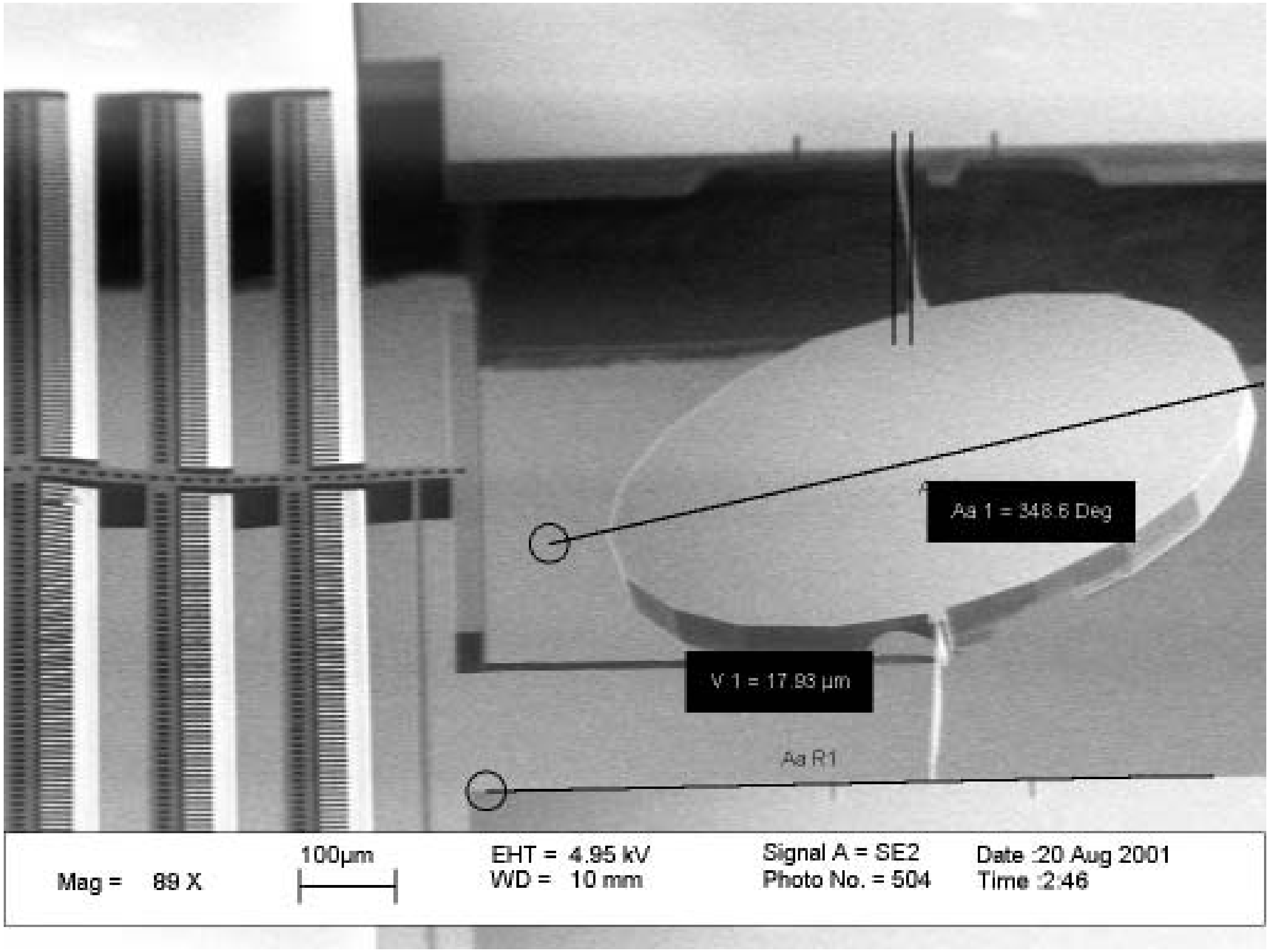
Milanović, *Transducers'01, Muenchen, Germany.*

3-level ARI-MEMS





Push-mode 1DoF mirror

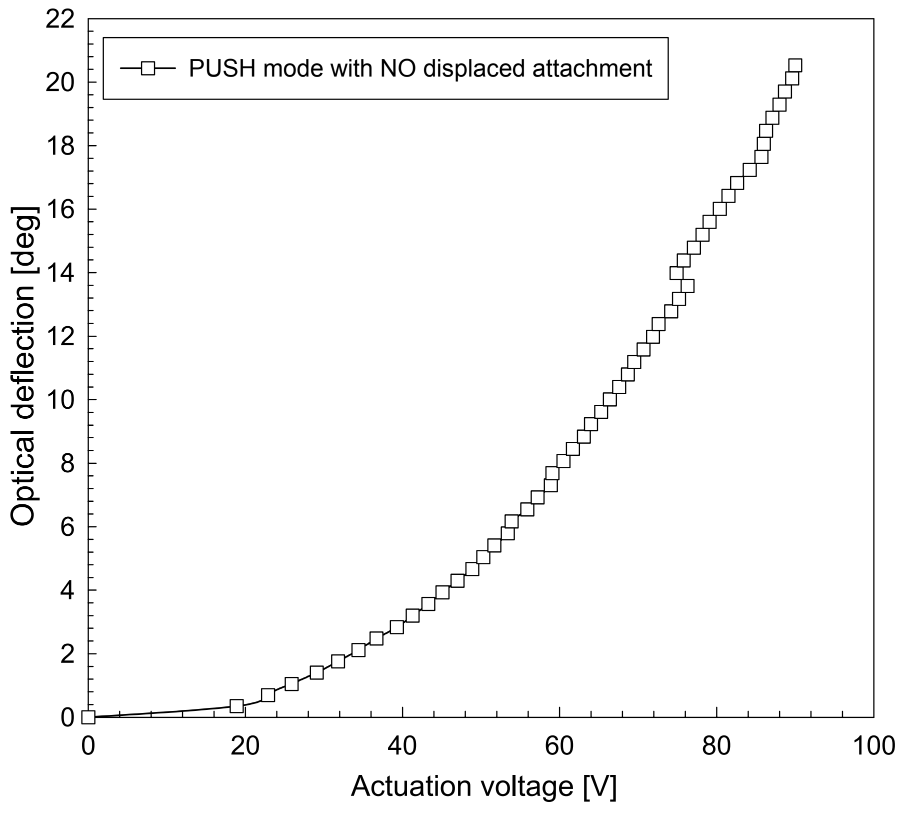


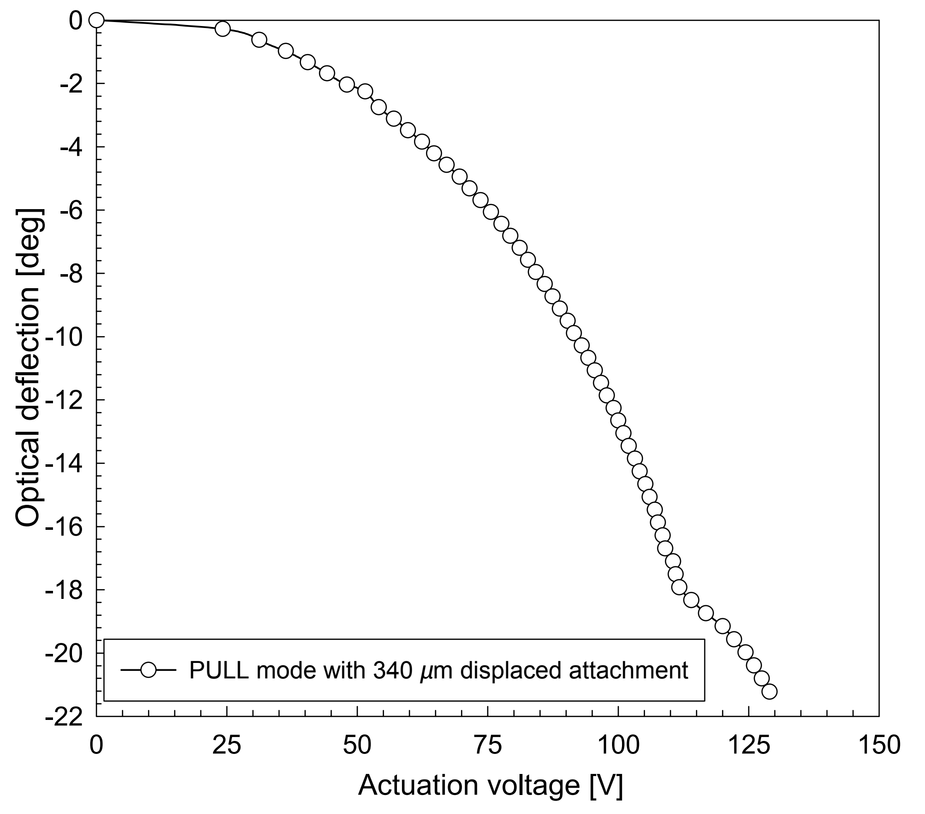
Device is actuated by SEM charging of the comb-drive

Adriatic Research Institute

Milanović *et al, MOEMS 2001*

Most recent 1DoF measurements – over 40° optical static deflection





Push-mode

Pull-mode (with displaced attachment)

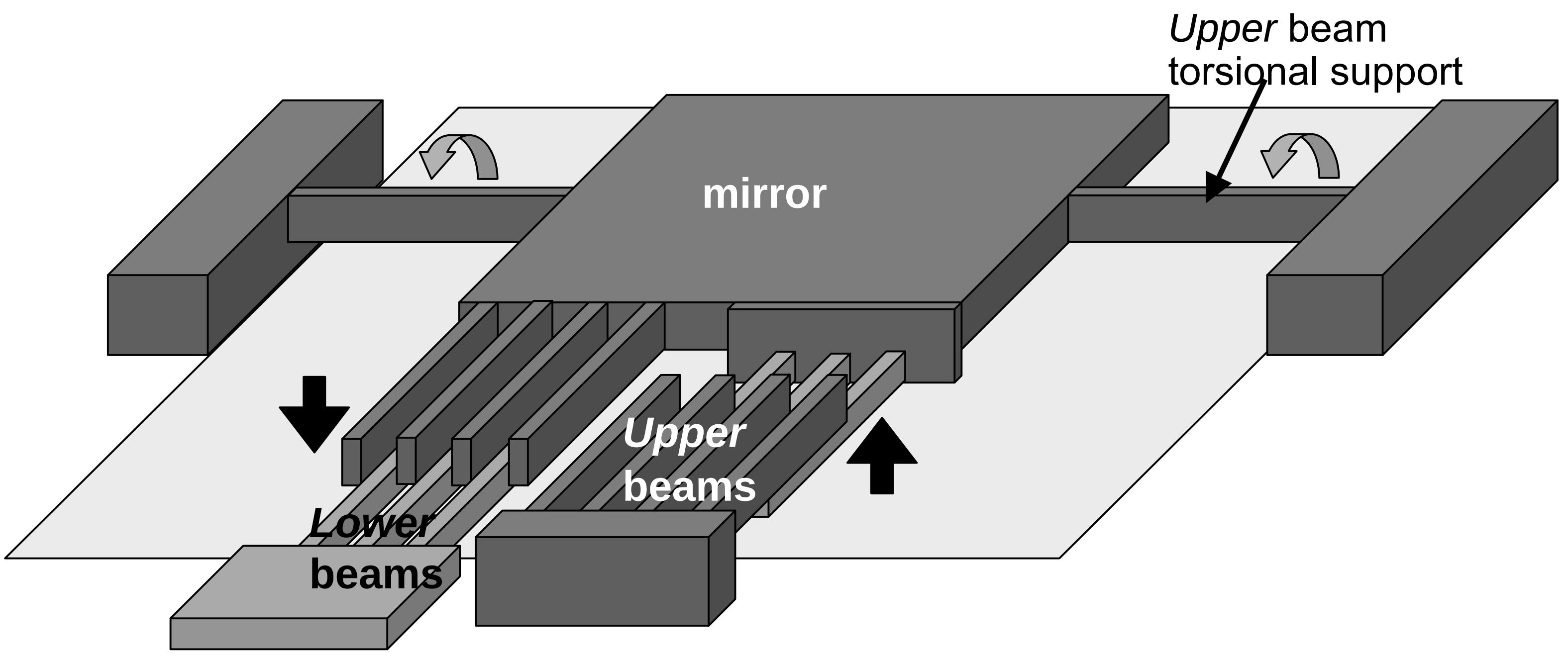
Milanović *et al, MOEMS 2001*

Adriatic Research Institute

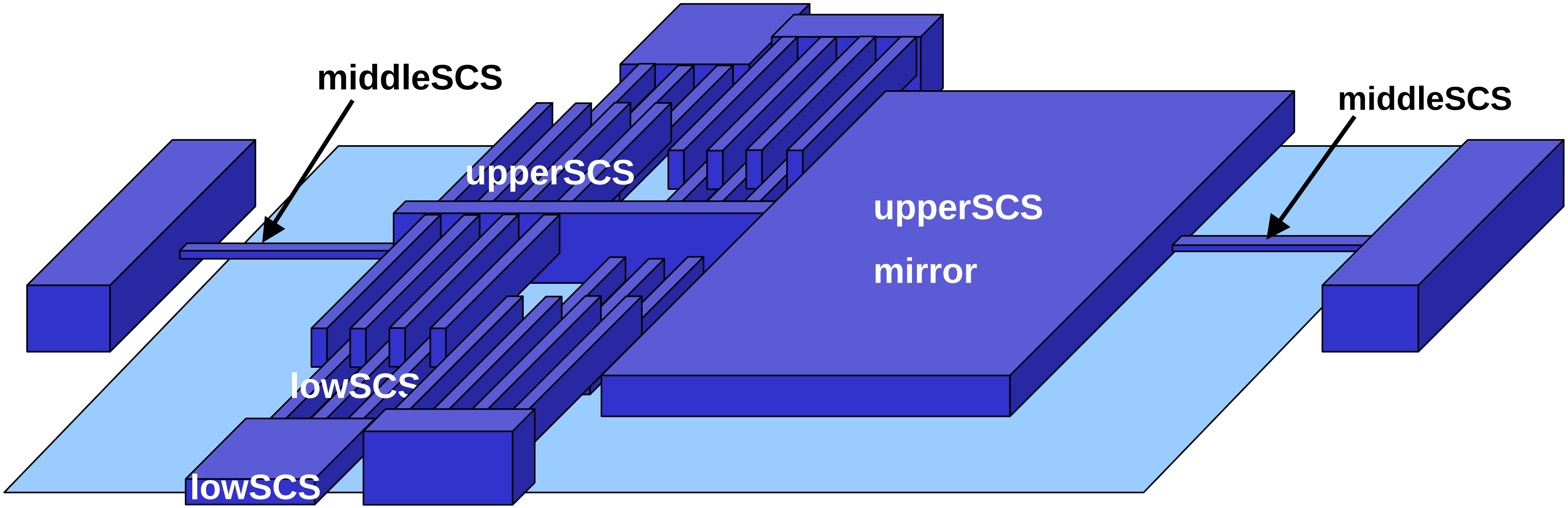
Conversion of in-plane motion to rotation - II

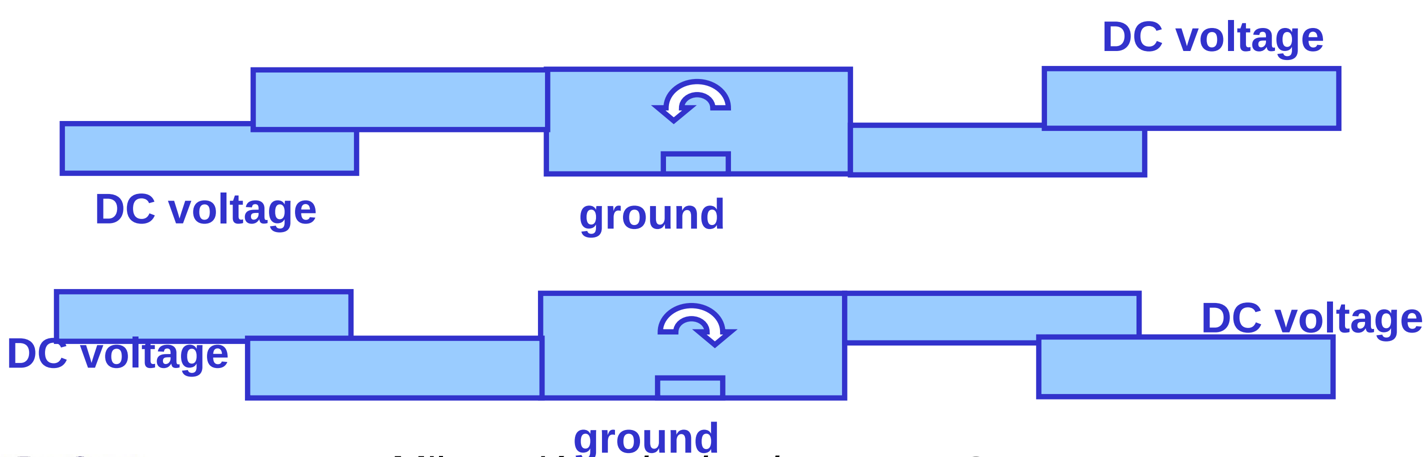
- Lower and Upper beams can be placed at minimum spacing that is DRIE aspect-ratio limited
- Lower and Upper beams self-aligned by same top mask

- **Vertical comb-drives** for rotation and piston motion



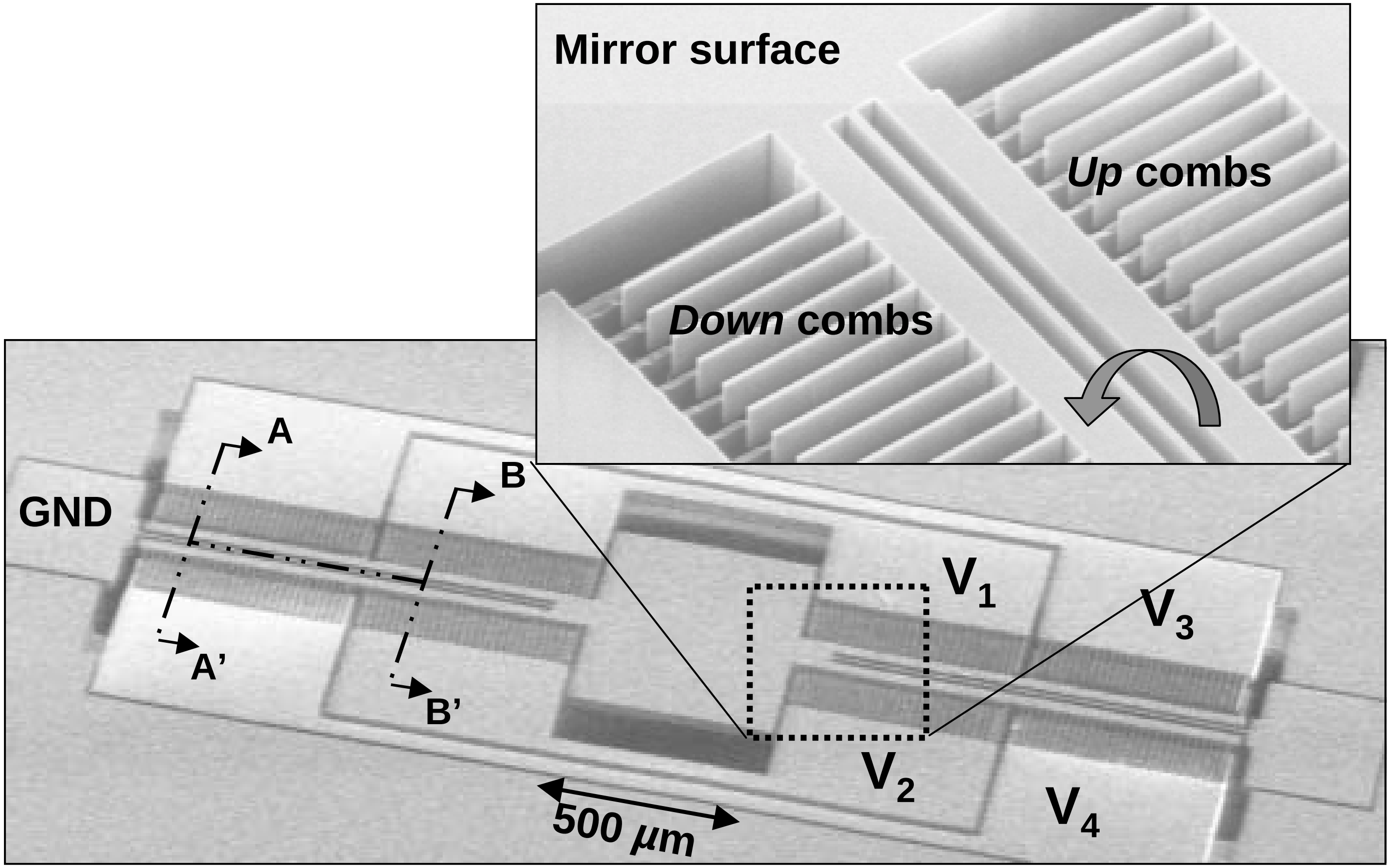
Device improvement example – pure torque actuation (both directions) and up/down piston motion





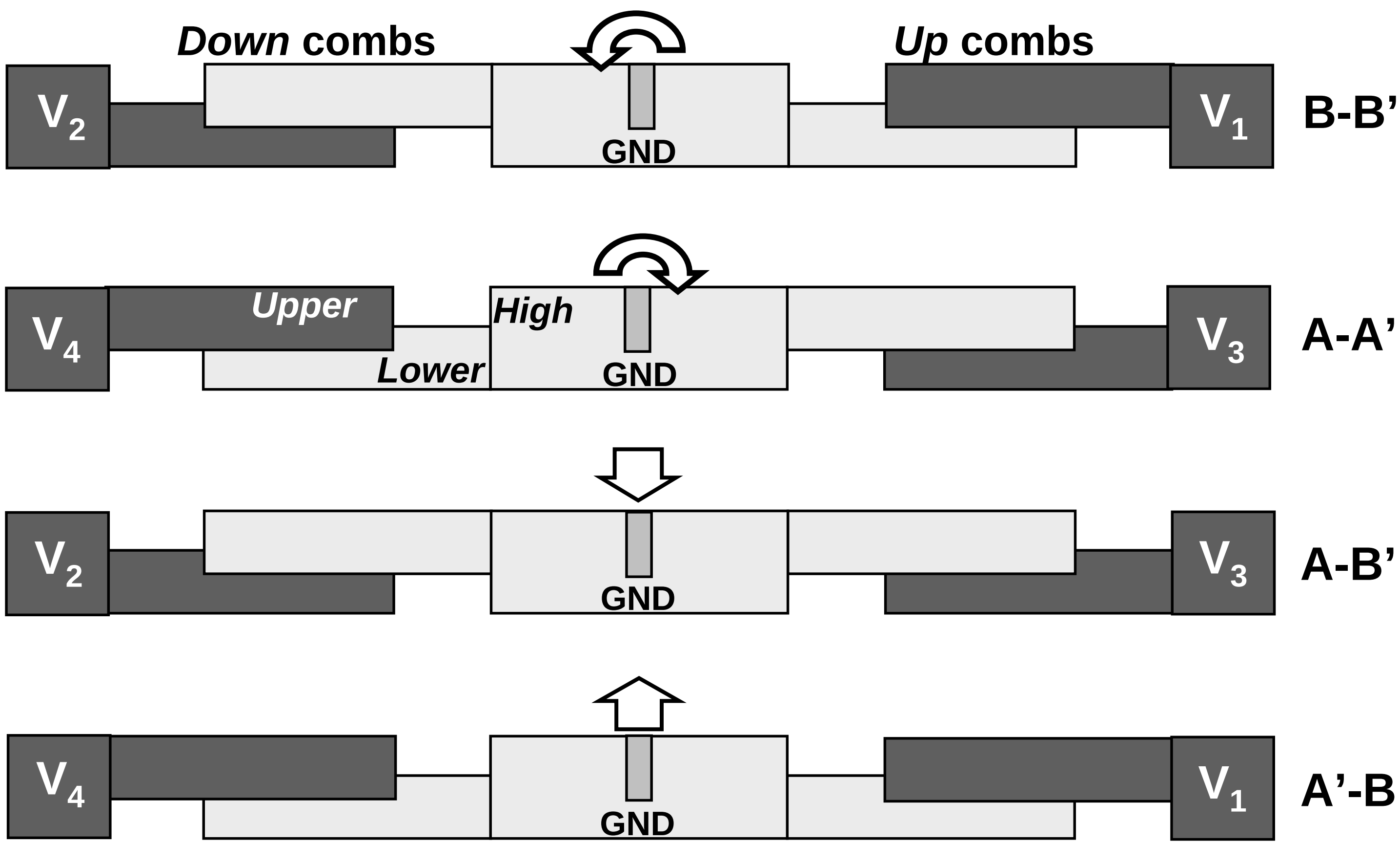
Milanović, *submitted to JMEMS*

Fabricated 1DoF Mirror with Independent Pistoning Control

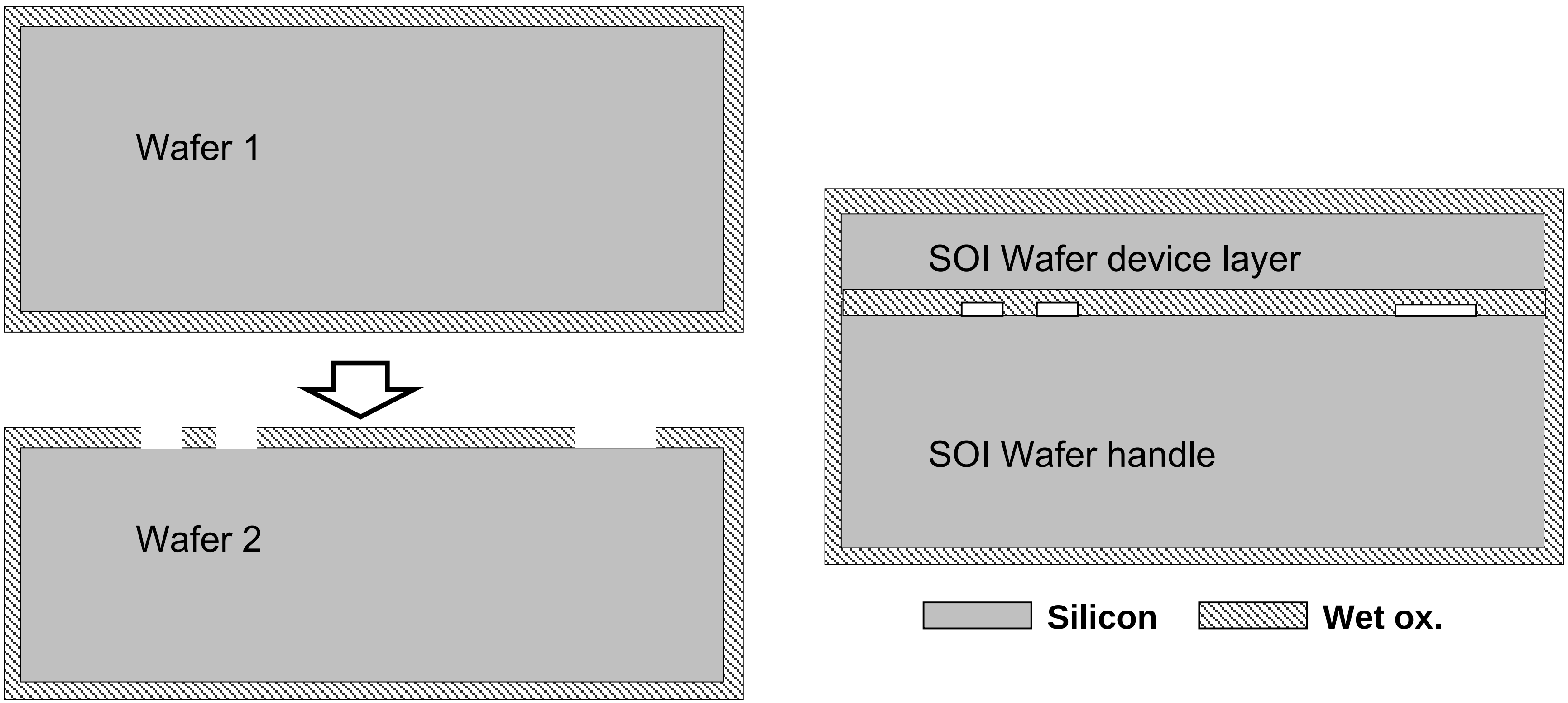


Milanović *et al, to appear in IEEE Photonics Tech. Lett.*
Milanović *et al, MOEMS'02, Switzerland, Aug. 02*

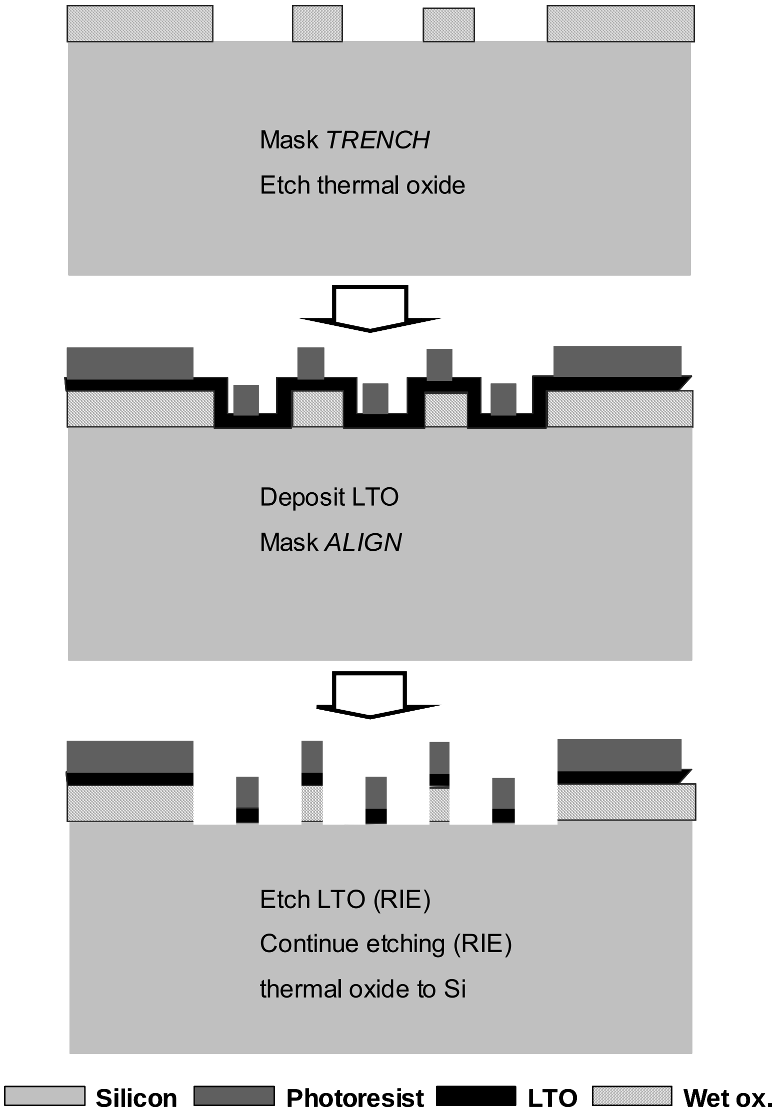
Multiple modes of actuation

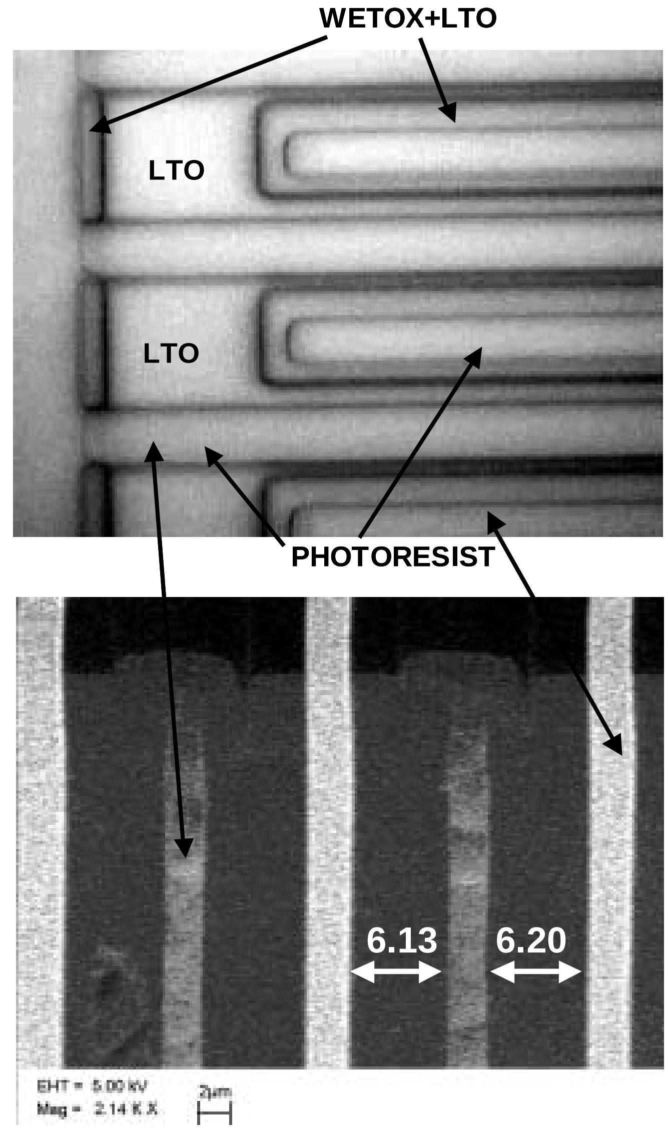


Fabrication: Embedded "Backup" mask



Fabrication: Mask Self-alignment process steps



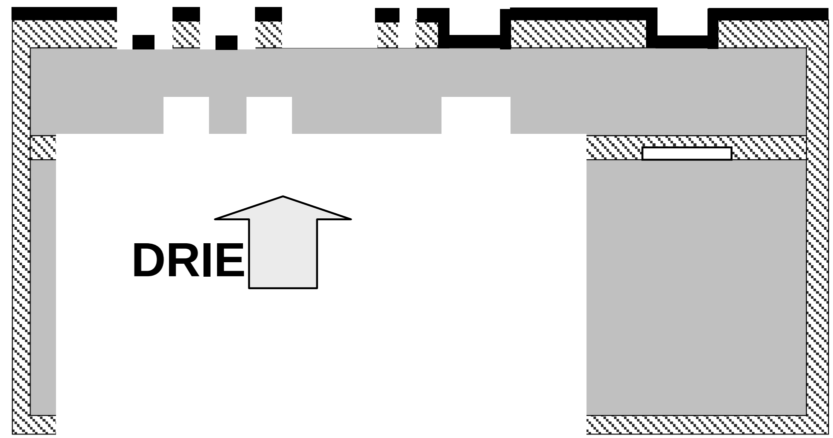


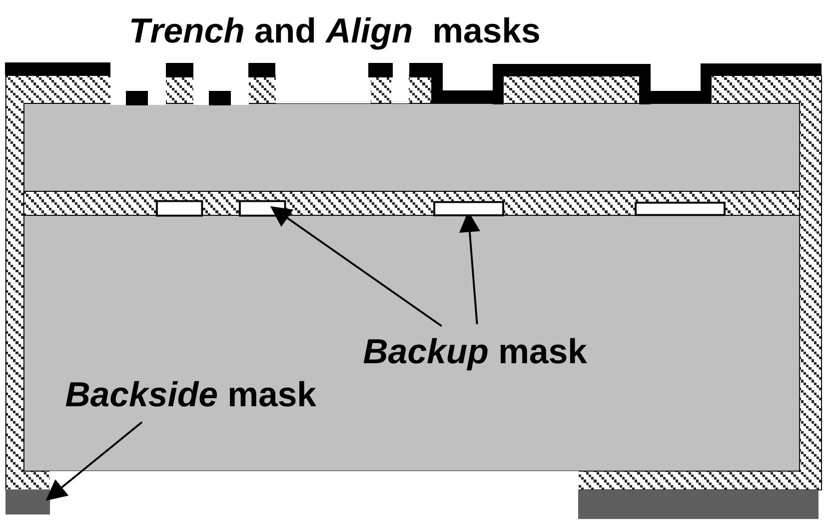
Adriatic Research Institute

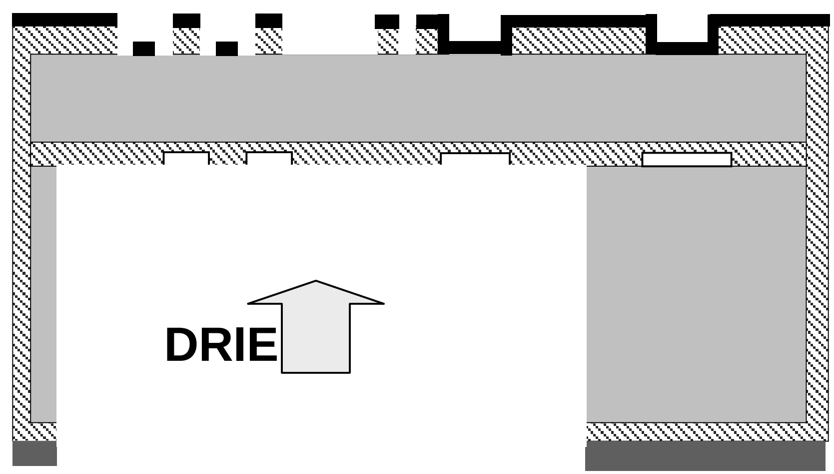
V. Milanović, IEEE, 12/2002

Fabrication: masks and backside steps

- All masks prepared before DRIE steps
- Front-side two oxide masks
- One embedded oxide mask
- Back-side thick-resist mask

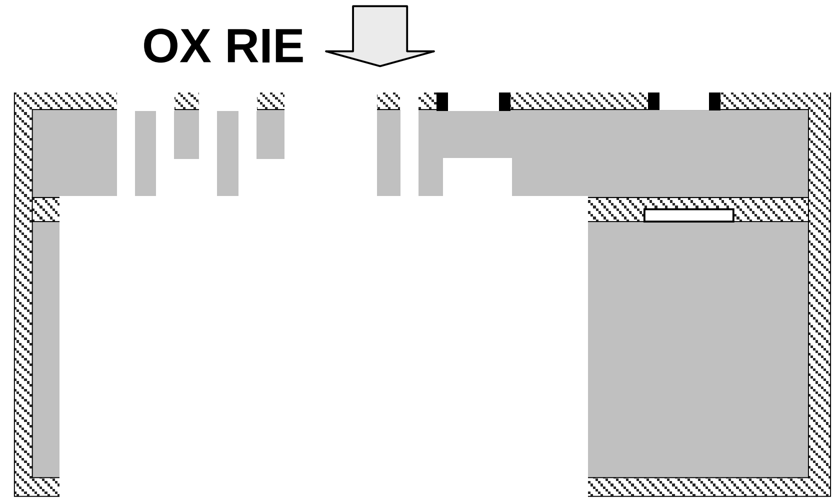


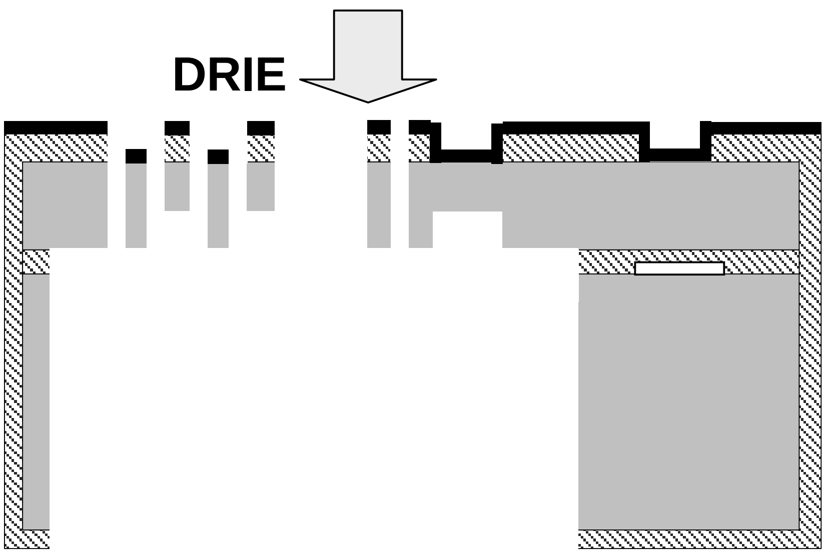


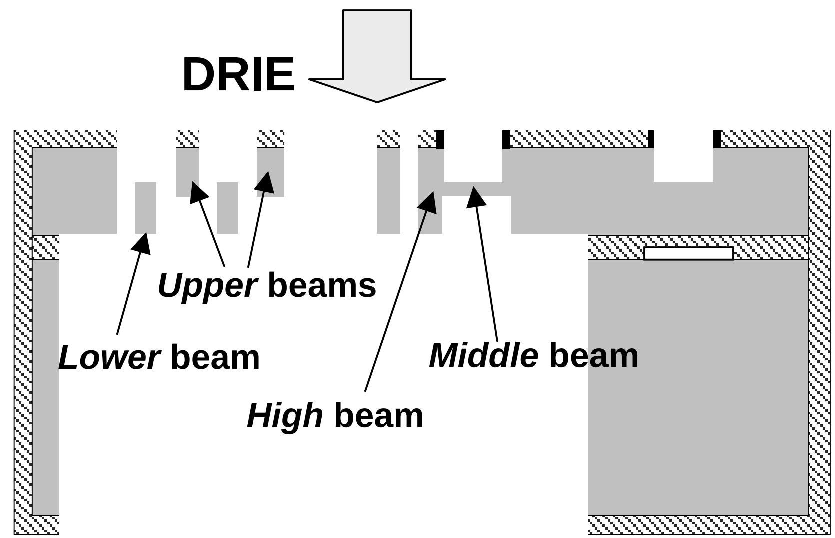


Fabrication: final, frontside steps

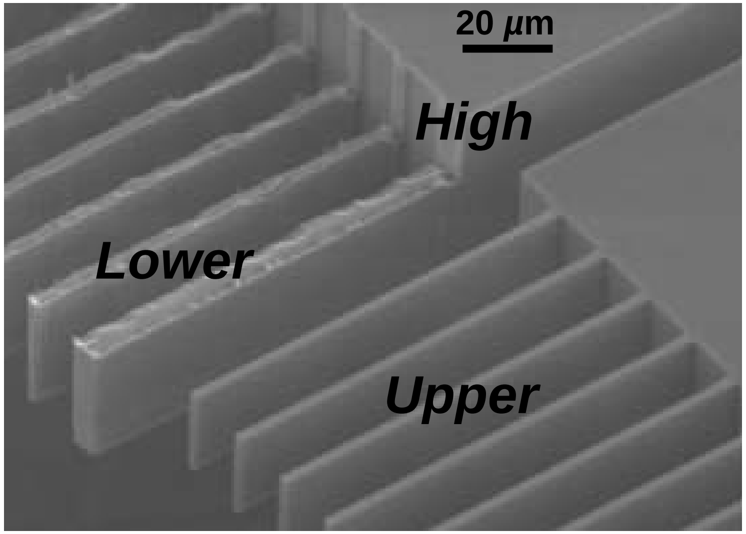
- After backside, wafer diced
- Front-side steps on chips
- Good cooling for structures is needed

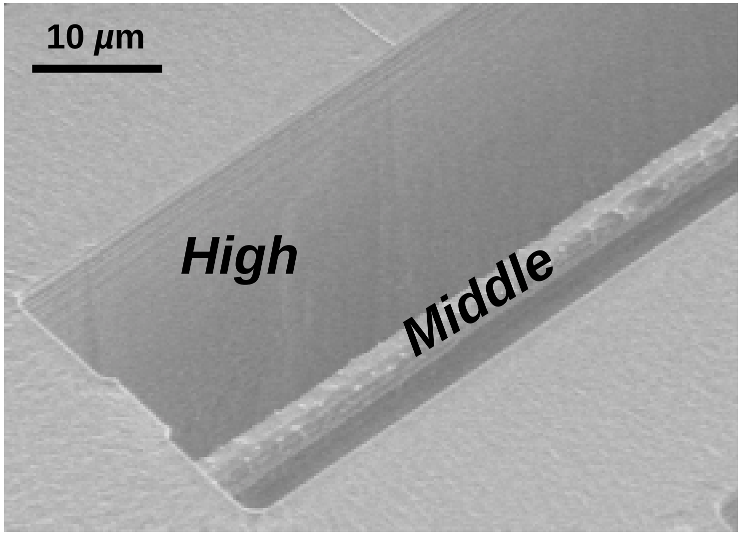


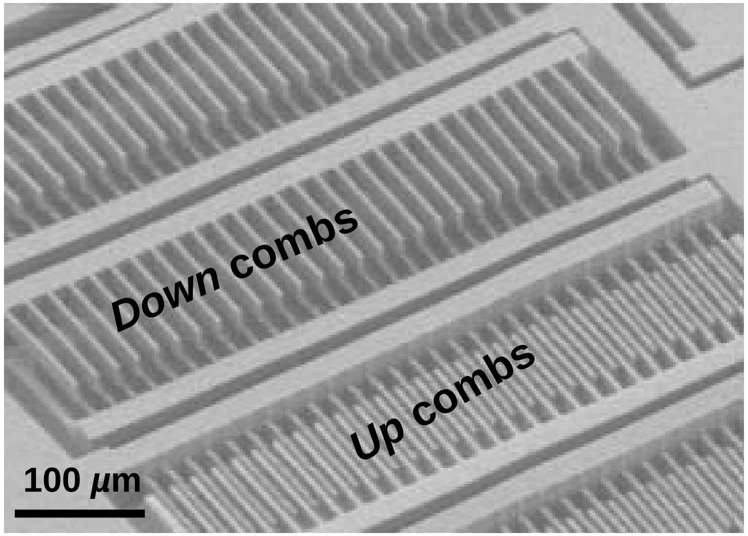




Resulting structures - II

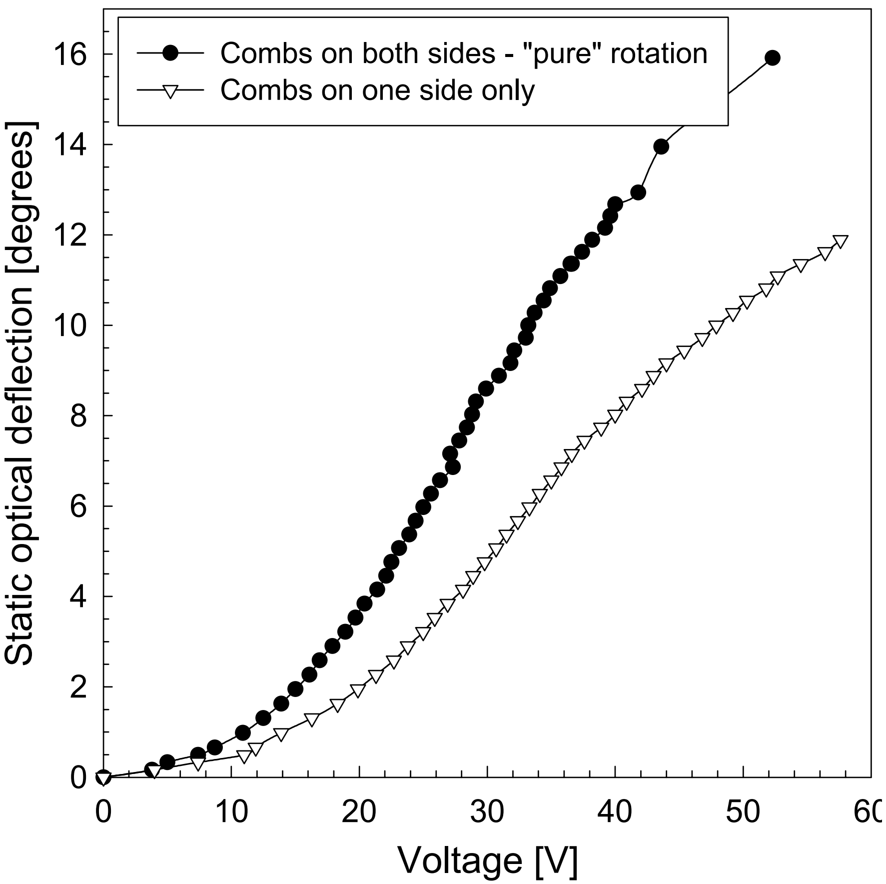


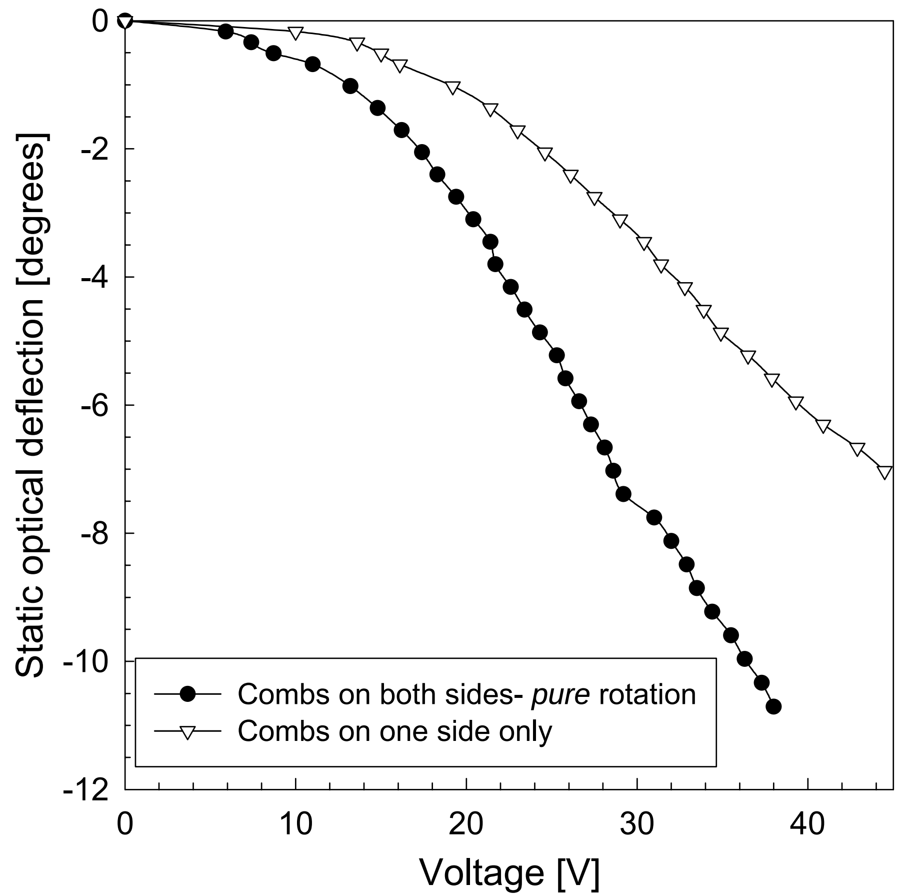




- Self aligned combdrives
- Compliant low aspect-ratio beams
- Isolated combdrives
- Opposing actuation combdrives

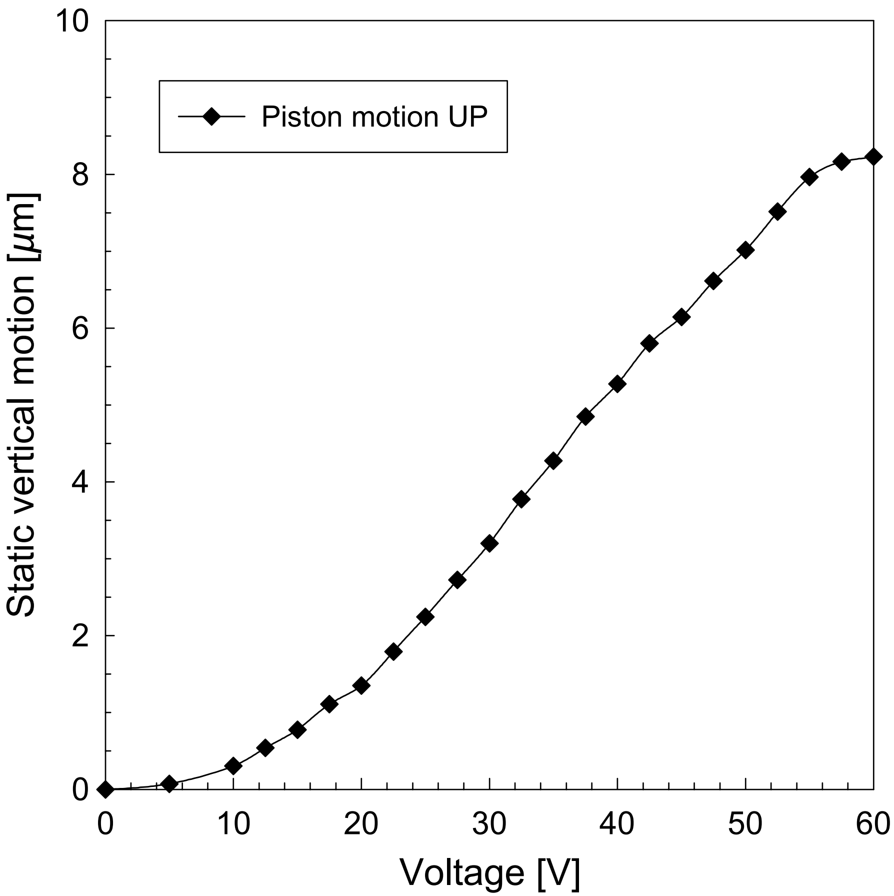
4-mode device: Rotation Measurements

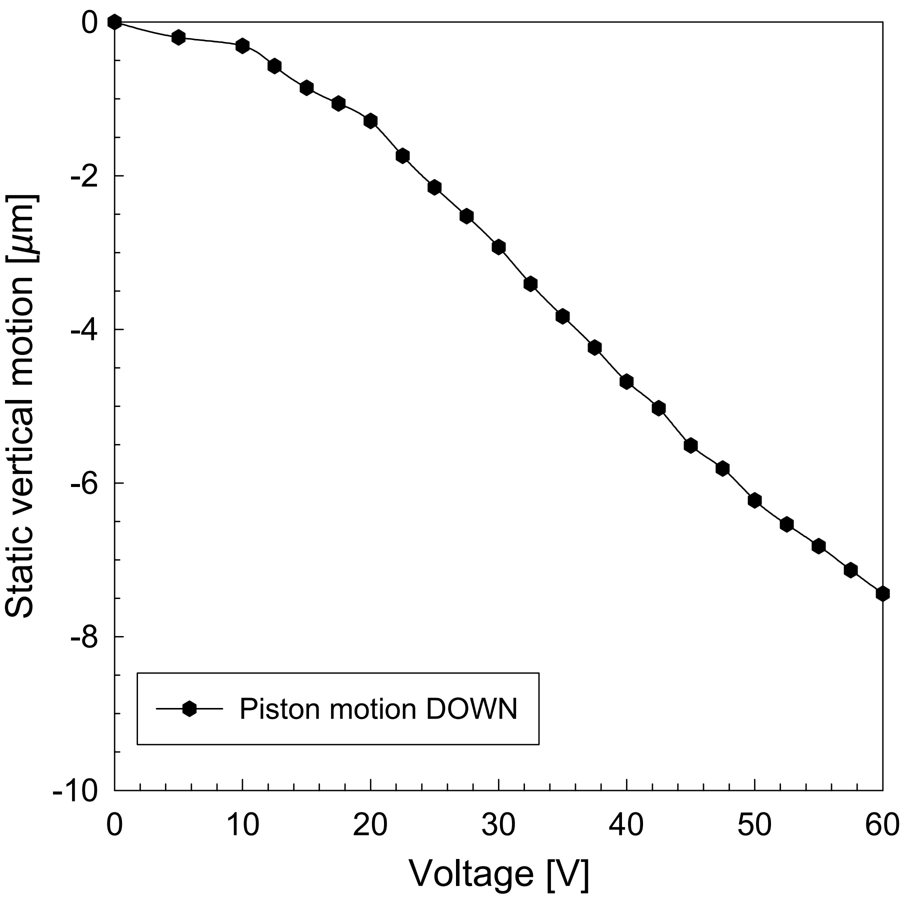




Milanović *et al, MOEMS'02, Switzerland, Aug. 02*

4-mode device: Up and Down Pistoning Measurements

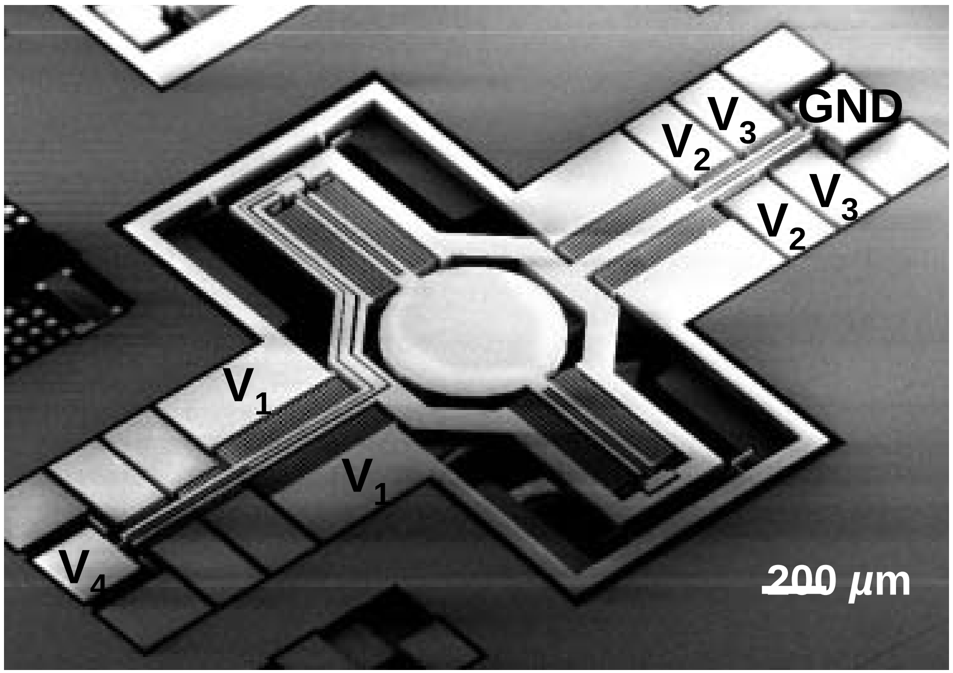


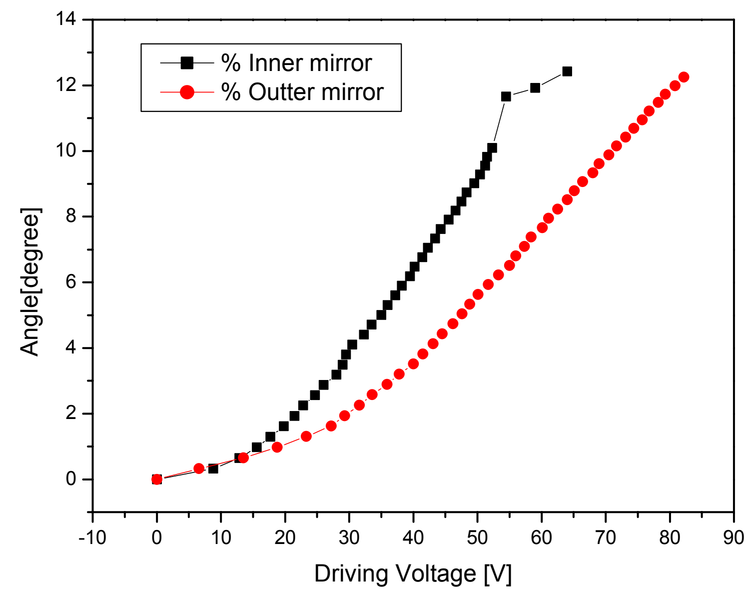


Milanović *et al, MOEMS'02, Switzerland, Aug. 02*

Adriatic Research Institute

Two-axis rotation and independent pistoning
- future adaptive optics arrays -





1DoF Micromirror				2DoF Micromirror					
Rotation [opt. deflect.]		Pistoning [µm]		Outter axis [opt. deflect.]		Inner axis [opt. deflect.]		Pistoning [µm]	
+	-	+	-	+	-	+	-	+	-
10° at 68V	-10° at 72V	8.0 at 60V	-7.6 at 60V	7.0° at 50V	-12.0 at 50 V	7.6° at 50V	n/a	n/a	n/a
24° at 130V	-20° at 123V	12 at 120V	-11 at 120V	15.6° at 100V	-20.3° at 100V	11.9° at 100V	n/a	7.0 at 100V	-6.0 at 100V

Kwon, *et al,* Optical MEMS 2002

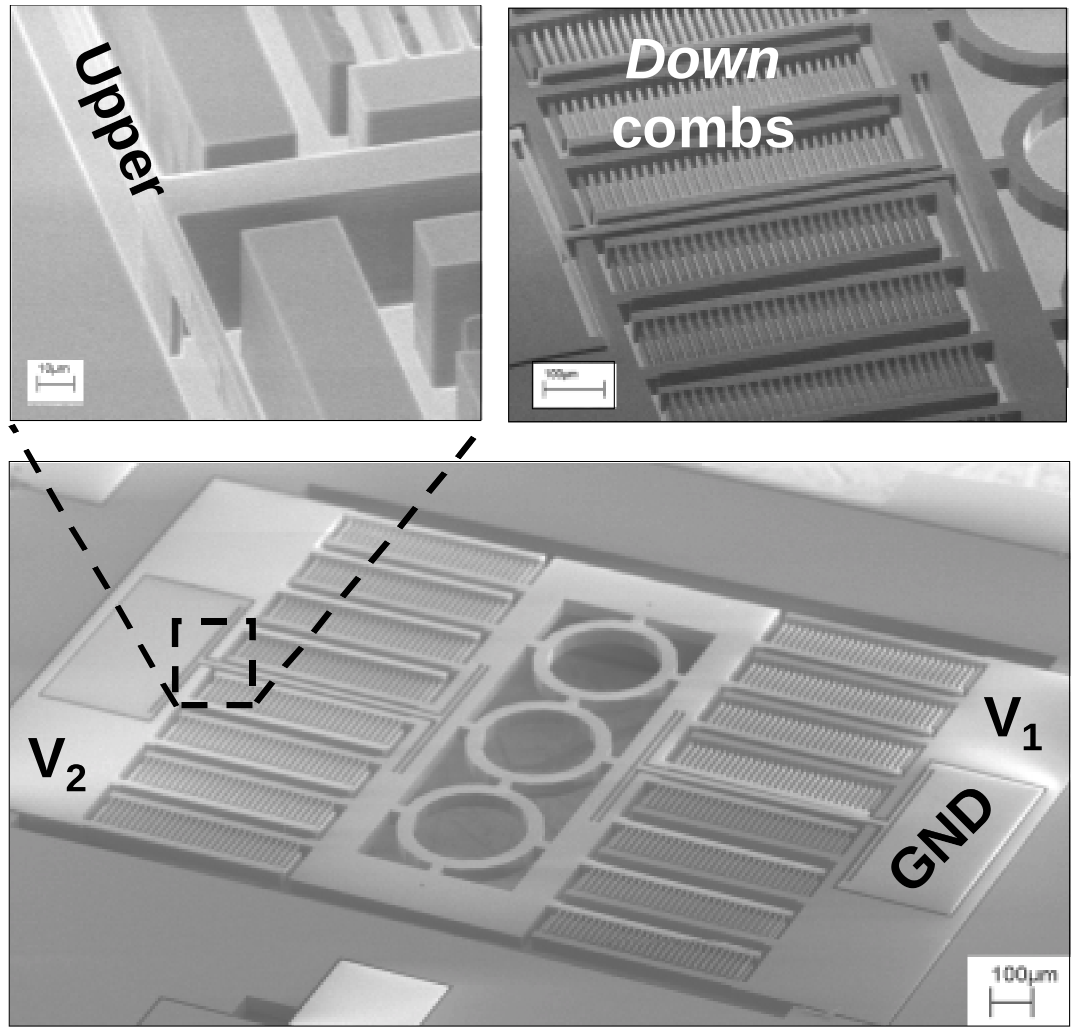
Low-voltage pistoning actuator for imaging applications

Down pistoning 8 *μ*m < 10V

Up/Down pistoning, -8 *μ*m to +8 *μ*m, <15V

At 8 *μ*m of piston, only 0.035° of tilt

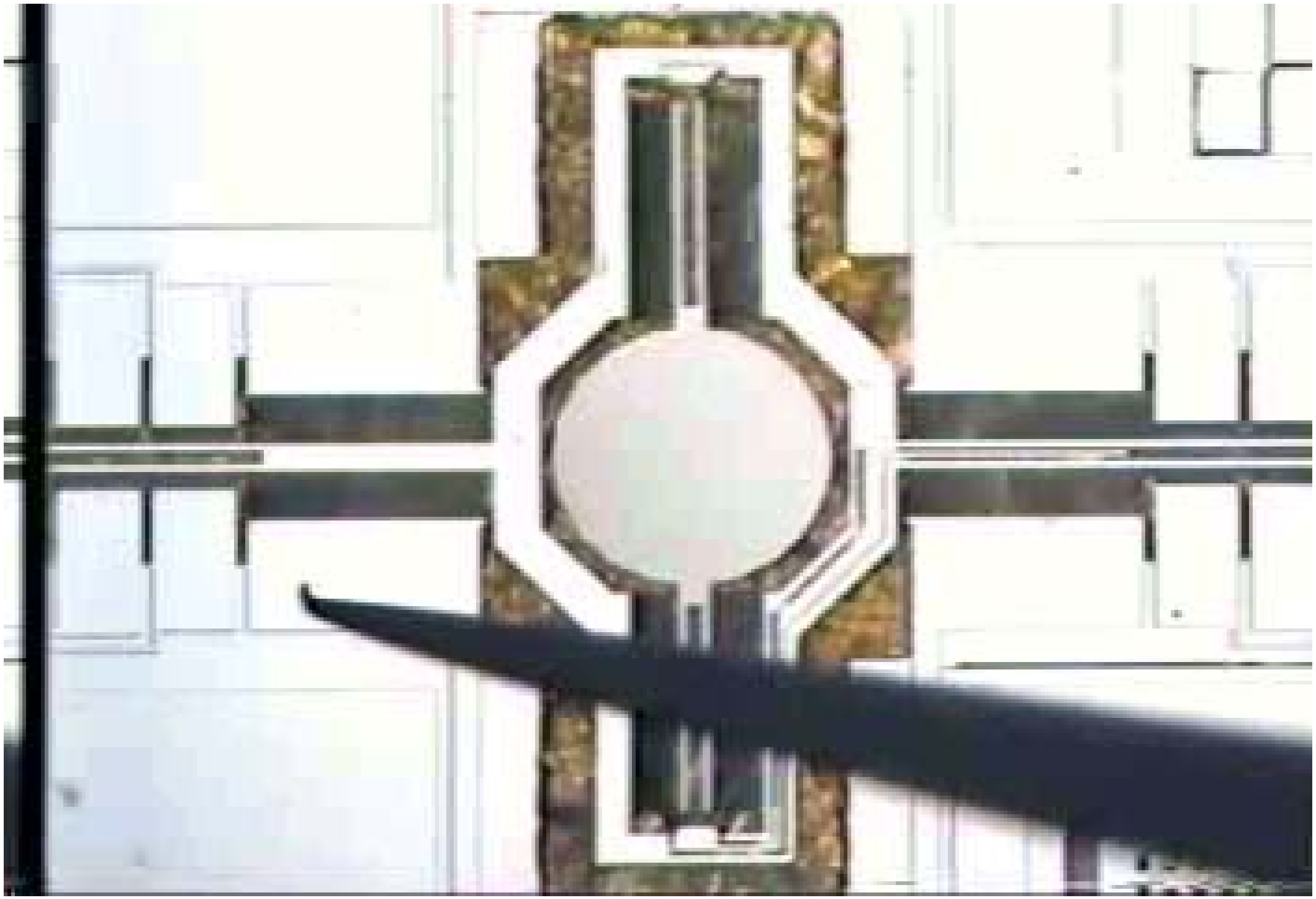
Tilt correction demonstrated



Kwon *et al, Hilton Head Workshop 2002*

Adriatic Research Institute

Demonstration video



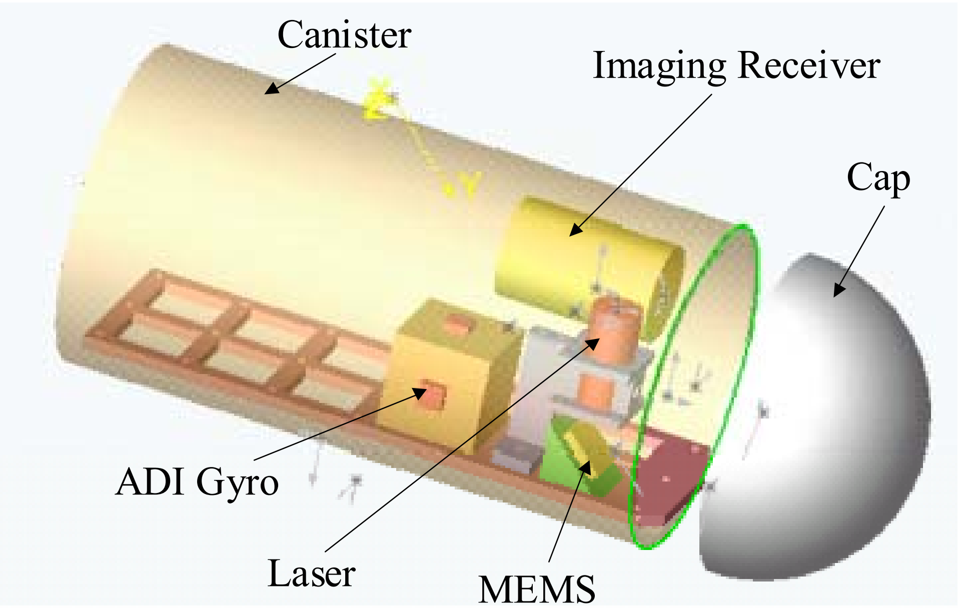
Outline

- Motivations and Background
  - Application Examples
  - Electrostatic actuators overview
  - Some micromirror examples
- High aspect ratio MEMS
  - Silicon on Insulator MEMS (SOI-MEMS)
  - Micromirrors in SOI-MEMS
- ARI Approach: Multilevel Beam SOI-MEMS
  - Fabrication and Results
  - Device examples
- Latest results with collaborators at UC Berkeley, demos
- Gimbal-less 2D Optical Scanner – *Kyoto* device

UAV (MLB Bat) Specifications

- 5 ft. wingspan
- Weight 13 lbs (including video equipment)
- Speed 25-50 miles/hr
- Cost $35,000
- Laser comm UAV to be
  - Gasoline engine, 18 lb at takeoff, 2

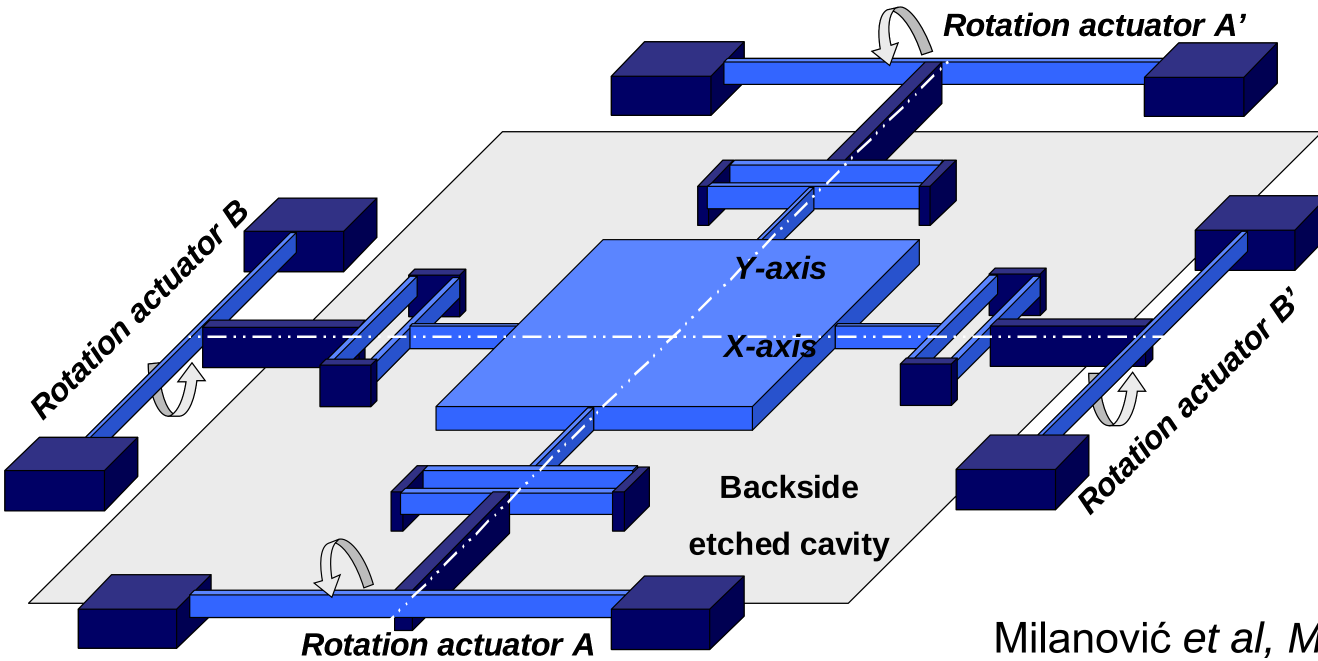
Pod Assembly



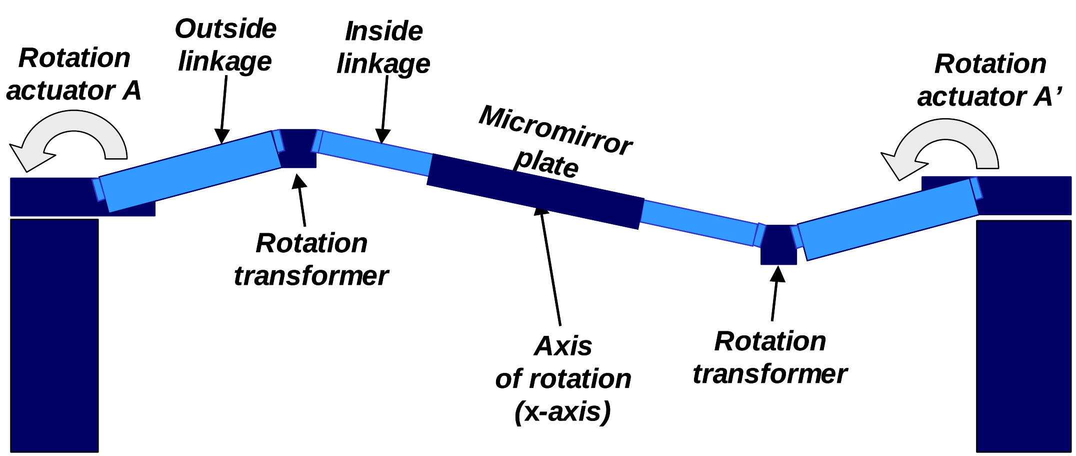
Outline

- Motivations and Background
  - Application Examples
  - Electrostatic actuators overview
  - Some micromirror examples
- High aspect ratio MEMS
  - Silicon on Insulator MEMS (SOI-MEMS)
  - Micromirrors in SOI-MEMS
- ARI Approach: Multilevel Beam SOI-MEMS
  - Fabrication and Results
  - Device examples
- Latest results with collaborators at UC Berkeley, demos
- Gimbal-less 2D Optical Scanner – *Kyoto* device
  - Toward high-frequency beam-steering micro-optical devices!

Gimbal-less 2D scanners – *Kyoto* device

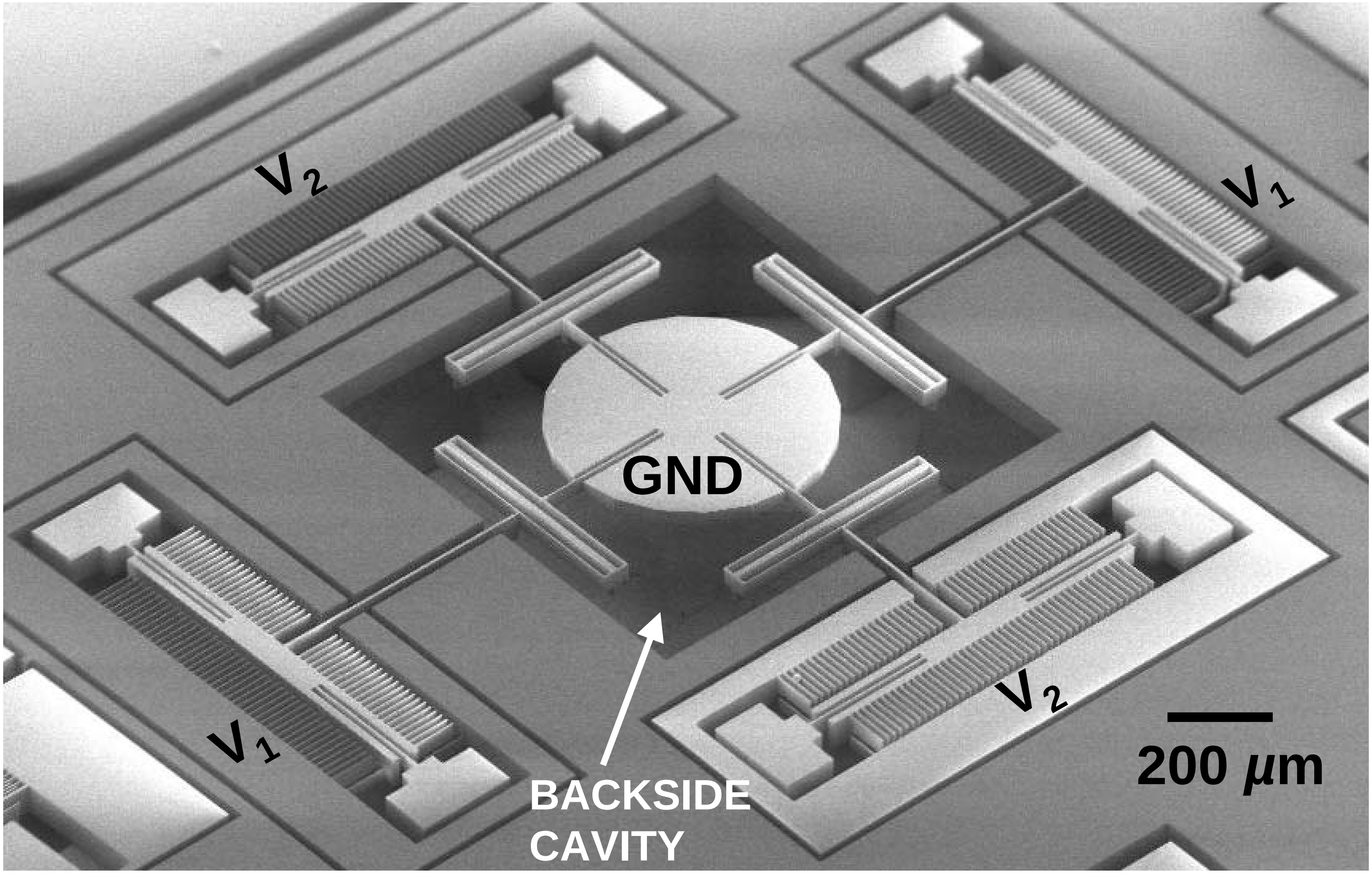


Milanović *et al, MEMS, Kyoto, Japan, Jan. 2003*



Adriatic Research Institute

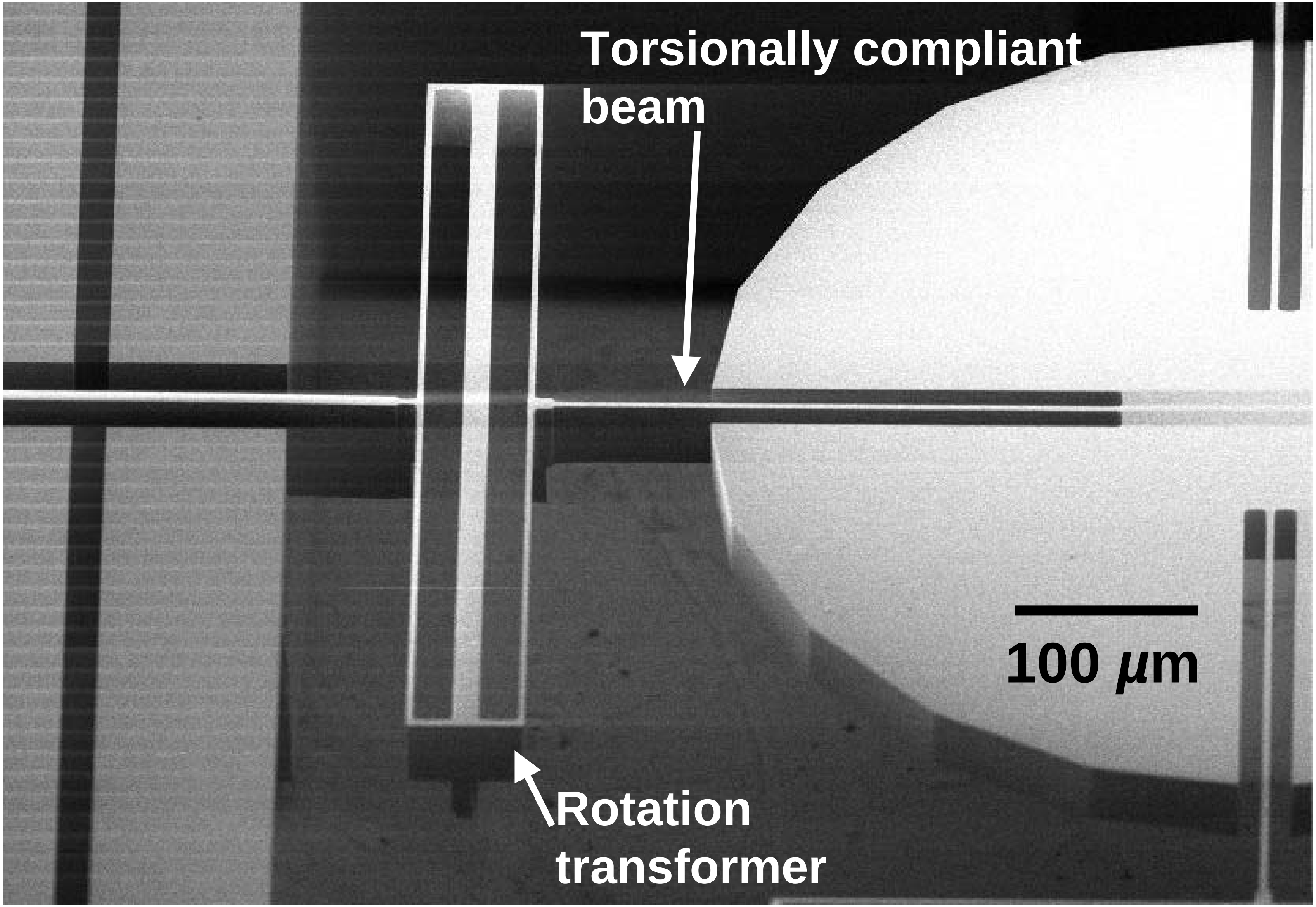
1st generation *Kyoto* device SEM



Adriatic Research Institute

Milanović *et al, MEMS, Kyoto, Japan, Jan. 2003*

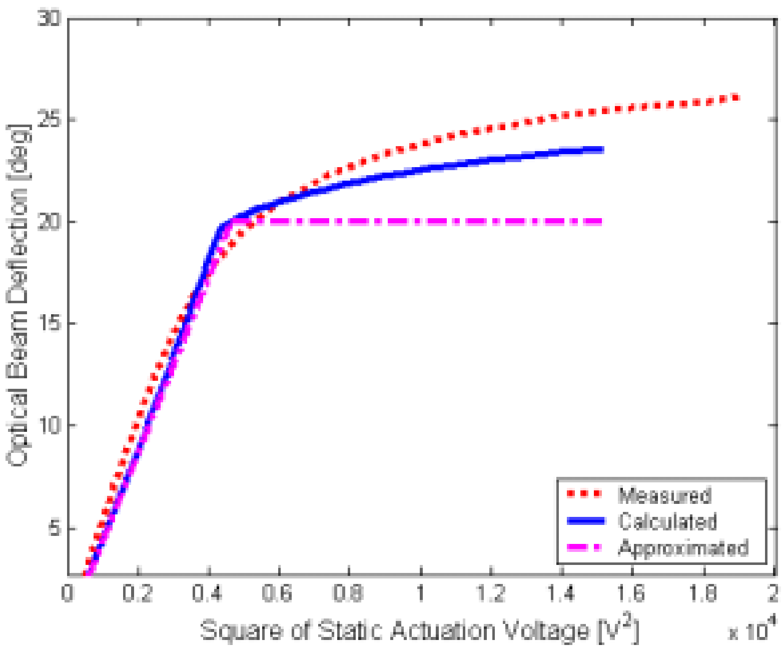
Mechanical transformer / linkages



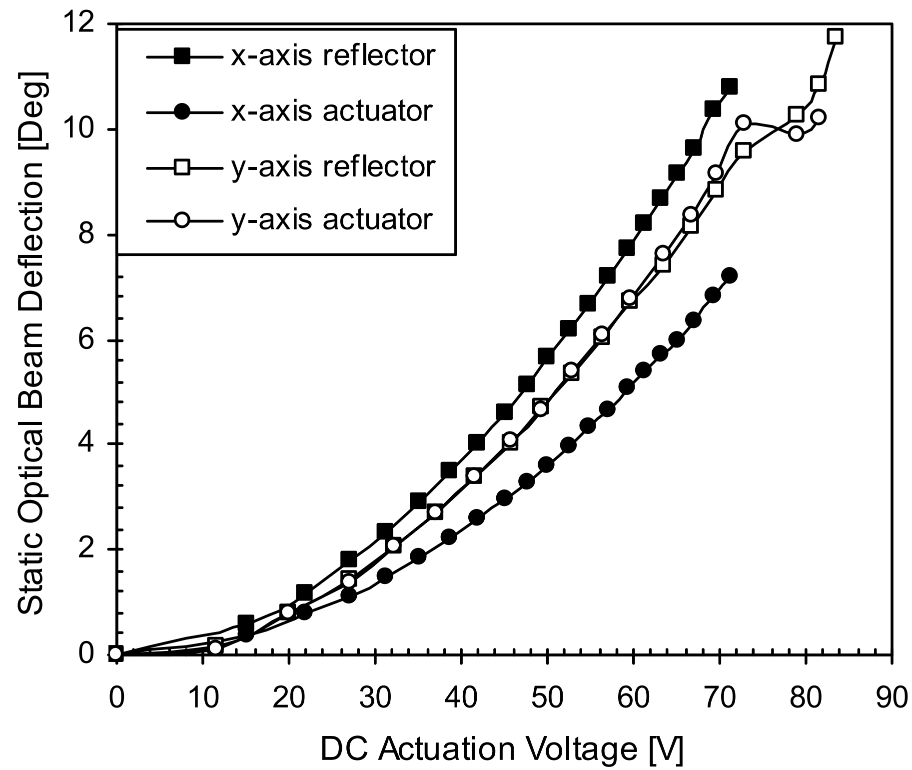
Milanović *et al, MEMS, Kyoto, Japan, Jan. 2003*

Characterization of a *Kyoto* device

X-axis 4.9kHz lowest res.
Y-axis 6.52 kHz lowest res.



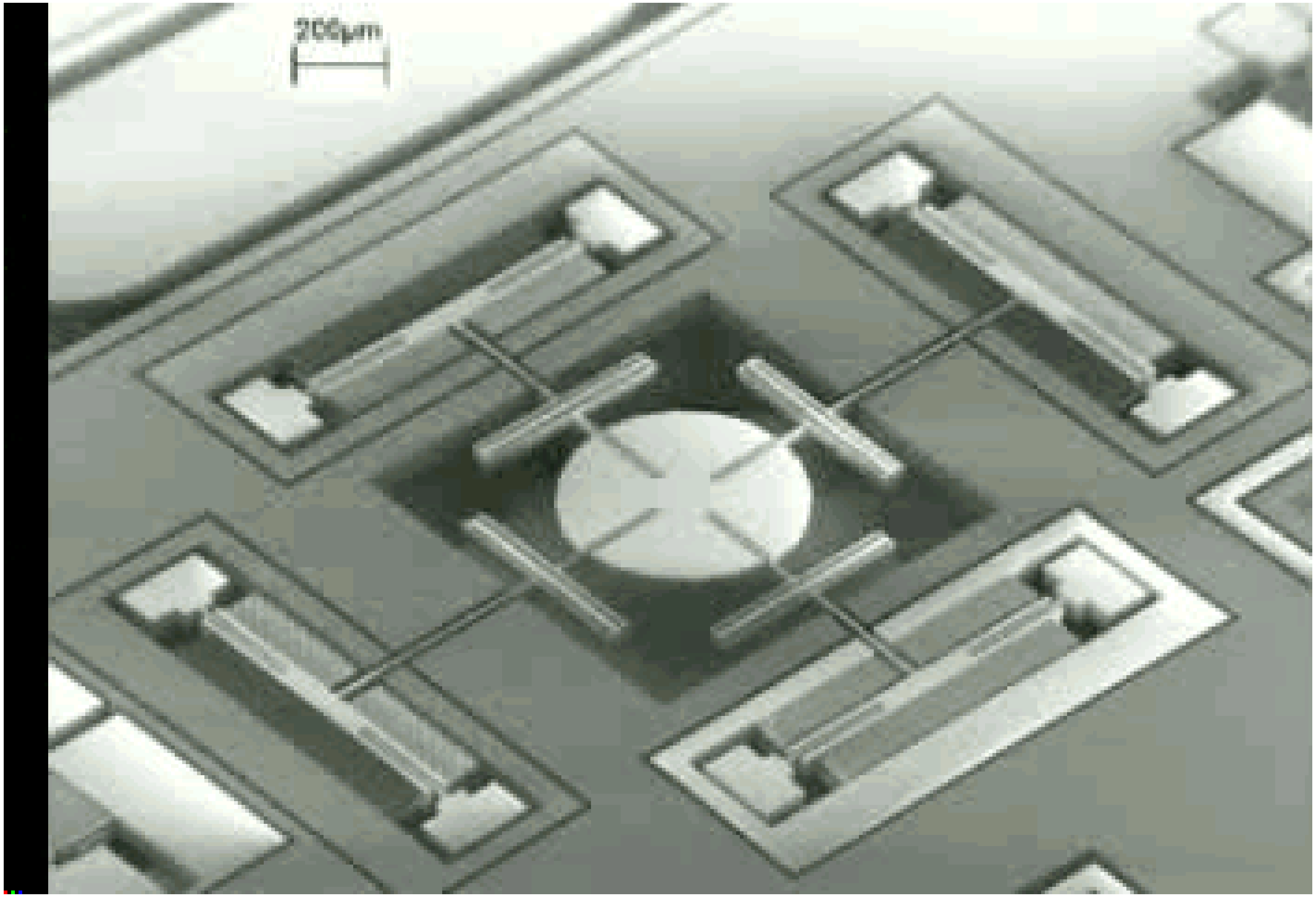
Single actuator rotation



Complete 2D scanner

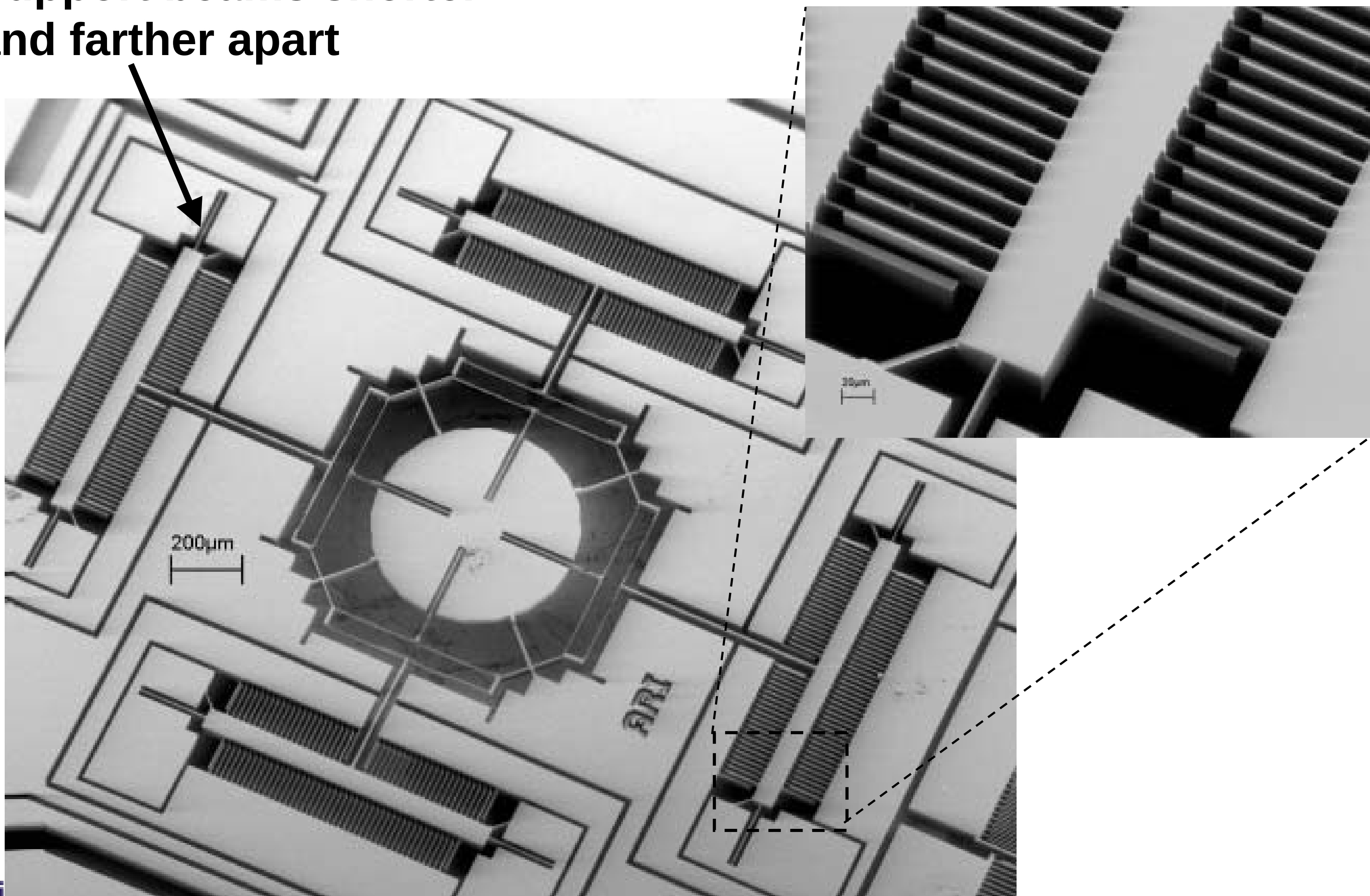
Milanović *et al, MEMS, Kyoto, Japan, Jan. 2003*

Demonstration video



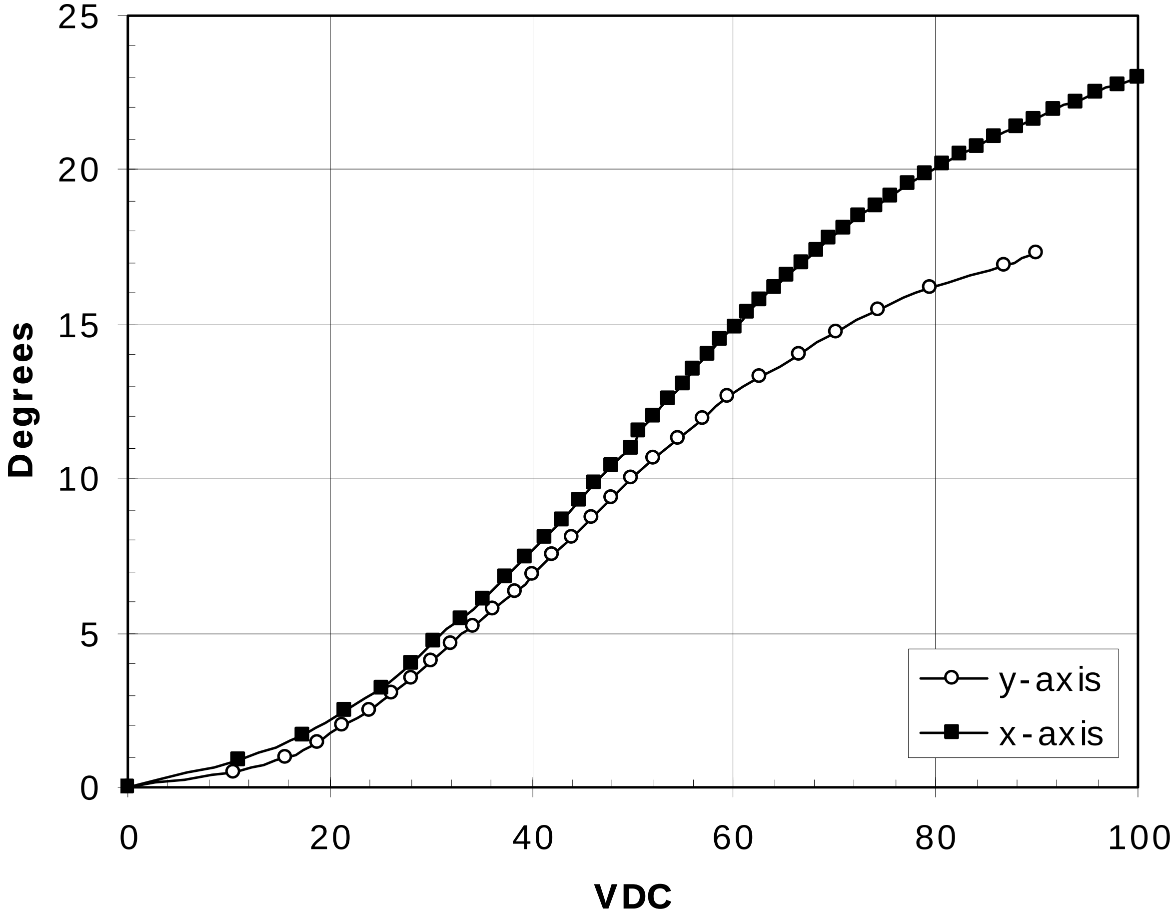
Latest tape-out with improved stability

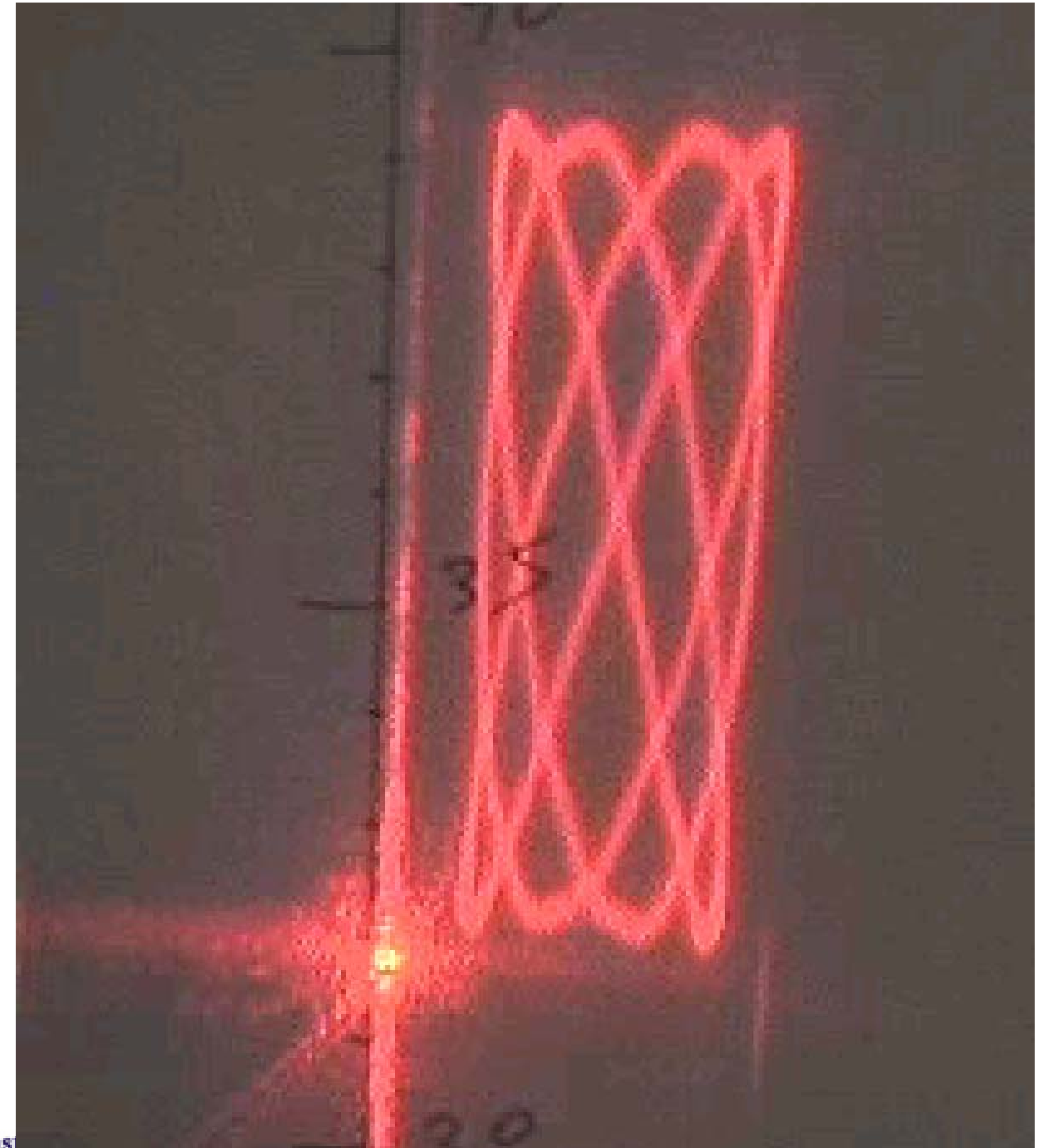
Support beams shorter and farther apart



Characterization of a large angle device – latest tape-out

X-axis 1.03 kHz lowest res.
Y-axis 1.36 kHz lowest res.




35

Summary

- New *class* of High Aspect Ratio MEMS is possible by providing additional degrees of freedom
  - Especially useful for Optical Applications!
- Many mechanical, optical, etc. applications can benefit from the technology
  - Microoptics, microrobotics, inertial sensing
- Technologies are maturing
  - variety of mechanical designs are being tested
  - models and tools (CAD) are being developed for beams, structures, layout
- ARI seeks research grants and commercial partners to further the work and apply to commercial applications
- Near the goal of >10kHz two-axis scanners with large angle static scanning
- Working toward large arrays (above + pistoning)