MEMS Actuation Using Electrostatic Combdrives

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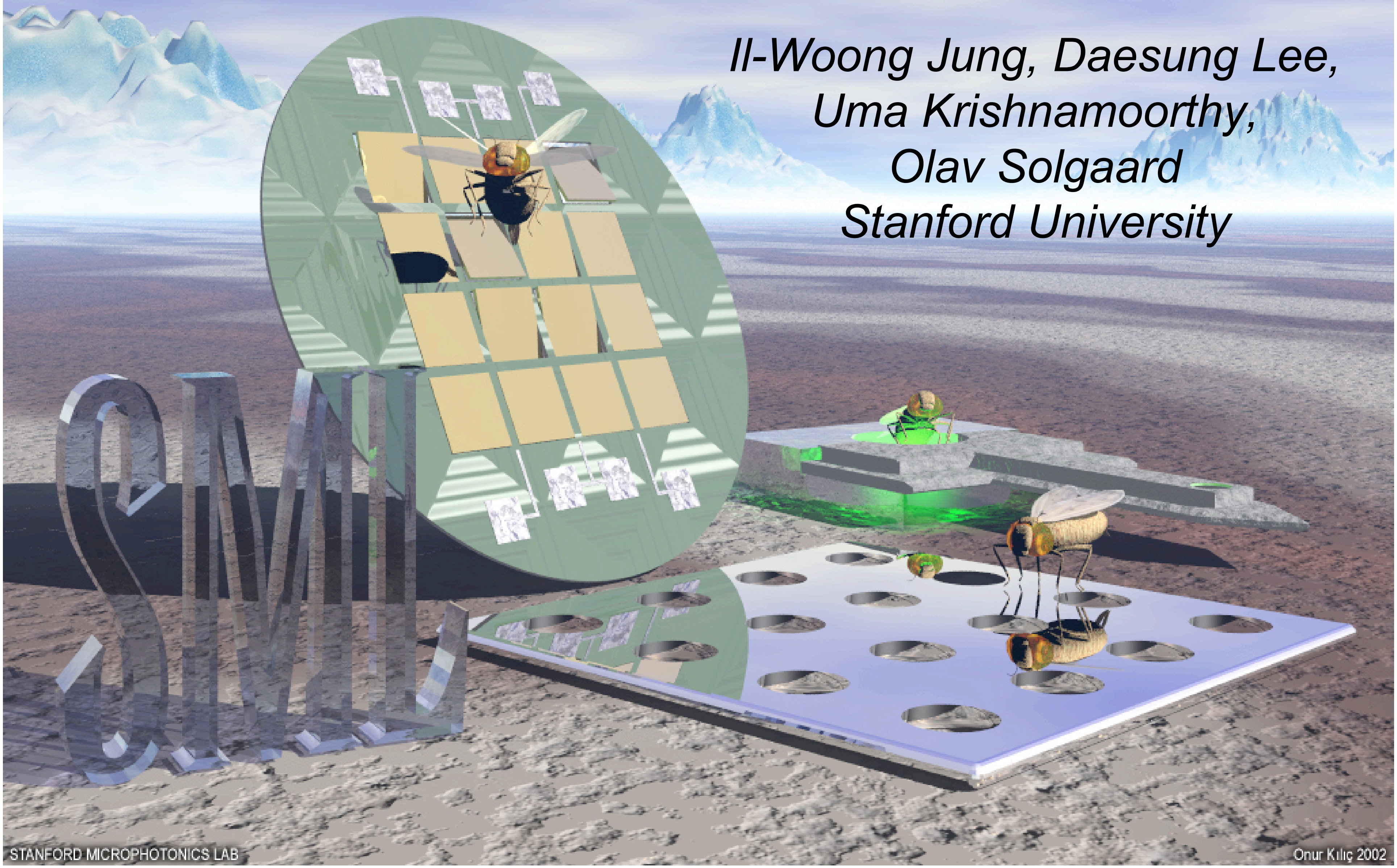
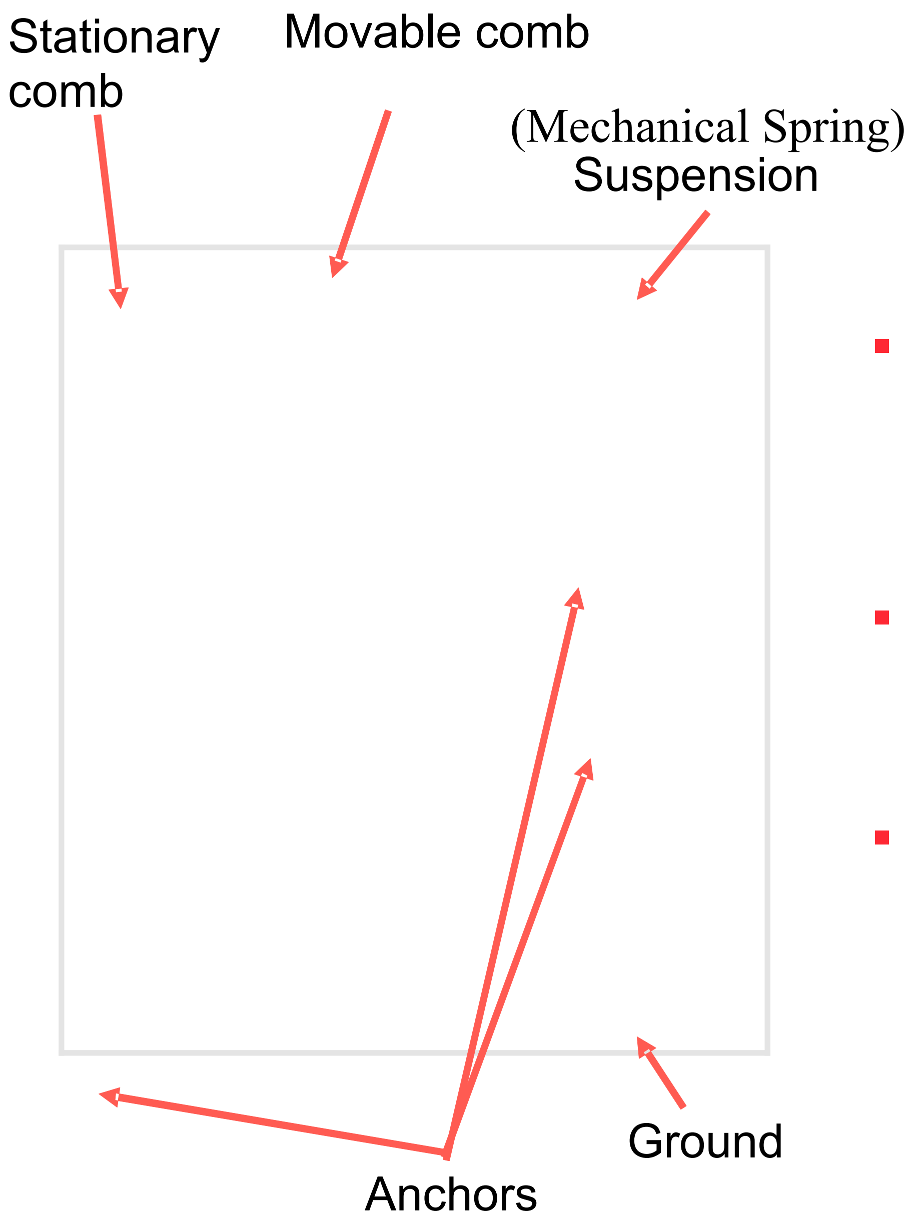


Outline

- What are electrostatic combdrives and why use them?
  - First order description of Electrostatic combdrives
  - Comparison of combdrives and parallel-plate actuators
- Combdrive Analyses
- Self-Aligned Vertical Combdrives
- Examples
  - Gimbaled 2-D MEMS Biaxial Scanner
  - Tip-tilt-piston Mirror Arrays
    - Design and Simulations
    - Fabrication
    - Characterization of First Generation Arrays
  - Large Throw Deformable Mirror Arrays

Combdrive Basics



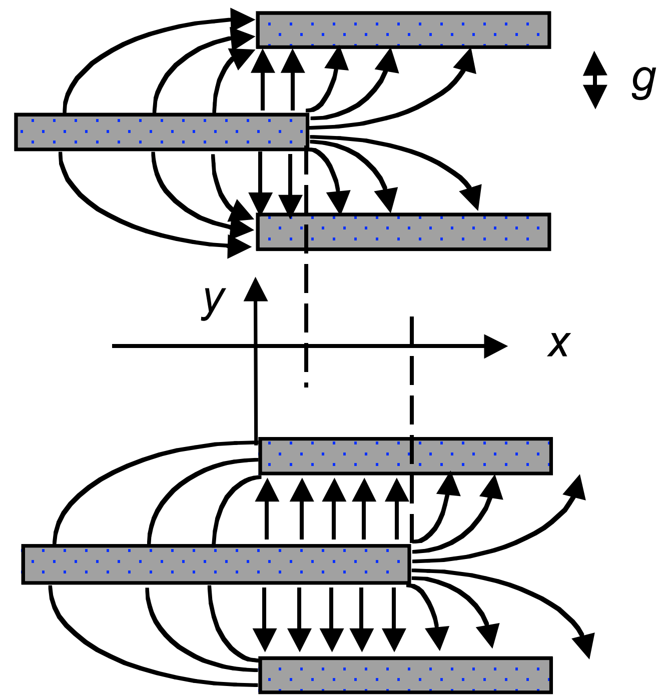
- The voltage across the interdigitated electrodes creates a force that is balanced by the spring force in the crab-leg suspension
- Note that combdrives that are fabricated in a single layer (as this one) are automatically self aligned
- This type of actuator is more complex to fabricate than parallel-plate actuators if the forces are to be applied vertically as in AO

Force in Combdrives

$$F = \frac{1}{2} \cdot V^2 \cdot \frac{\partial C}{\partial x}$$

$$F = \frac{1}{2} \cdot V^2 \cdot \frac{2N \cdot \varepsilon \cdot h}{g}$$

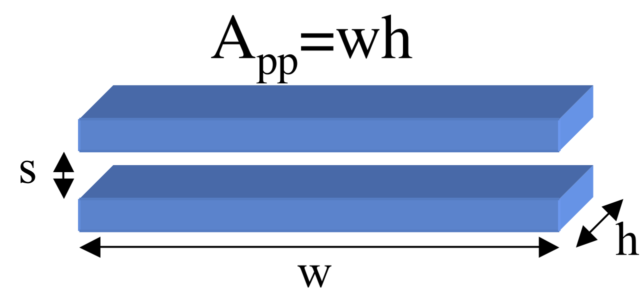
$$F = V^2 \cdot \frac{N \cdot \varepsilon \cdot h}{g}$$



N is number of comb-fingers, *h* is the thickness of the comb-fingers (perpendicular to the plane in the figure), and *g* is the width of gap between the comb-fingers

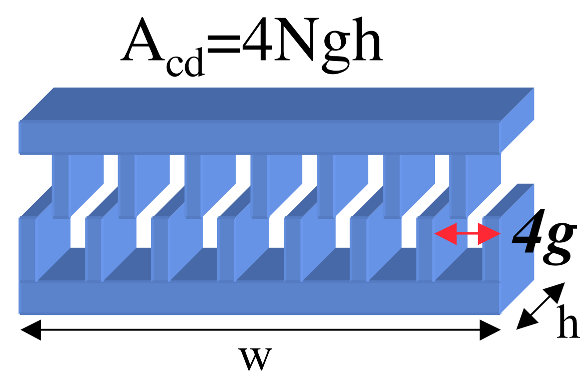
Combdrive vs. parallel plate

$$\text{Parallel plate: } F_{pp} = \frac{A_{pp}\varepsilon_0 V^2}{2s^2}$$



$$\text{Combdrive: } F_{cd} = \frac{N\varepsilon_0 h V^2}{g}$$

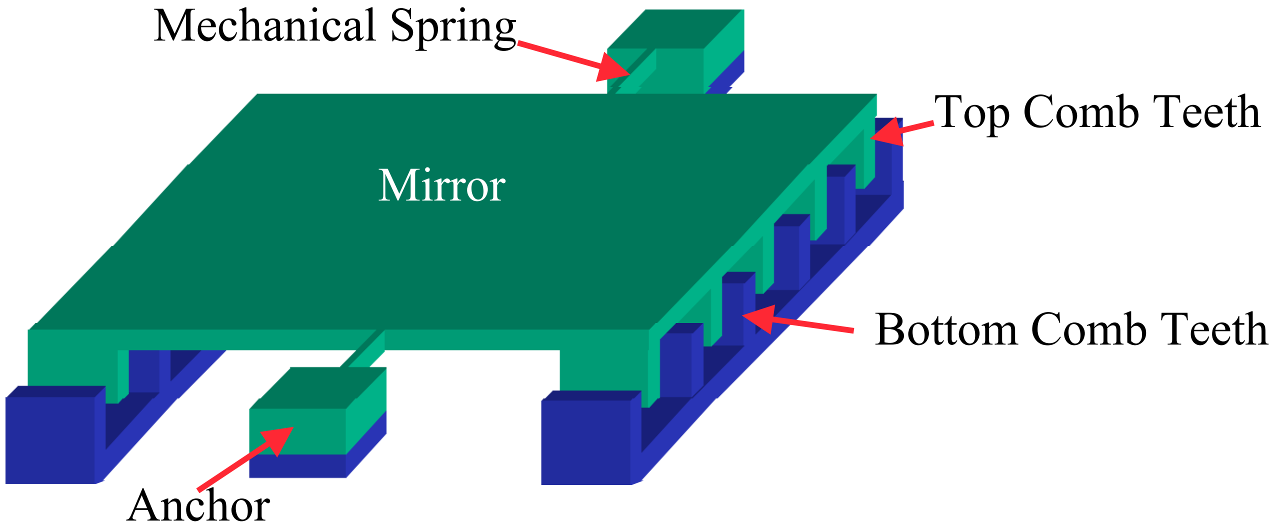
$$A_{cd} = 4Ngh \Rightarrow F_{cd} = \frac{A_{cd}\varepsilon_0 V^2}{4g^2}$$



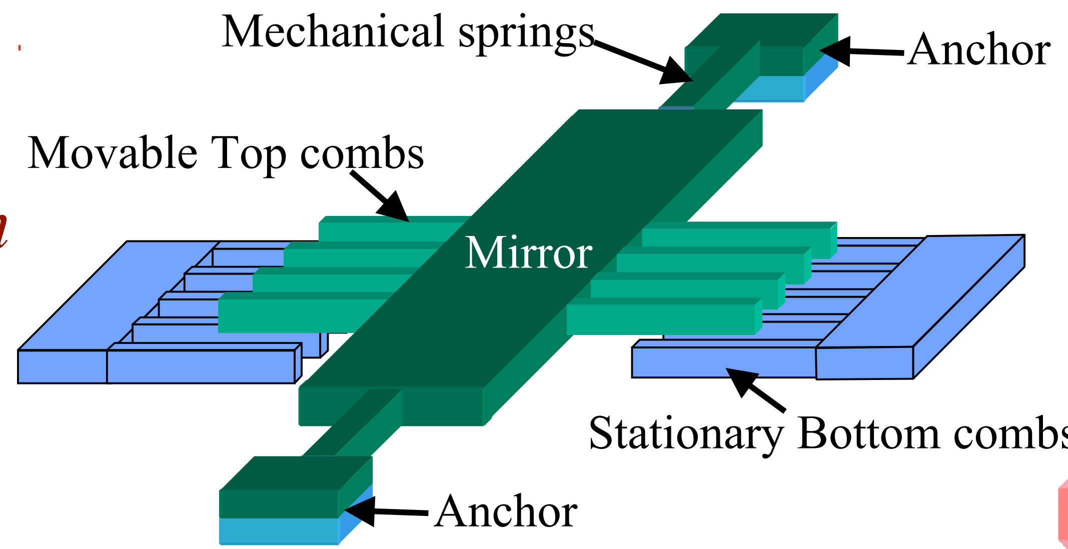
$$\frac{F_{cd}}{F_{pp}} = \frac{s^2}{2g^2} \approx \frac{9}{2}\frac{(\text{Displacement})^2}{(\text{Lithographic limit})^2}$$

Combdrives good for large displacements and large forces (broad-band AO/Tip-tilt)

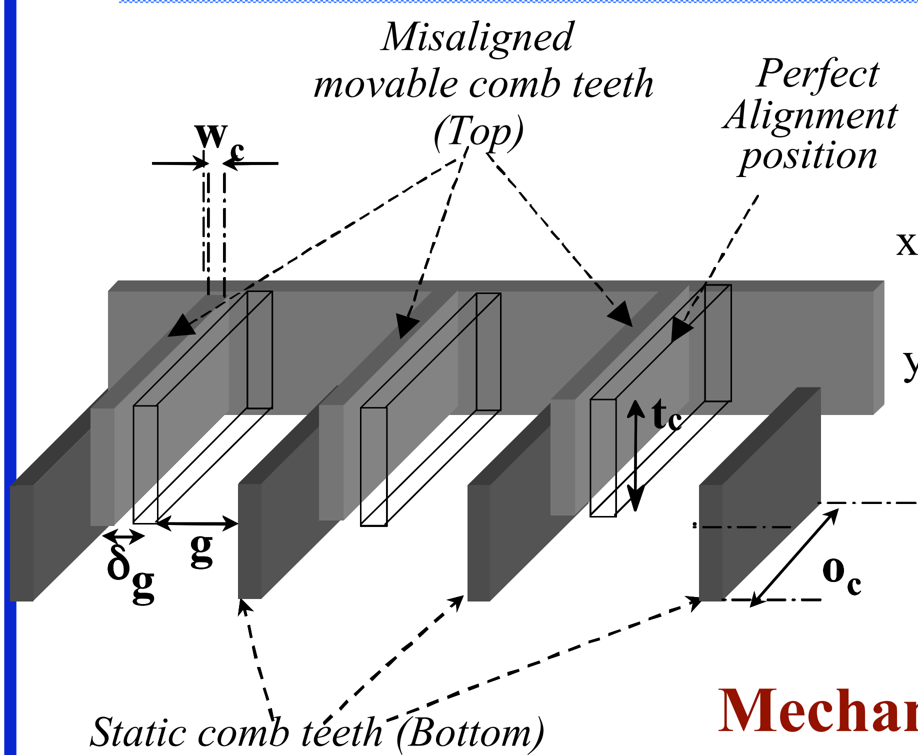
Piston motion - Vertical Comb Drive Actuator

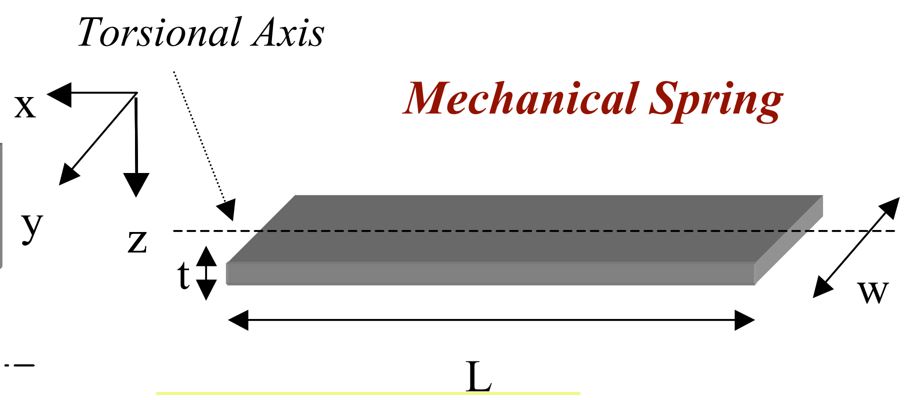


Simple Implementation



Vertical Combdrive Analysis





$$F_{mech,z} = k_z z$$

Mechanical Spring constants (k)

$k_x = \frac{Ewt}{L}$	$k_y = \frac{Ew^3t}{L^3}$	$k_z = \frac{Ewt^3}{L^3}$
$k_\theta = \frac{Gwt^3}{L}\left[\frac{1}{3} - 0.2\frac{t}{w}\left(1 - \frac{t^4}{12w^4}\right)\right]$		

Stability Analysis

Force balance equations

$$No_c \varepsilon_0 V^2 \left[\frac{1}{2(g - \delta g - x)} + \frac{1}{2(g + \delta g + x)} \right] = k_z z$$

$$No_c \varepsilon_0 z V^2 \left[\frac{1}{2(g - \delta g - x)^2} - \frac{1}{2(g + \delta g + x)^2} \right] = k_x x$$

Stability conditions

$$k_z - \frac{1}{2} \frac{\partial^2 C}{\partial z^2} V^2 \geq 0$$

$$k_x - \frac{1}{2} \frac{\partial^2 C}{\partial x^2} V^2 \geq 0$$

Solutions at perfect alignment $\delta g = 0$

Maximum sustainable voltage

$$V_{\max} = g \sqrt{\frac{\sqrt{0.5 k_x k_z}}{N \varepsilon_0 o_c}}$$

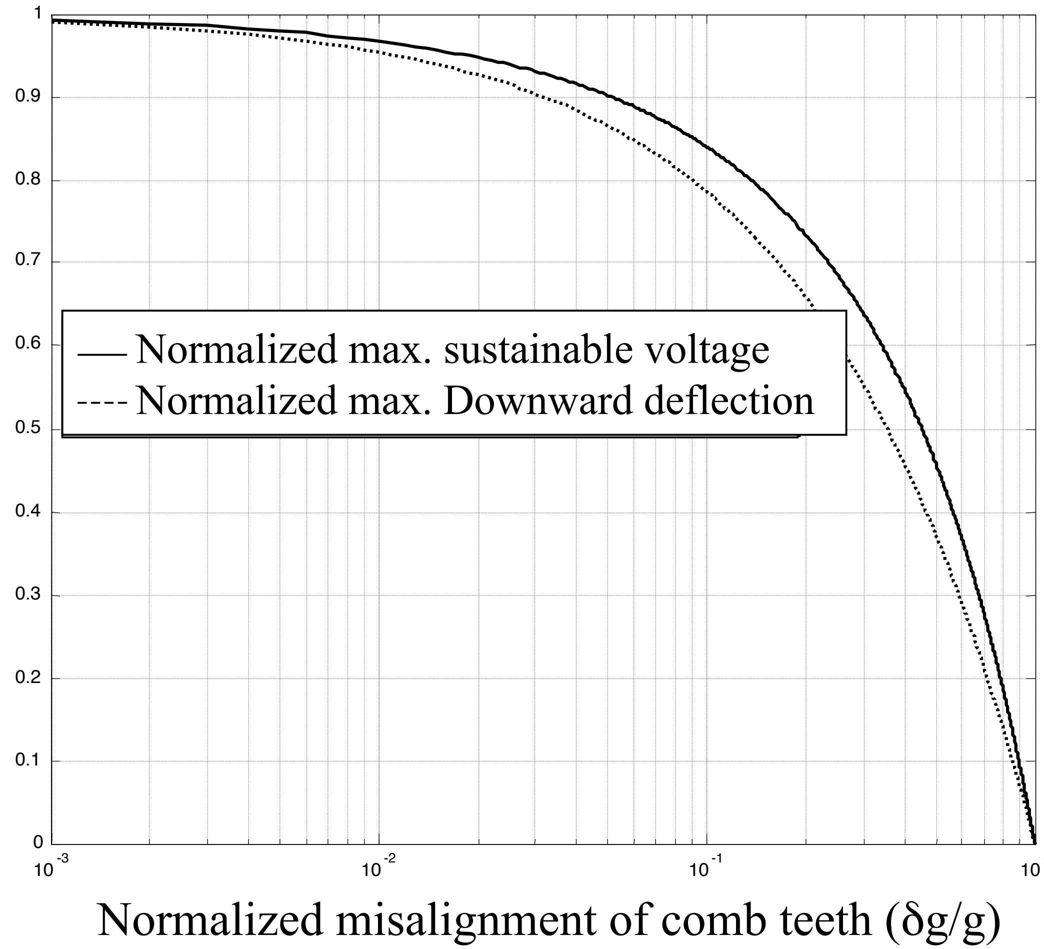
Maximum deflection

$$z_{\max} = g \sqrt{\frac{k_x}{2 k_z}}$$

Misalignment related Instability

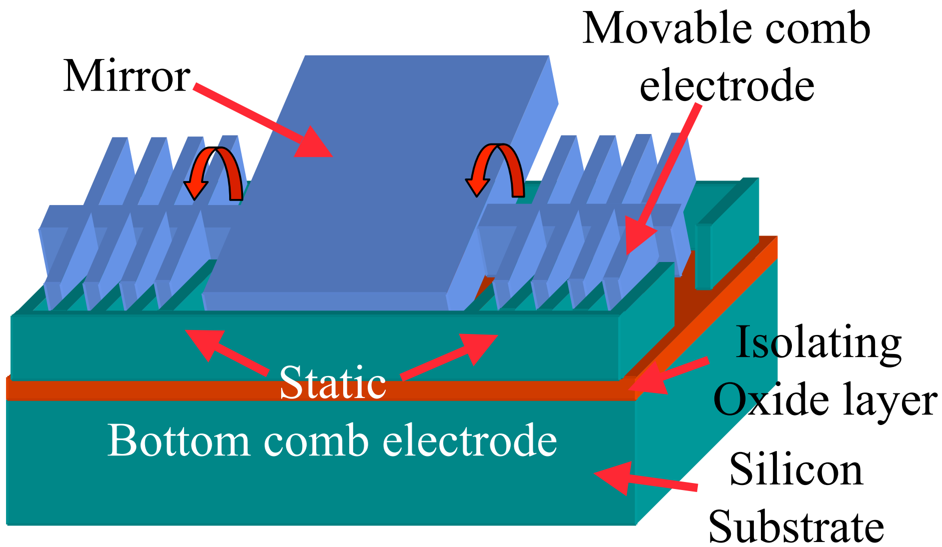
$$\frac{V_{max}(\delta g \neq 0)}{V_{max}(\delta g = 0)}$$

$$\frac{z_{max}(\delta g \neq 0)}{z_{max}(\delta g = 0)}$$

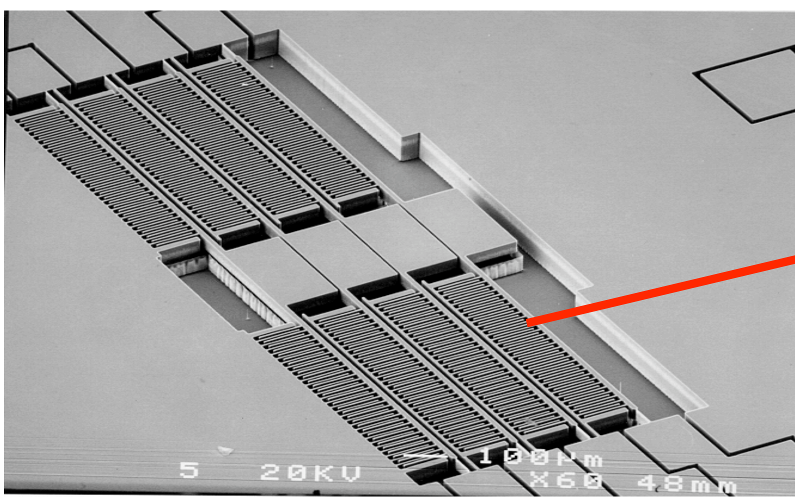


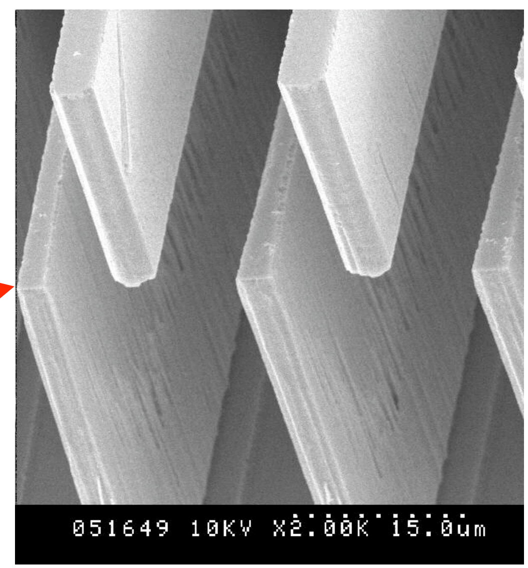
Conclusion:
Vertical Combs should be "self aligned"

Micromirrors with Self-Aligned Vertical Comb Actuators



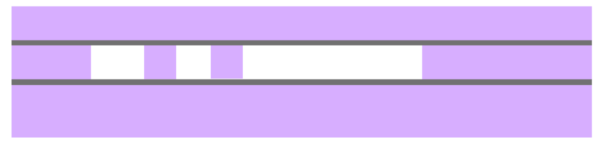
- Two SOI layers stacked on the substrate – precise thickness control
- Large force and controllable range of motion



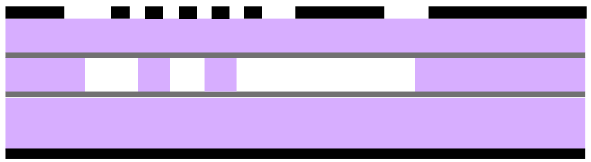


Self-Aligned Actuator Fabrication Process

(a) DRIE of coarse patterns (Mask 1)

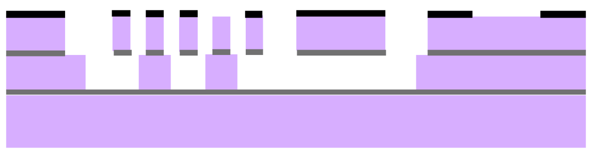


(b) Thermal oxidation, fusion bonding, grinding, and polishing

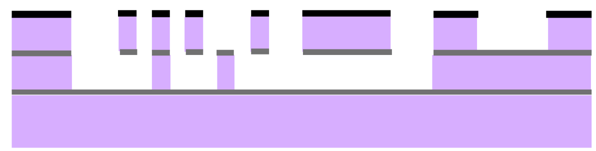


(c) Self-alignment mask patterning (Mask 2) after LTO deposition

(d) Partial etching of the LTO layer (Mask 3)



(e) DRIE of the upper device layer followed by d
irectional oxide etch



(f) DRIE of lower device layer patterned by Mas
k 2 and the upper device layer patterned by Ma
sk 3

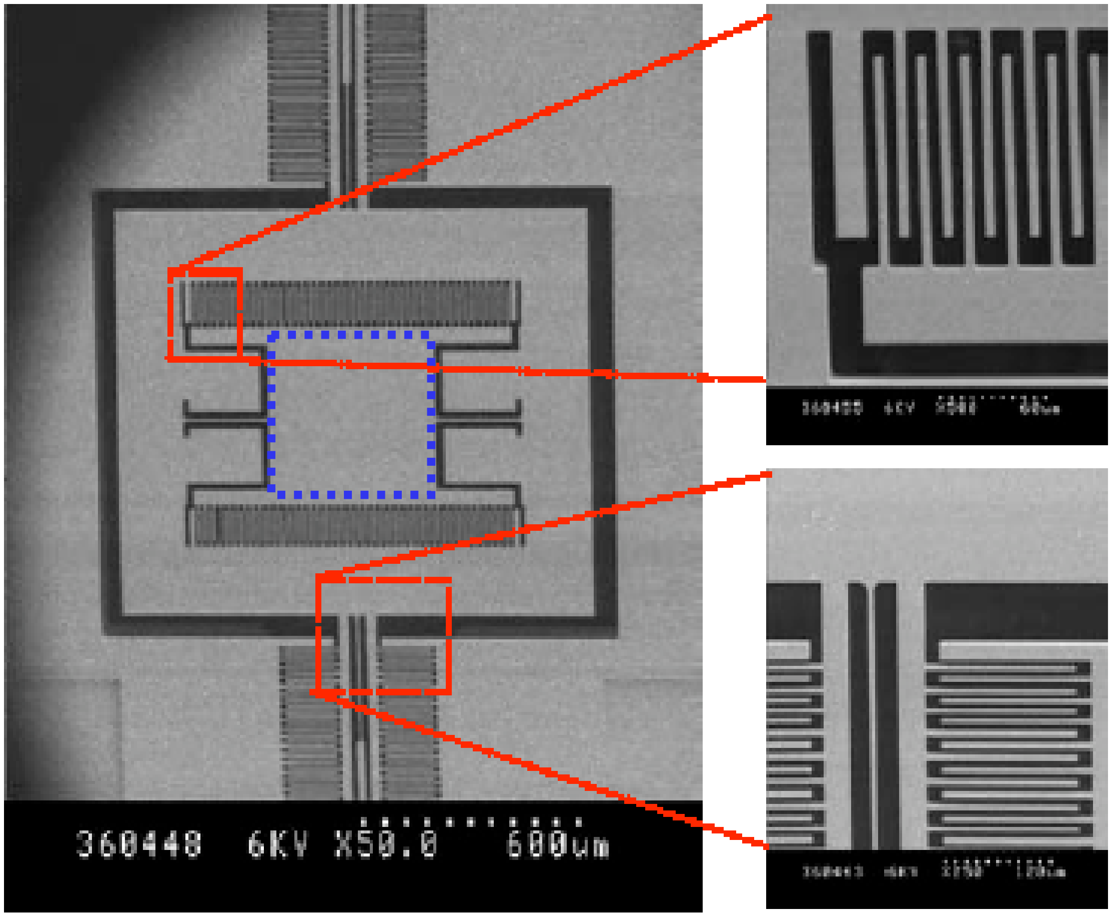
(g) Backside patterning and DRIE followed by direct
ional oxide etch from back and front-side (Mask 4)

SCS

Thermal oxide

Masking LTO

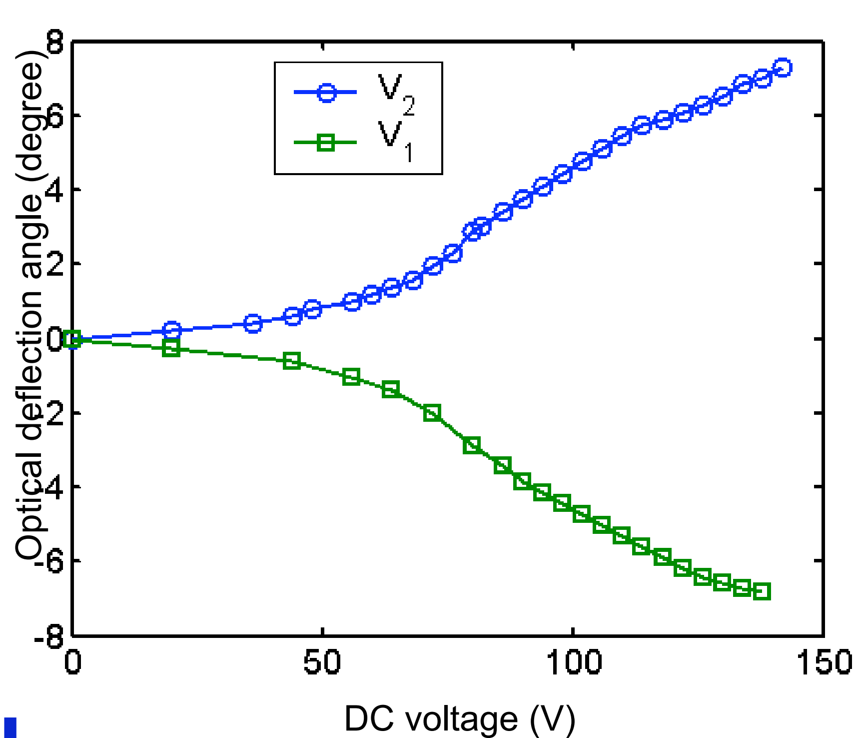
MEMS Biaxial Scanner

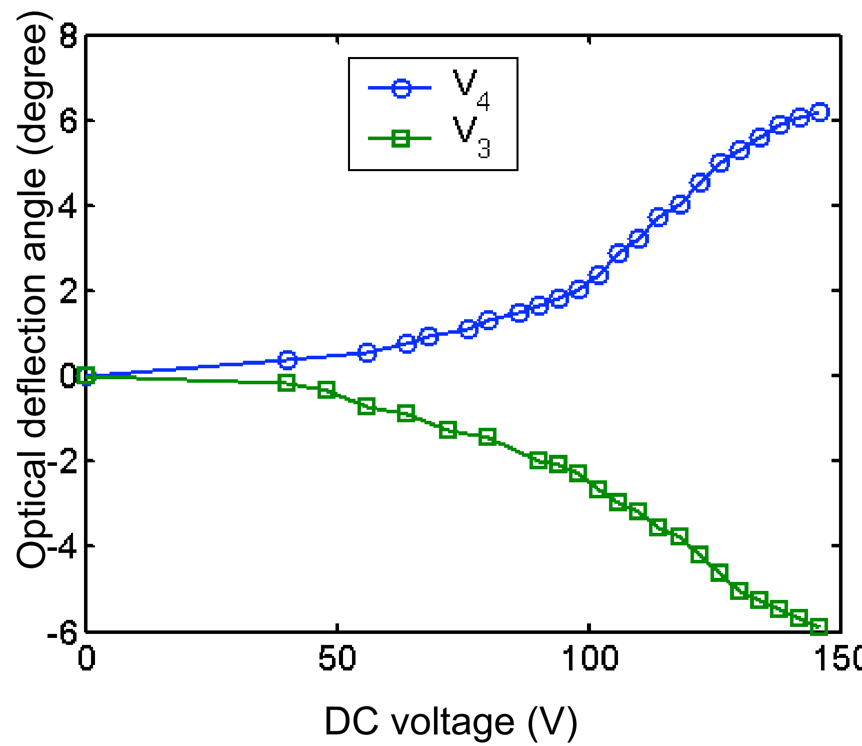


- Static Optical Deflection
  - Inner Axis: +/-7.5° at 133V
  - Outer Axis: +/-7.8° at 200V
- Resonant Freq.
  - Inner Axis: 3.5kHz
  - Outer Axis: 980Hz

500µmx500µm

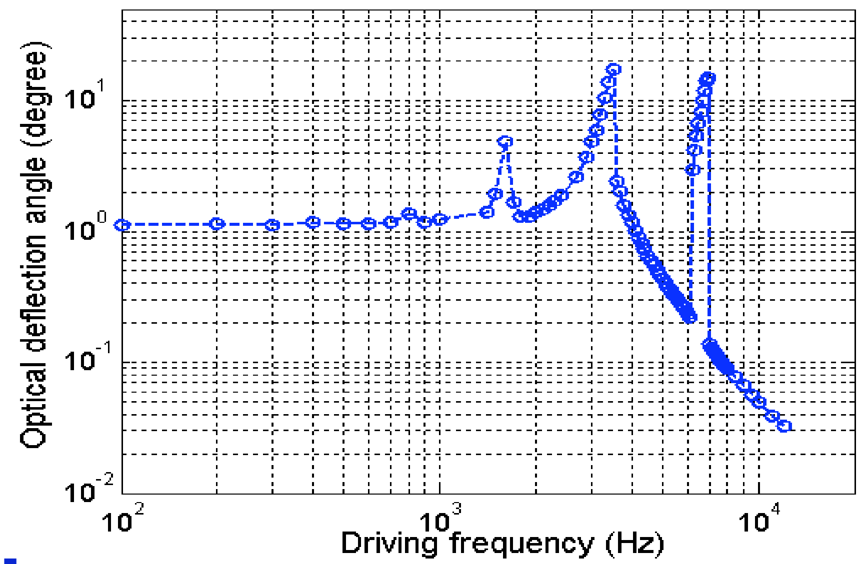
Mirror Rotation

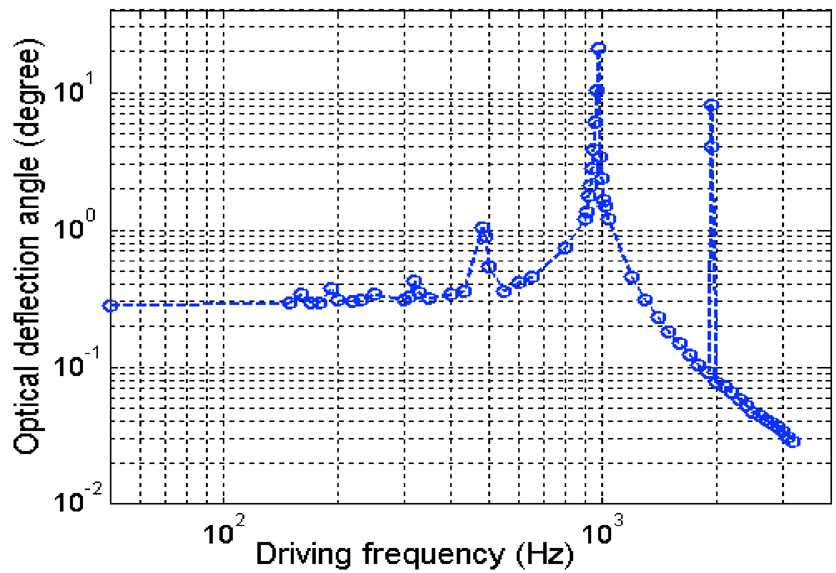




- Static optical deflection of the inner (left) and outer frame (right)

Frequency Response





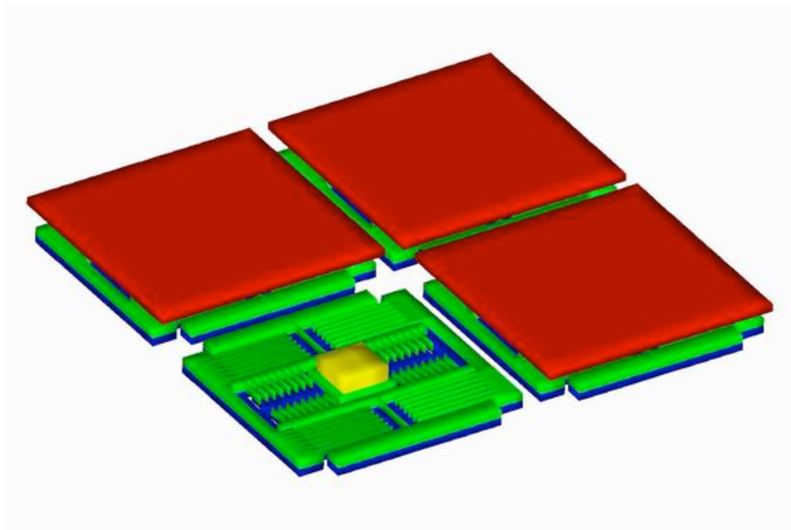
- Frequency Response of inner (left) and outer frame (right)
  - Driving voltage: (42+10sinωt)V on both axes
  - Resonant frequency: 3.5 kHz with ± 8.8° optical deflection on the inner axis and 980 Hz with ± 10.5° optical deflection on the outer axis

Tip-Tilt Mirrors (CCIT)

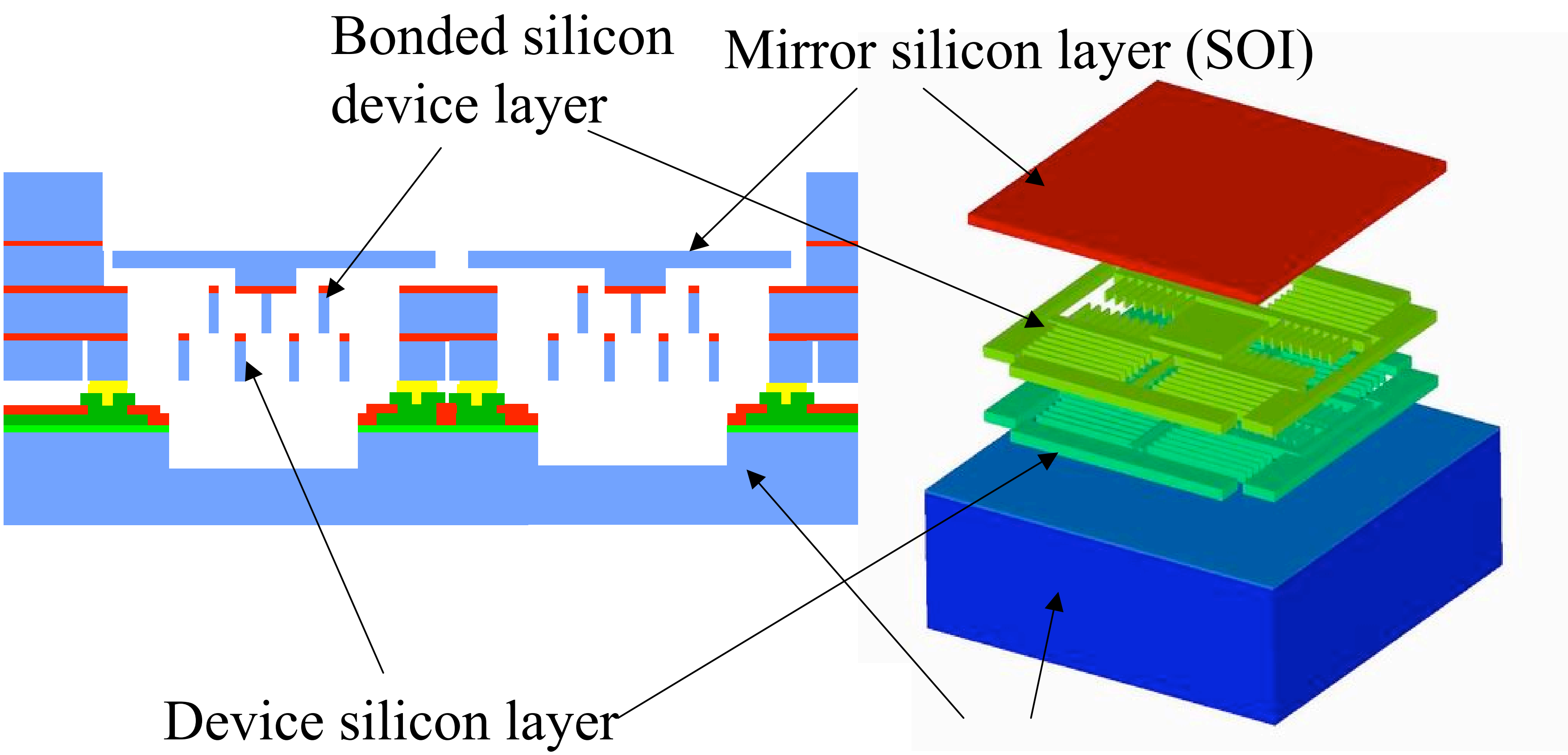
Specifications:

Pixel Size: 100 μm
Pixel Count: 1024x1024
Pixel Flatness: λ/50 @ 1.55 μm
Response Time: 10 μs / 100 μs
Fill Factor: 98%
Phase Resolution: 8 bits
Tip/tilt Angle: ±10° mechanical
Pixel Stoke: λ/2 @ 1.55 μm

For large deflections at small pixel sizes, the comb teeth gaps will need to be small (~1.0μm) for high density and large forces!



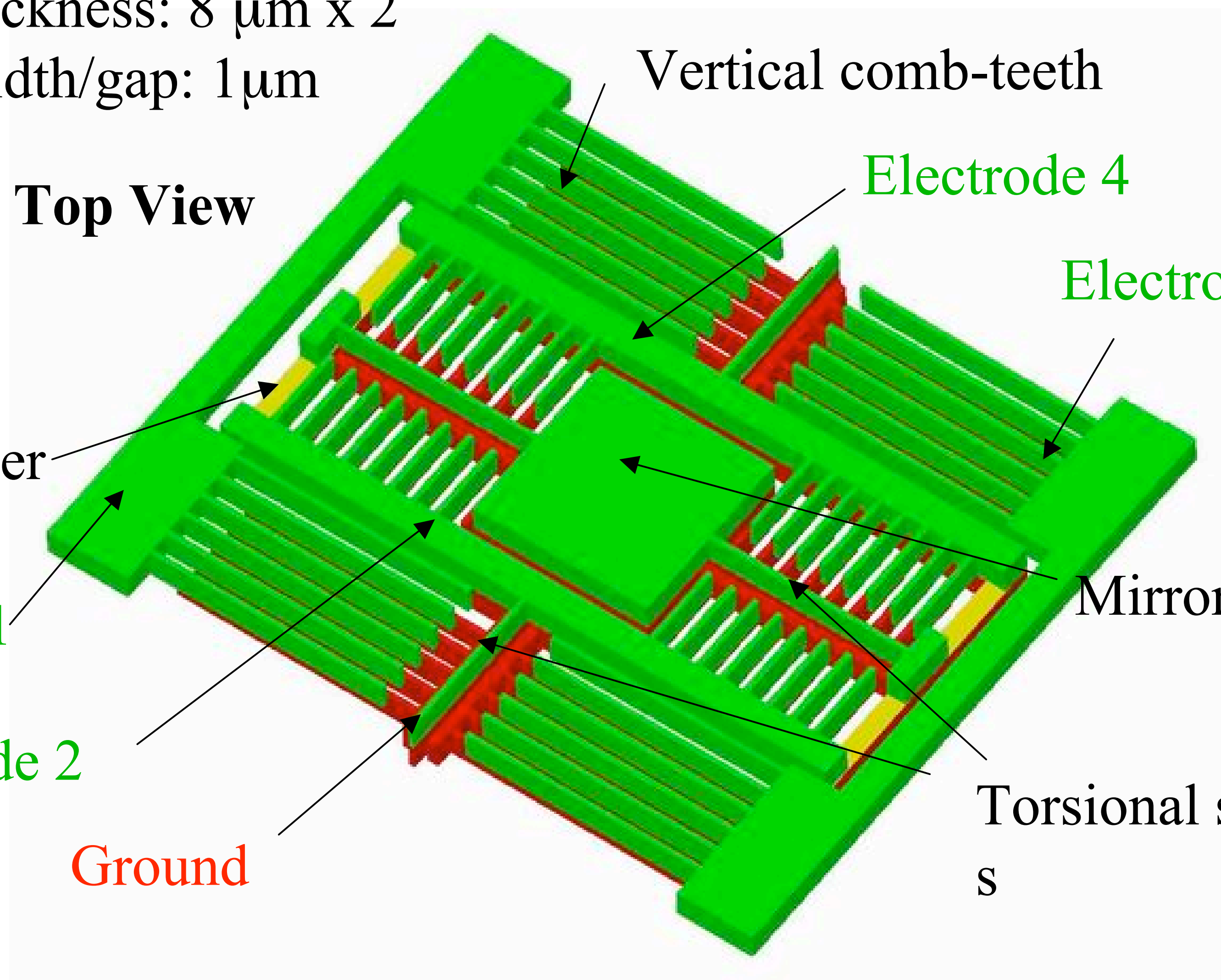
Tip-Tilt-Piston Mirror Structure



*Buried oxide layers not indicated

Actuator Design

Device Size: 100 μm
Layer thickness: 8 μm x 2
Comb width/gap: 1μm



Summary of Device Simulation

	Design Goals	Designed Device Simulation Results
Pixel Size	100 μm	100 μm
Pixel Flatness	λ/50 @ 1.55 μm	λ/50 achieved using SOI mirror
Response Time	10 μs (piston) 100 μs (tip/tilt)	< 10 μs (piston) < 100 μs (tip/tilt)
Fill Factor	98 %	94 %
Pixel Stroke	λ/2 @ 1.55 μm	>λ/2 @ 1.55 μm
Tip/tilt Angle	±10° mechanical	±10° mechanical

- Mirror flatness achieved with an SOI mirror process
- Tip & tilt angles of ±10° mechanical simulated
- Pixel stroke & response time satisfy requirements
- Actuation voltages below 200V
- Fill-factor of 94 %

1st Generation Objectives

- Conservative Design
  - First generation design has 3.0um actuator gaps.
  - Spring thickness > width. Implemented to reduce mask/etch steps required.
- Objectives for first generation design
  - Focus on process development
  - Get working devices to characterize both t he process and the device design
  - Avoid tight alignment of coarse bottom co mbs to upper vertical combs in vertical co mbdrive self-alignment: ±0.5um for 1.0um comb gaps
- Process Development
  - Multi-layer wafer bonding of patterned sili con

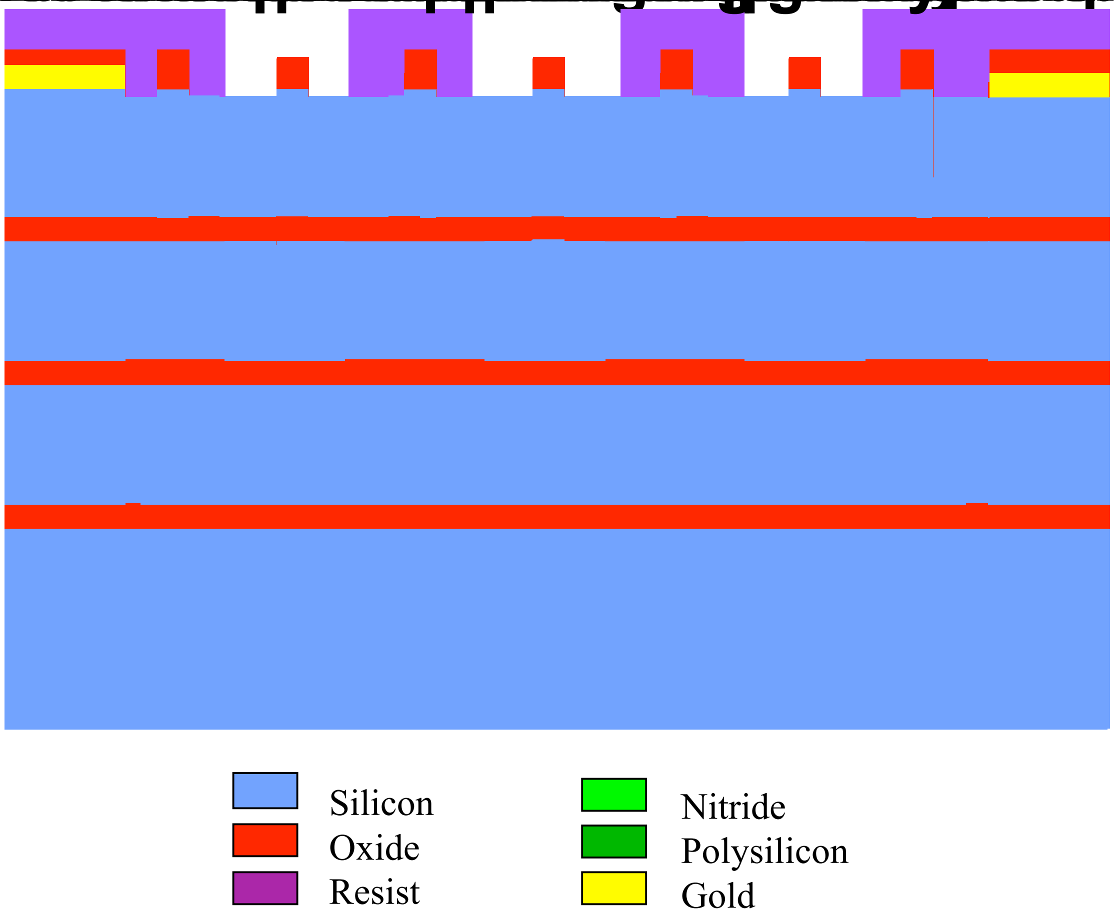
Actual Device Specifications

- Pixel Size: 360 um
- Pixel Count: 3x3 Array
- Pixel Flatness: λ/50 @ 1.55 um
- Comb Width/Gap: 3 um
- Response Time: ~20 us/~100 us*
- Fill Factor: 99%
- Tip/tilt Angle: ±1°,±2° mechanical @200V*
- Pixel Stoke: λ/3 @ 1.55 mm*

*simulated values

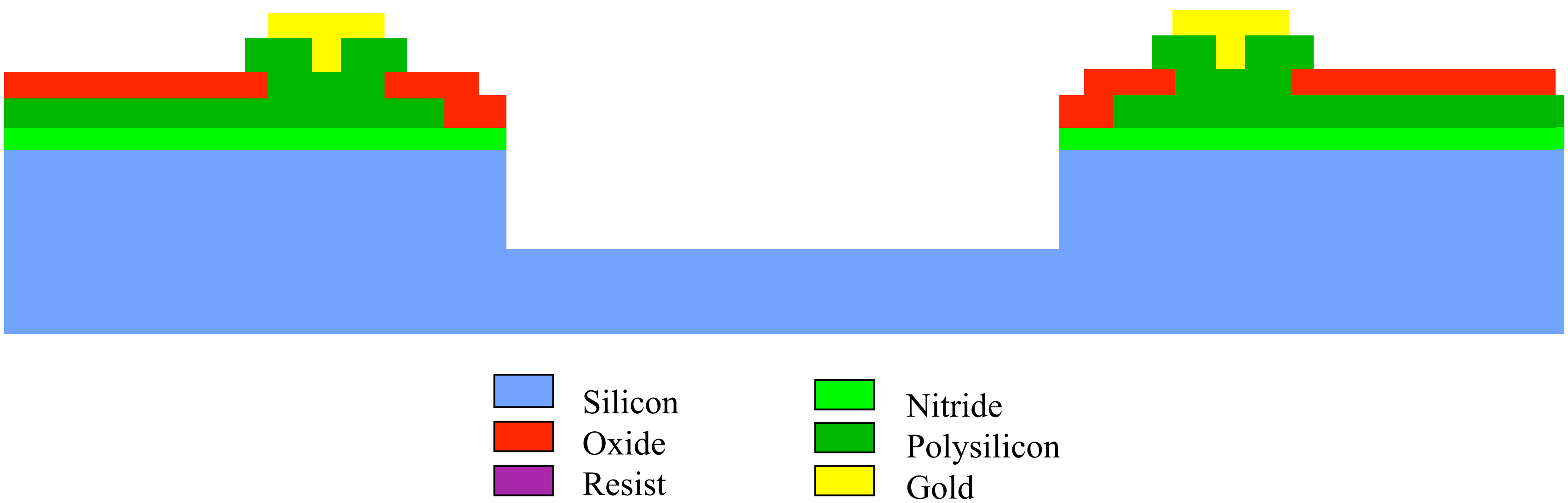
Fabrication Process – Mirror and Actuator Chip

[illegible]

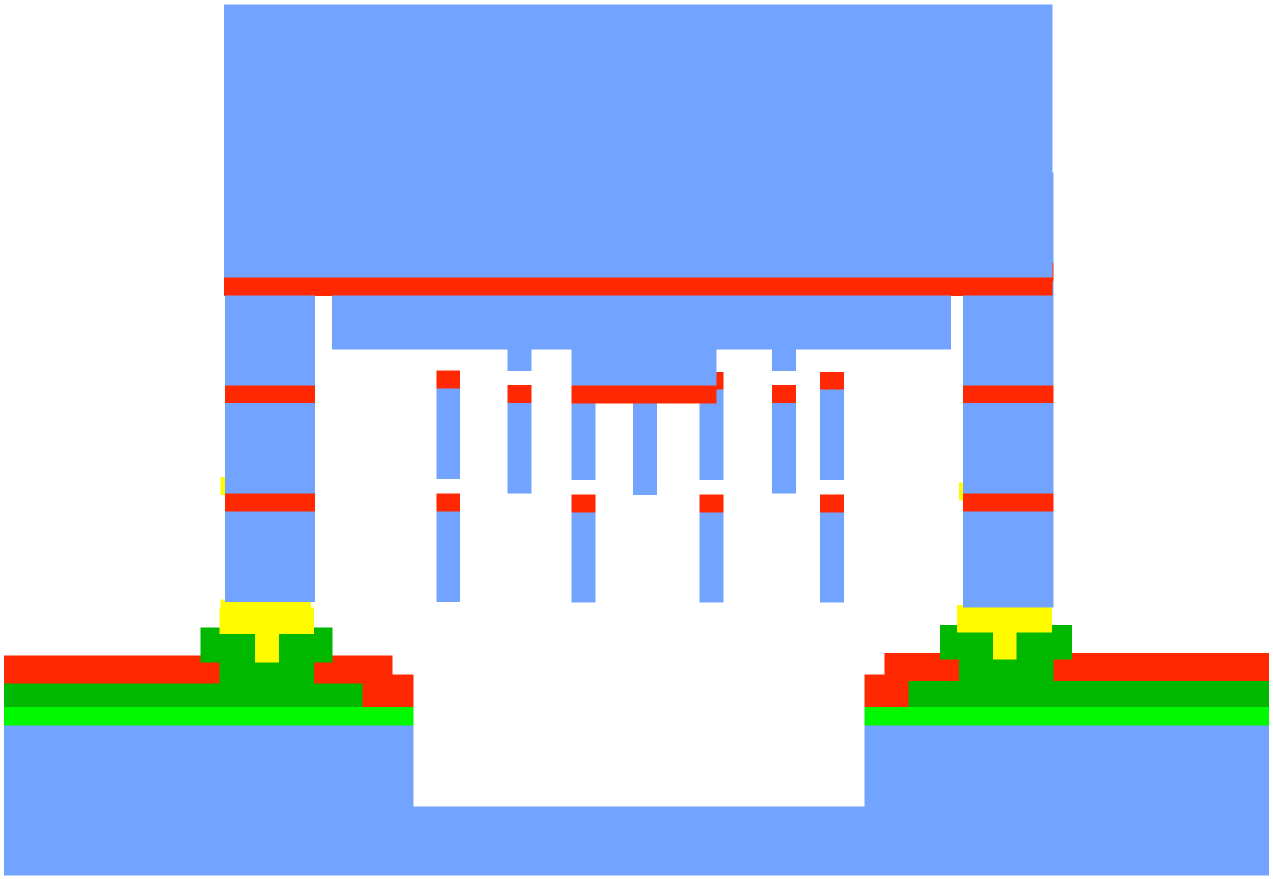


Fabrication Process – Wiring/Interconnect Chip

Etch oxide … Deposit … and pattern poly … pattern gold

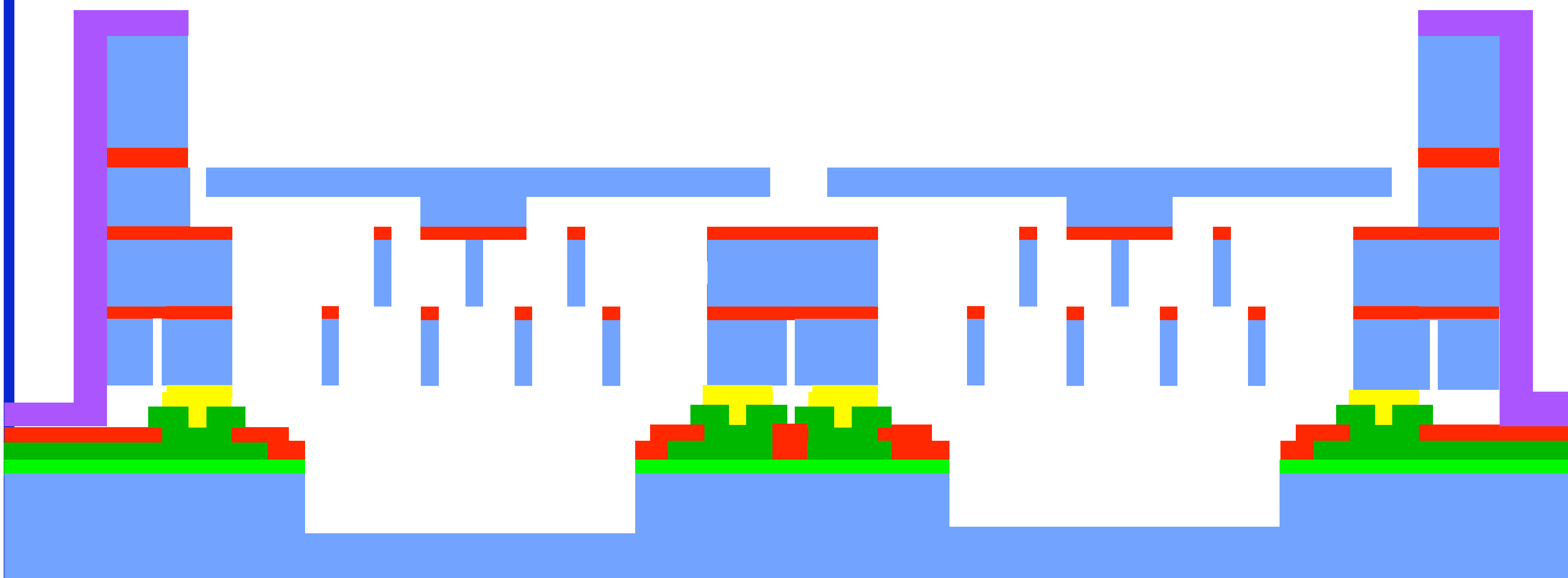


Fabrication Process – Flip-chip Bonding



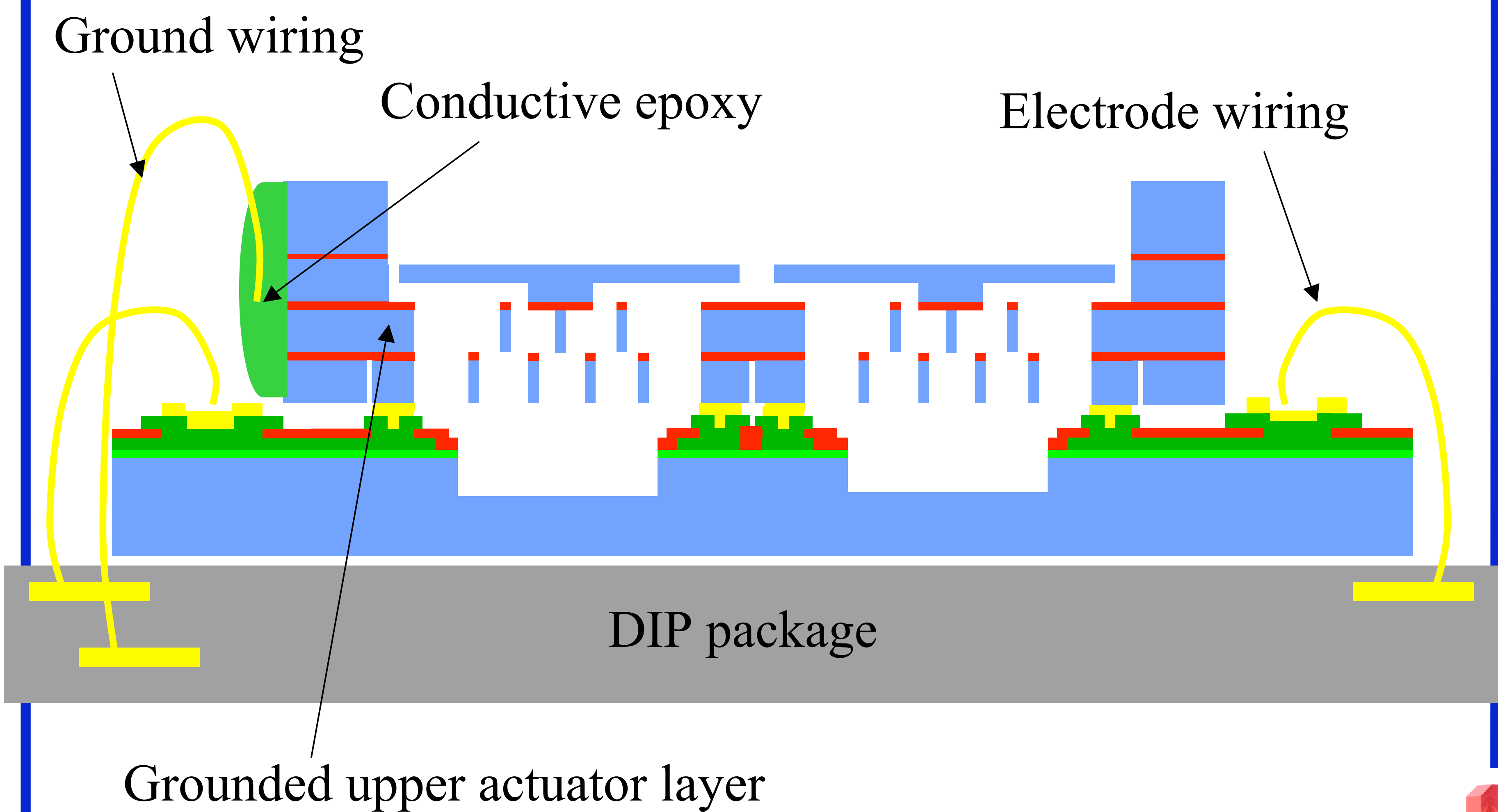
Fabrication Process – Substrate Release

Mask with kapton tape and DRIE silicon substrate



Release using dry etch steps – no need for CPD (critical point drying)

Wire Bonding



Fabricated Device Dimensions

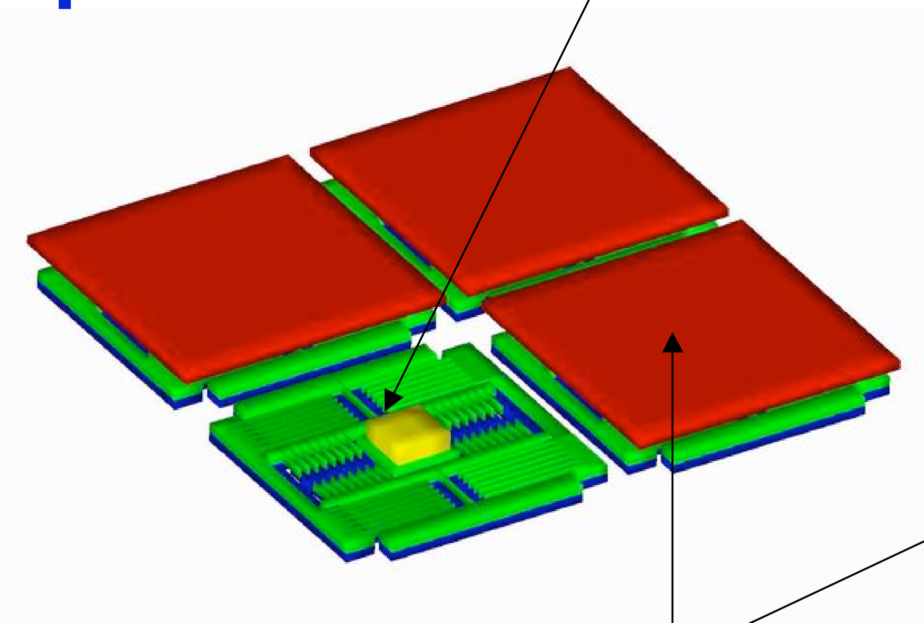
Simulated and fabricated device dimensions

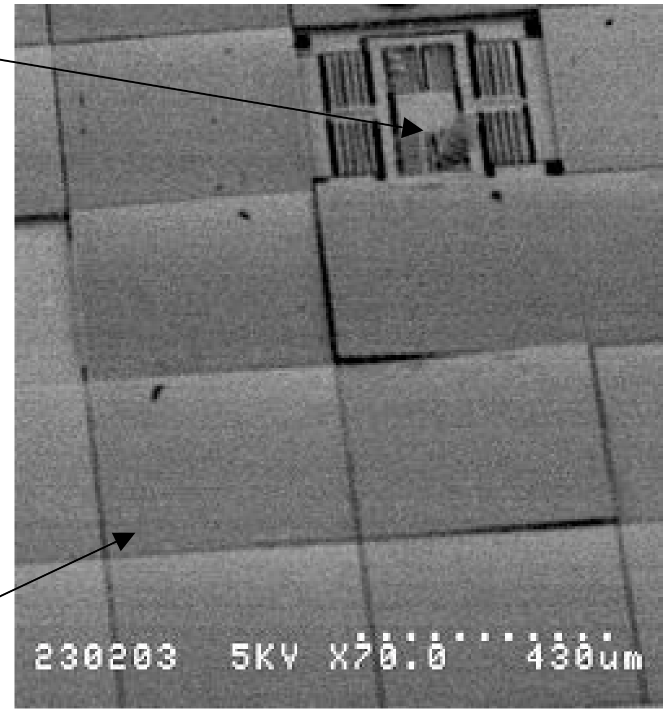
	Simulated device	Fabricated device*
Pixel Size	360μm	360μm
Layer Thickness Top	10.0μm	~12.0μm
Layer Thickness Bottom	10.0μm	~8.0μm
Spring Thickness	10.0μm (inner axis) 20.0μm (outer axis)	12.0μm (inner axis) 20.0μm (outer axis)
Combteeth/Spring Width	3.0μm	3.0μm (top), ~2.5μm (bottom)
Combteeth Gaps	3.0μm	~3.25μm

*SEM analysis

Fabricated Mirror Array

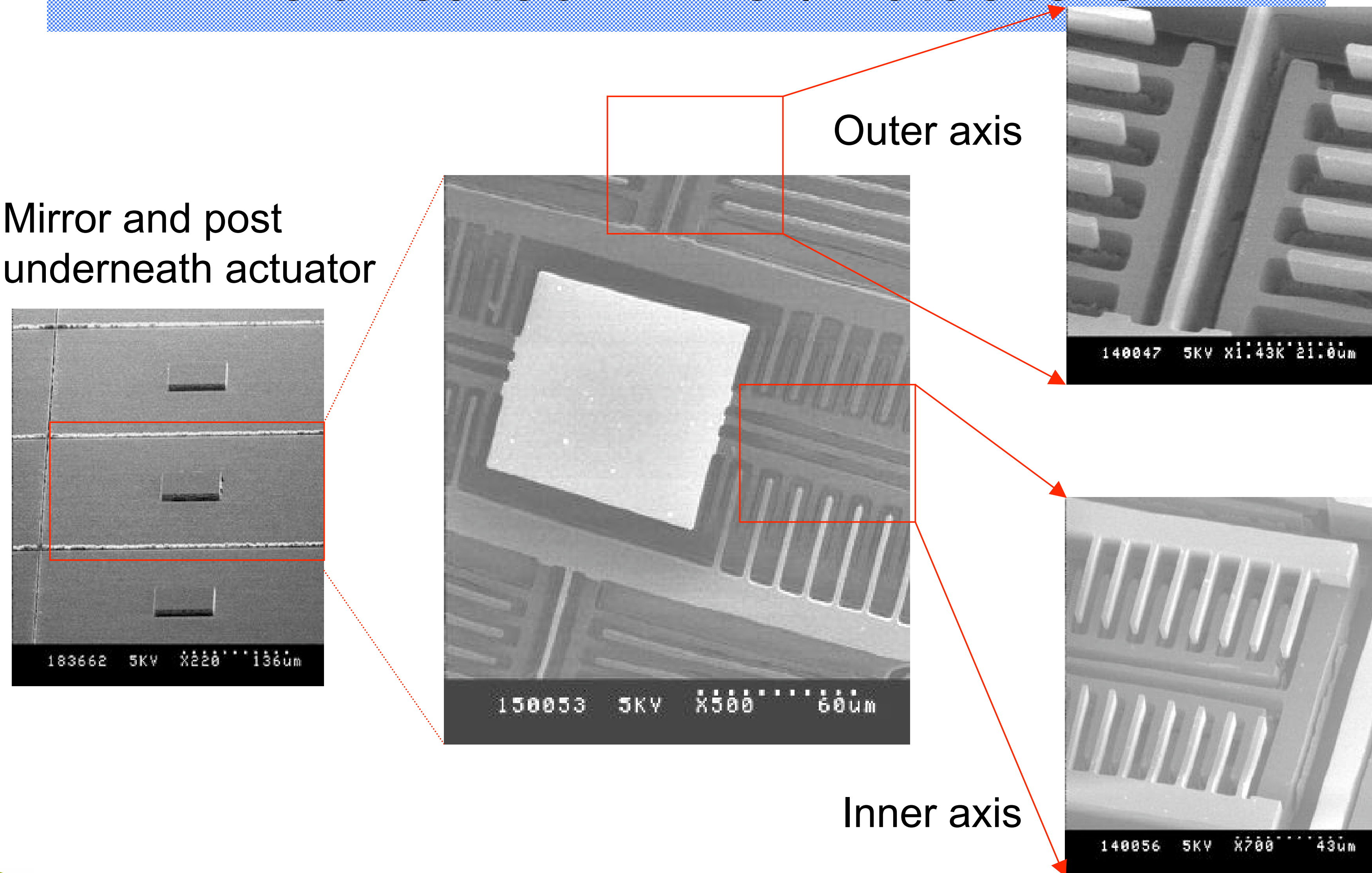
Pixel with mirror removed



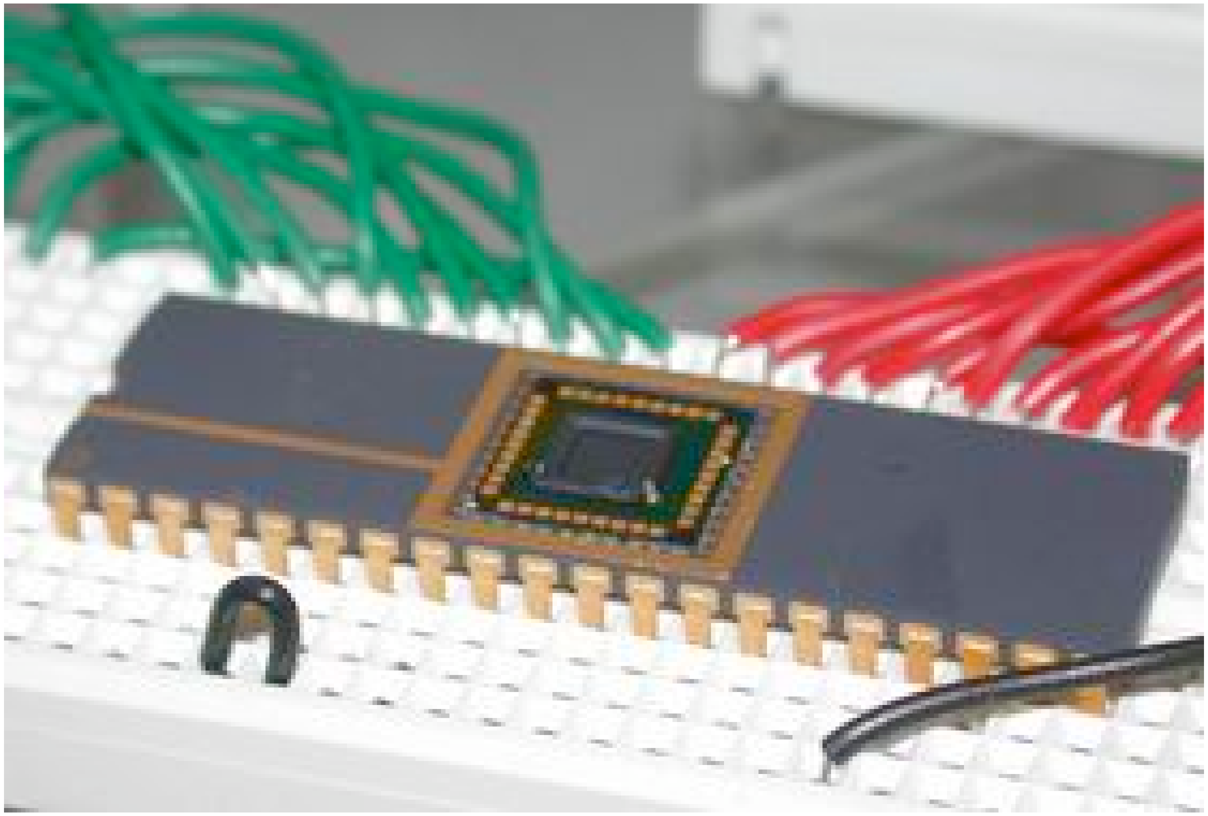


Pixel with mirror

Fabricated Mirror/Actuators



First Generation Mirror Array



Chip wire-bonded to DIP package for testing

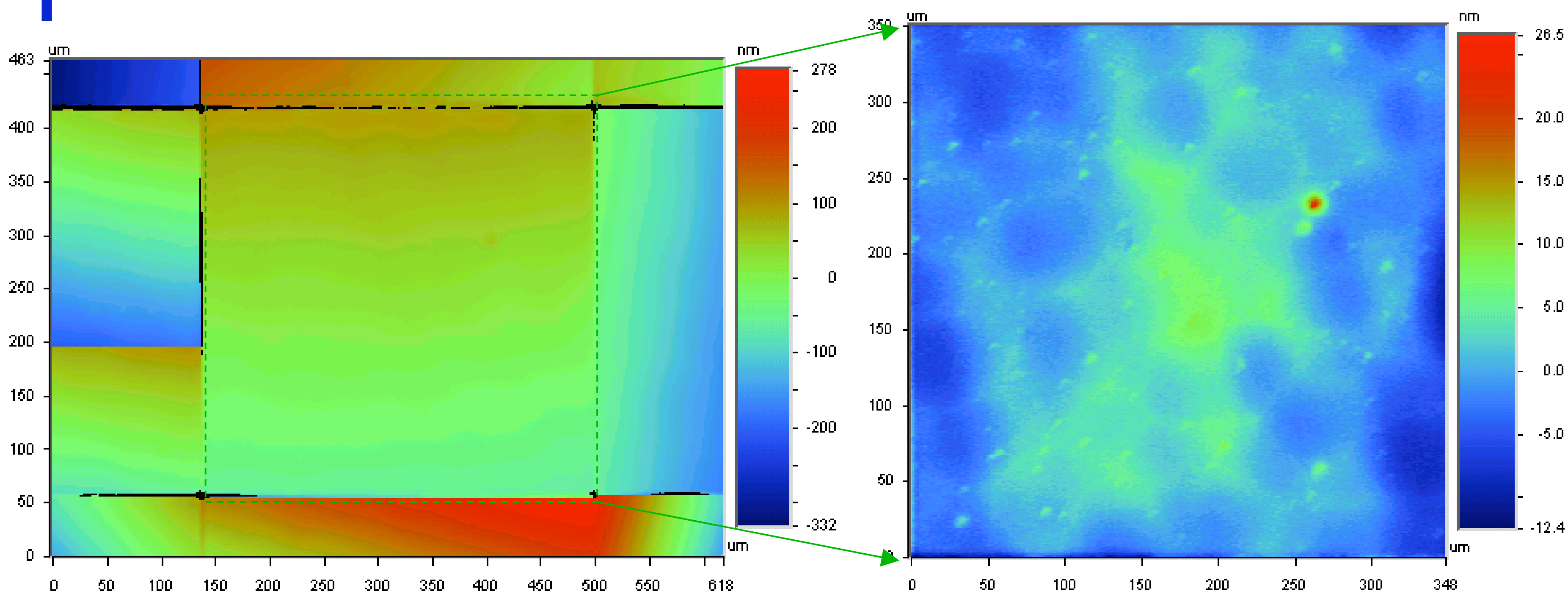
Mirror Surface Profile

Pixel Size: 360μm

Pixel Curvature: 2.0m

RMS Surface Roughness: 3.15nm

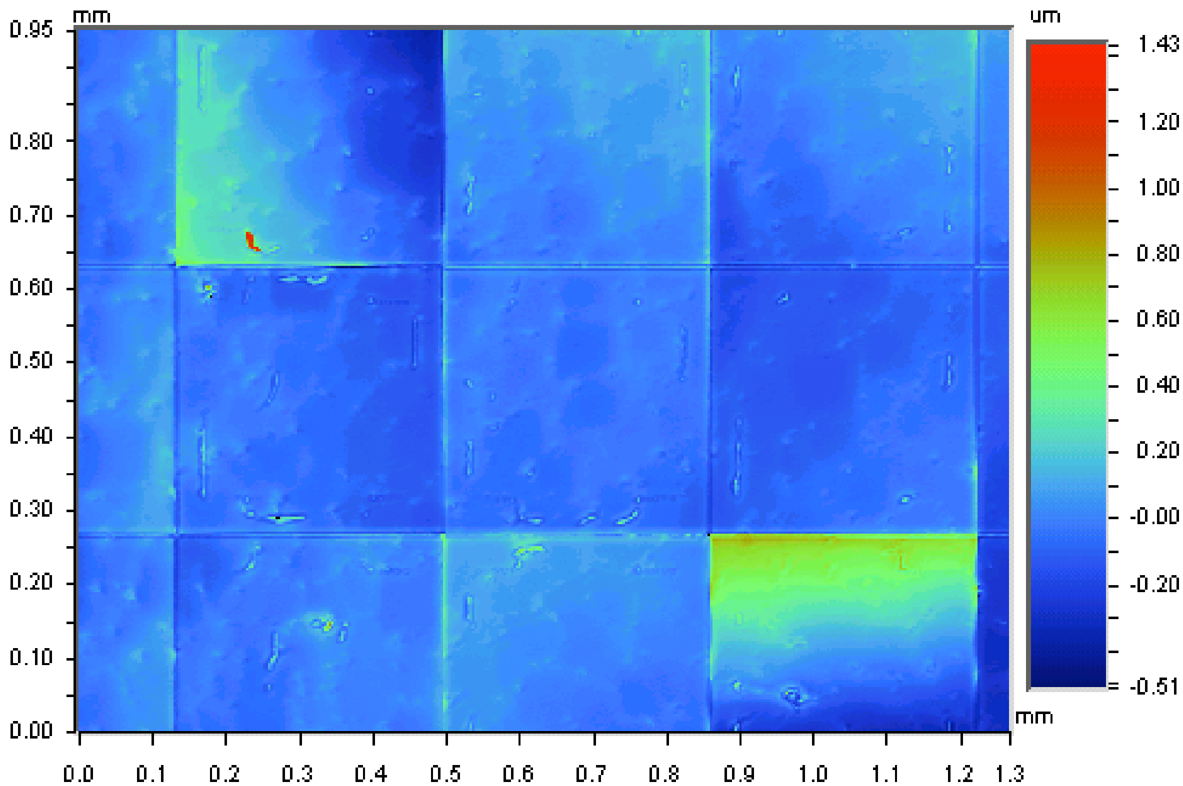
<< λ/50@1.55nm



Measurements done on Wyko® profiler

Array Surface Profile

Minimal initial tilt of unbiased mirrors after release



*surface quality poor for this array due to processing error

Measurement Results

	Simulations	Measurement
Pixel Size	360μm	360μm
Pixel Flatness	λ/50 @ 1.55μm	3nm (« λ/50 @ 1.55μm)
Natural Frequency Tip-til t	10.4kHz (inner axis) 13.6kHz (outer axis)	10.0kHz (inner axis) 12.5kHz (outer axis)
Natural Frequency Piston	54kHz	>54kHz
Fill Factor	99%	99%
Pixel Stroke	λ/3 @ 1.55mm	λ/16 @ 1.55mm
Tip-tilt Angle	±1° inner axis ±2° outer axis	±0.1° inner axis ±1.7° outer axis
Max. Operation voltage	200V	140V

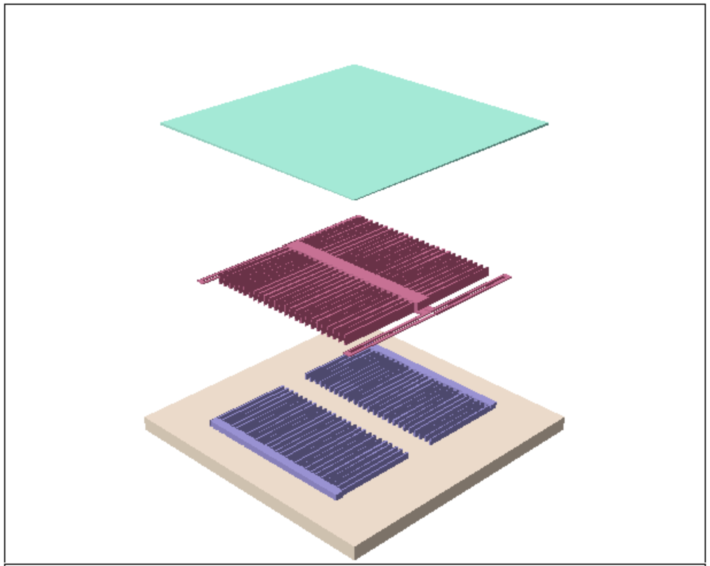
Large-Stroke Deformable Mirror Arrays

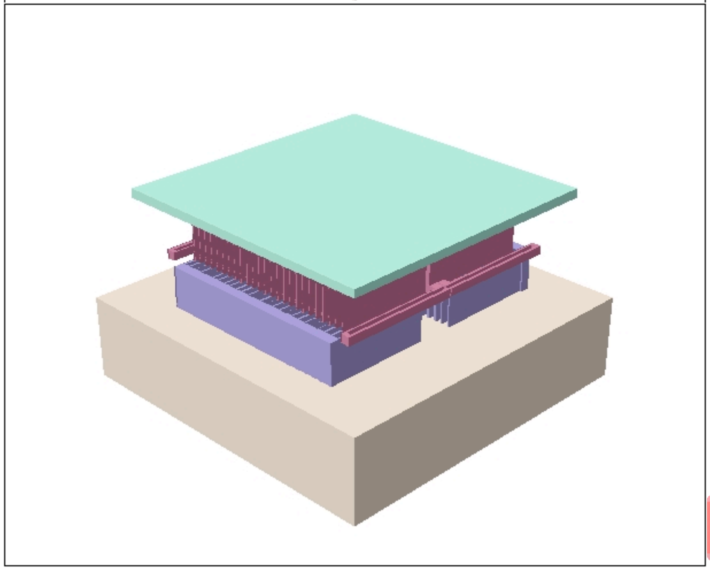
DESIGN OBJECTIVES:

- 20 μm of vertical displacement with 100V applied to the underlying electrodes
- Resonance frequency >1kHz
- High fill factor (>98%)
- RMS surface error of <30nm

METHOD EMPLOYED:

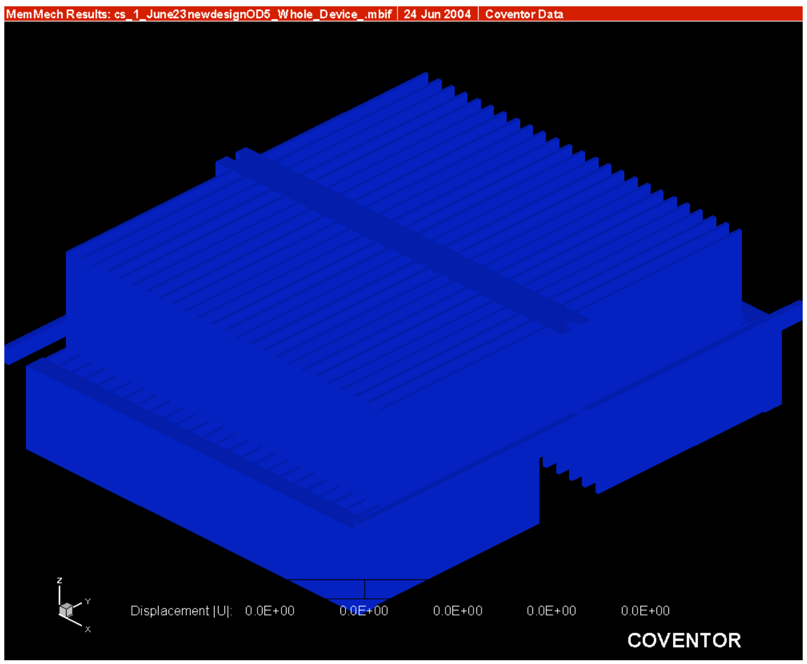
- Use a self-aligned vertical comb drive structure and appropriate spring designs
- Spring design and optimizing layer thicknesses
- Mirror/Pixel size and spacings
- Using single-crystalline silicon as our mirror layer

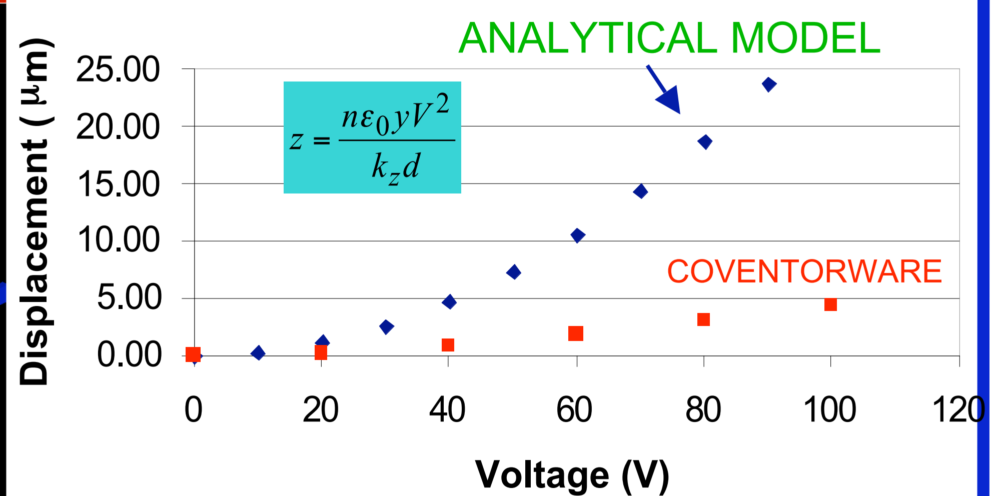




Simulation Results

Coventor modal analysis of Mirror: Mode 1: 4.78 kHz





Where z = displacement
d = gap between combs
n = number of combs
y = comb overlap

Conclusions

- Use Combdrives for applications that require large forces (broad band AO and tip-tilt)
- Self-aligned vertical combdrives with small comb gaps of ~1.0um are necessary to achieve the high forces necessary at small device sizes of 100um
- Successful designs with large force, large displacement vertical comb drives
  - Gimbaled Biaxial Scanner
    - Large deflections and large forces demonstrated
  - Tip-Tilt 1st Generation device
    - A conservative device with 3.0um comb gaps was designed and successfully fabricated.
    - New fabrication process for high-fill factor mirror arrays with tip-tilt-piston vertical comb actuators has been verified
  - Ongoing Development of Large Displacement deformable piston mirror arrays

Device Characteristics

- Angle limitation of inner axis
  - Stiffer springs due to larger than designed spring thickness: Grinding/polishing process has a TTV(total thickness variation) of 2.0um
  - Less force due to increase in comb gaps: Bottom comb teeth may have been etched in width due to multiple etching steps, increasing gaps between upper and lower teeth
- Voltage limitation
  - Weak comb teeth: Bottom combs may have become weak in the transversal direction due to a decrease in comb thickness and width causing faster pull-in

Fabricated Wiring/Interconnect Chip

Flip-chip gold bond pads

Poly wiring lines