MEMS Spatial Light Modulator for Optical Maskless Lithography

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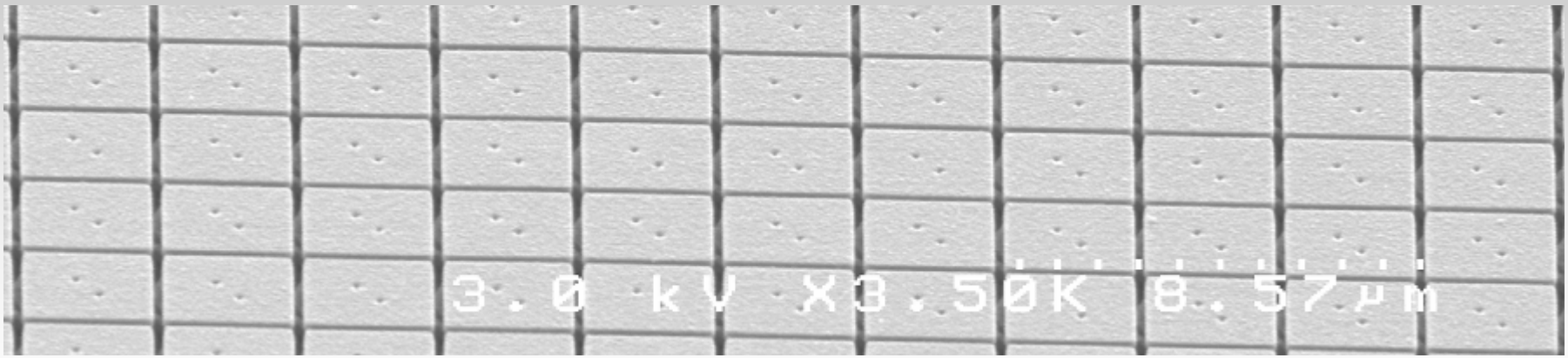

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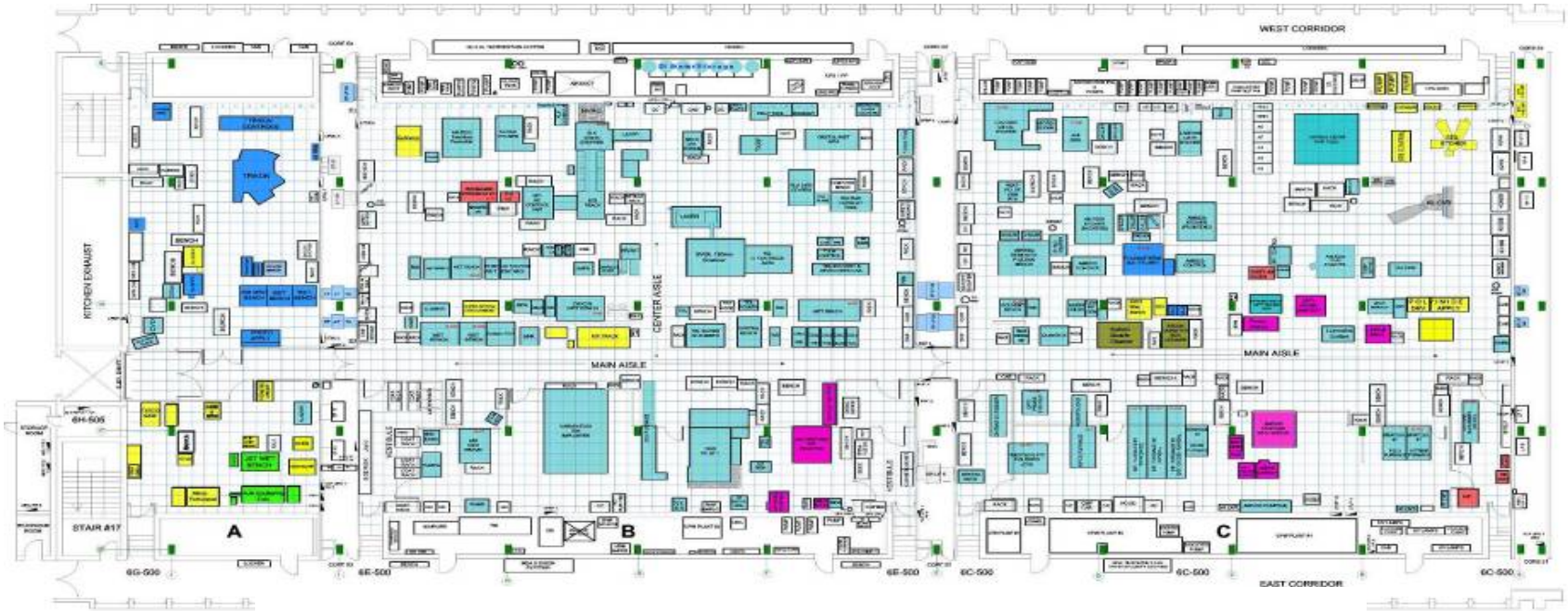

New Jersey Nanotechnology Consortium

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Dr. Joe Mangano (DARPA)

Drs. C. Hanson, D. Mullin (SPAWAR San Diego)

Introduction

MEMS Spatial Light Modulator (SLM) capable of replacing photomasks in state-of-the-art lithography applications

SLM for Maskless Lithography, enabling:
- Feature: Sub 50nm CD
- Throughput: One 300mm wafer level per hour

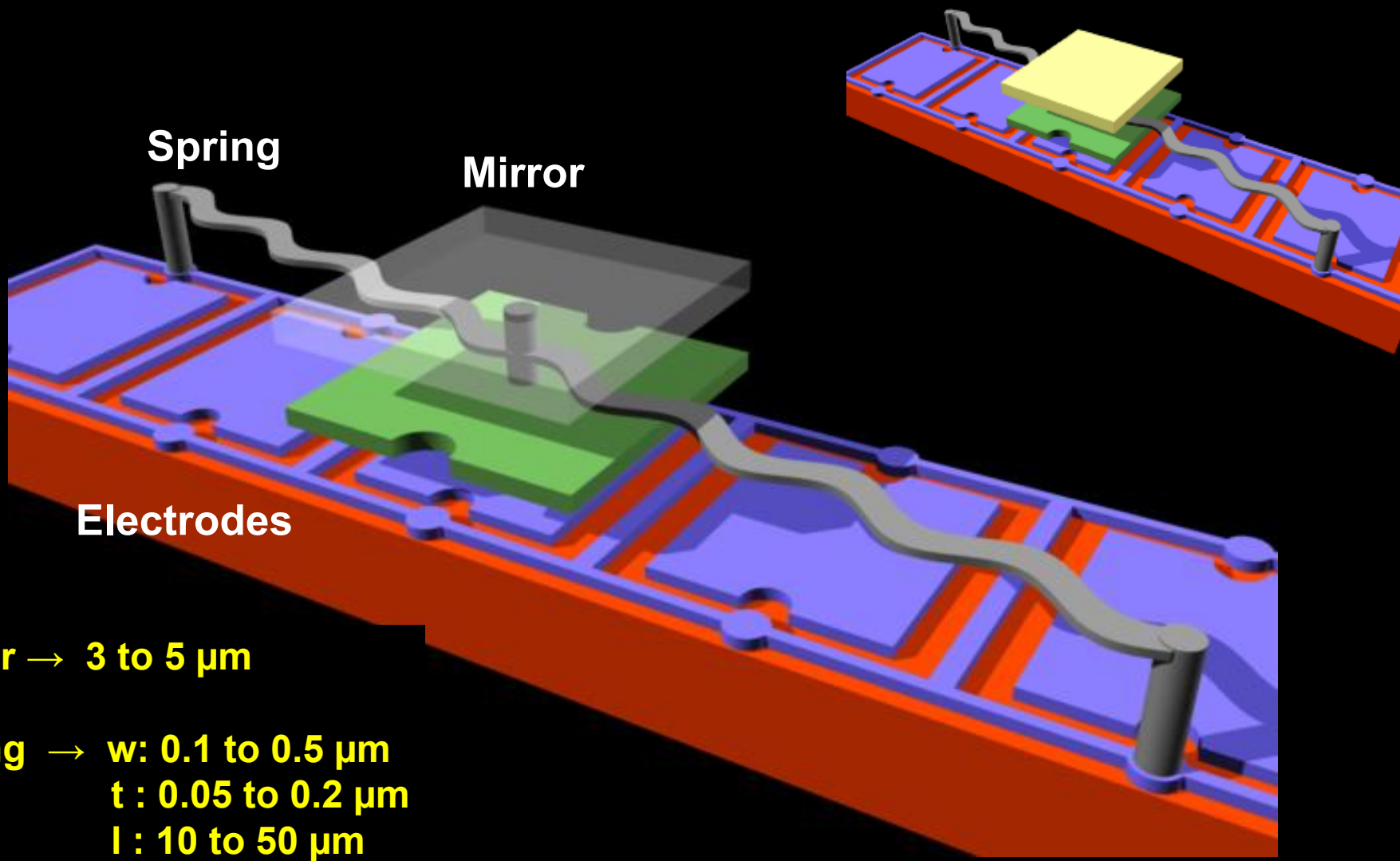
Full MEMS SLM Technical Goals:

1. Pixel count > 10M
2. Pixel size ≤ 3 μm
3. Fill factor >90%
4. Reflectivity >90%
5. Piston stroke >70 nm,
6. Frame rate 10kHz
7. Continuous motion with +/- 1nm
8. Integrated electronics

This talk: MEMS technology module

1. Pixel count 128x512, scalable to 10M
2. Pixel size 3 μm and 5 μm
3. Fill factor >90%
4. Reflectivity 90% @ 193nm
5. Piston stroke > 70 nm,
6. Response time 10μsec
7. Continuous motion with +/- 1 nm
8. External drive: 4V

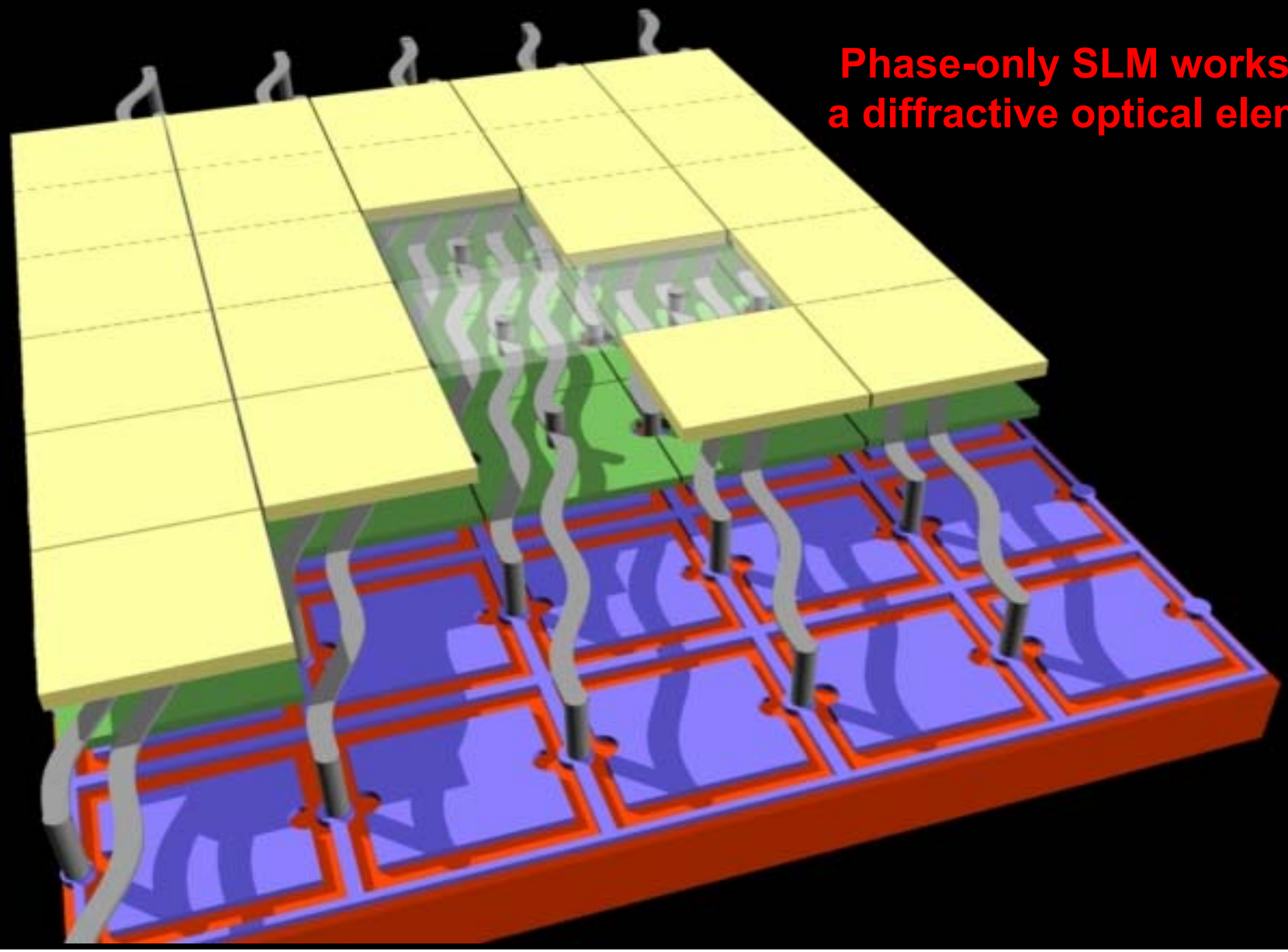
Single Mirror Schematic



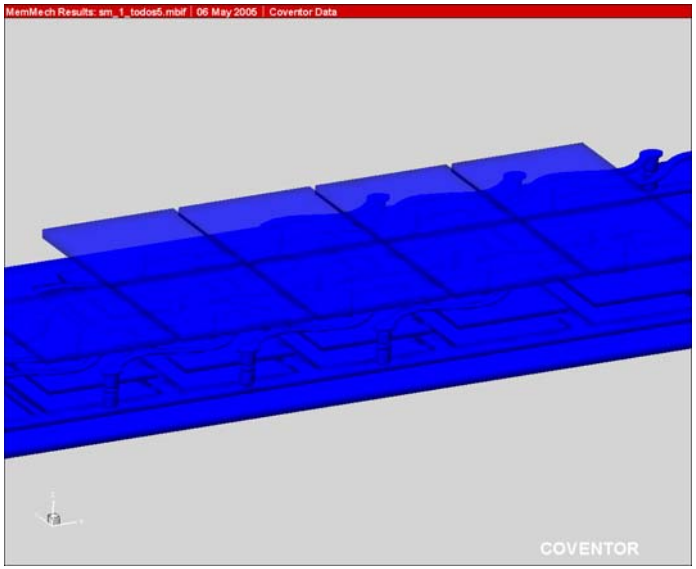
Mirror → 3 to 5 µm

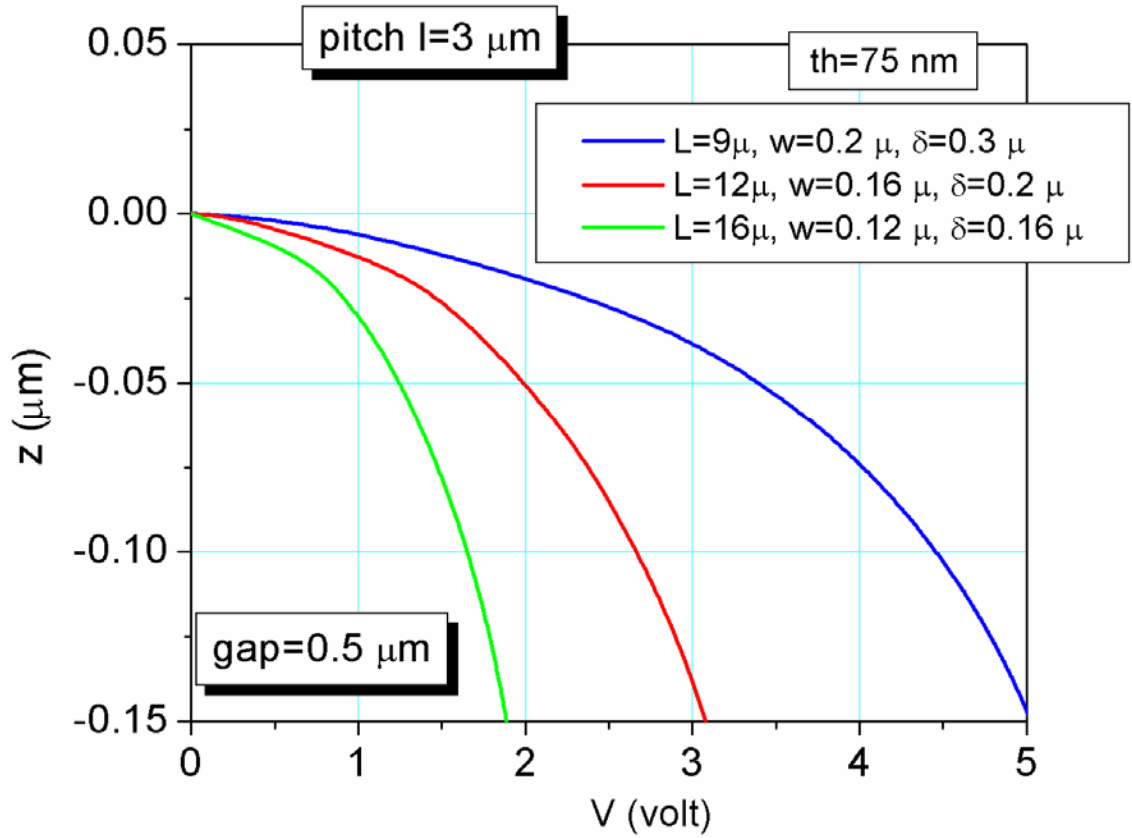
Spring → w: 0.1 to 0.5 µm
t : 0.05 to 0.2 µm
l : 10 to 50 µm

Phase-only SLM works as a diffractive optical element



Design and Performance



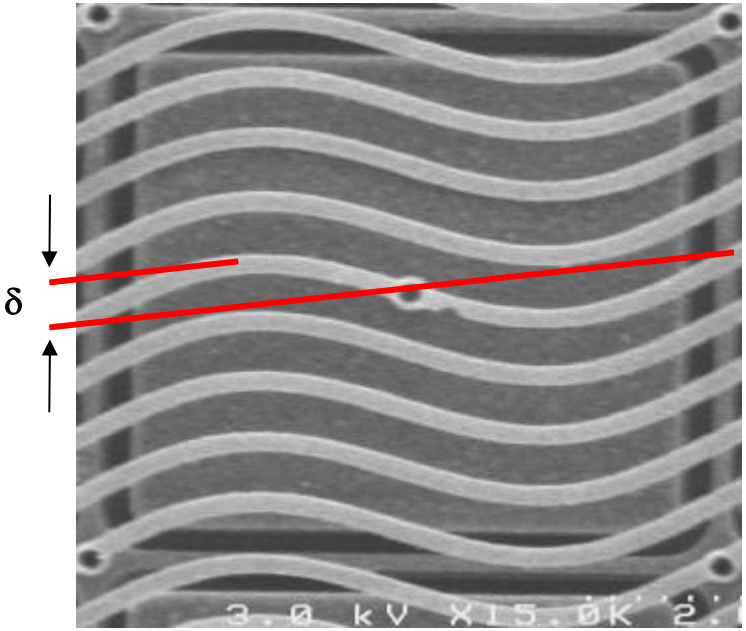


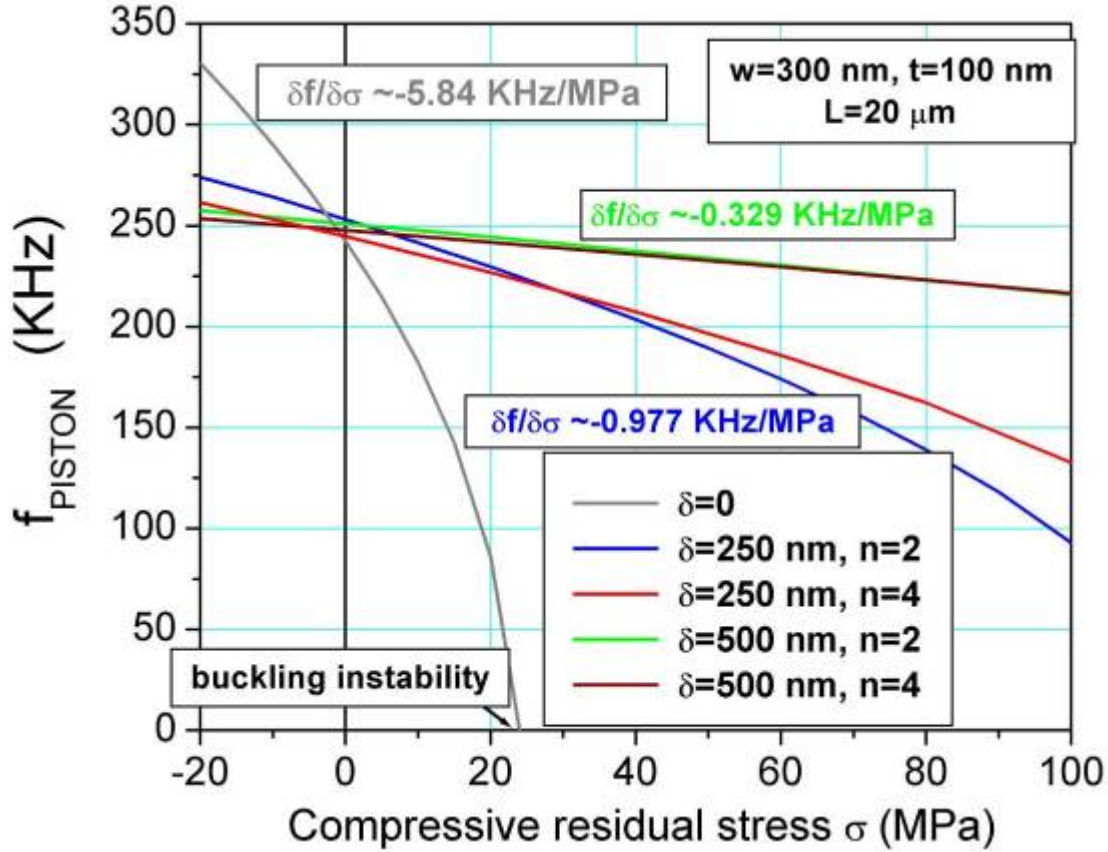
Design Issues

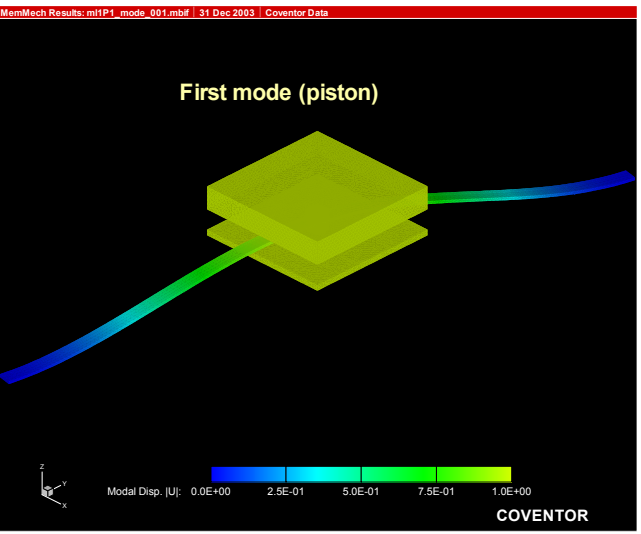
- pitch, geometry
- range
- mirror flatness
- unwanted motion, i.e. tilt
- speed
- CD required
- thickness
- residual stress
- stress gradient
- voltage

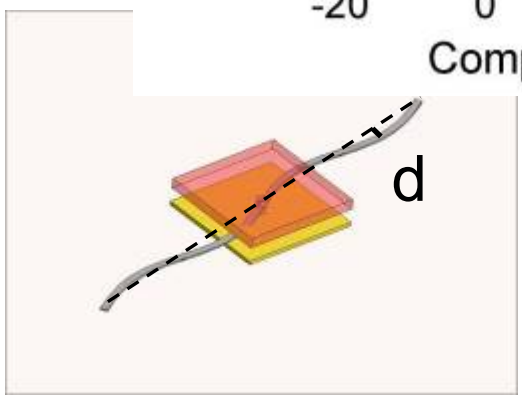
Very long and thin springs: stress???

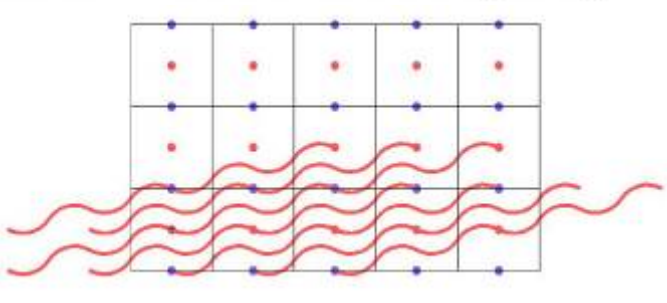
Stress-relieved Curved Springs







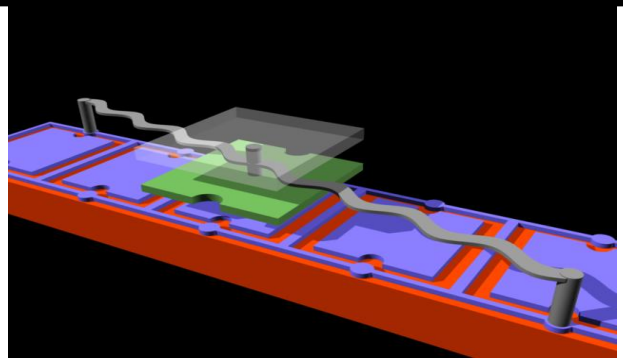




V.A. Aksvuk et.al. *Mirror Tech 2006* *aksvuk@lucent.com*

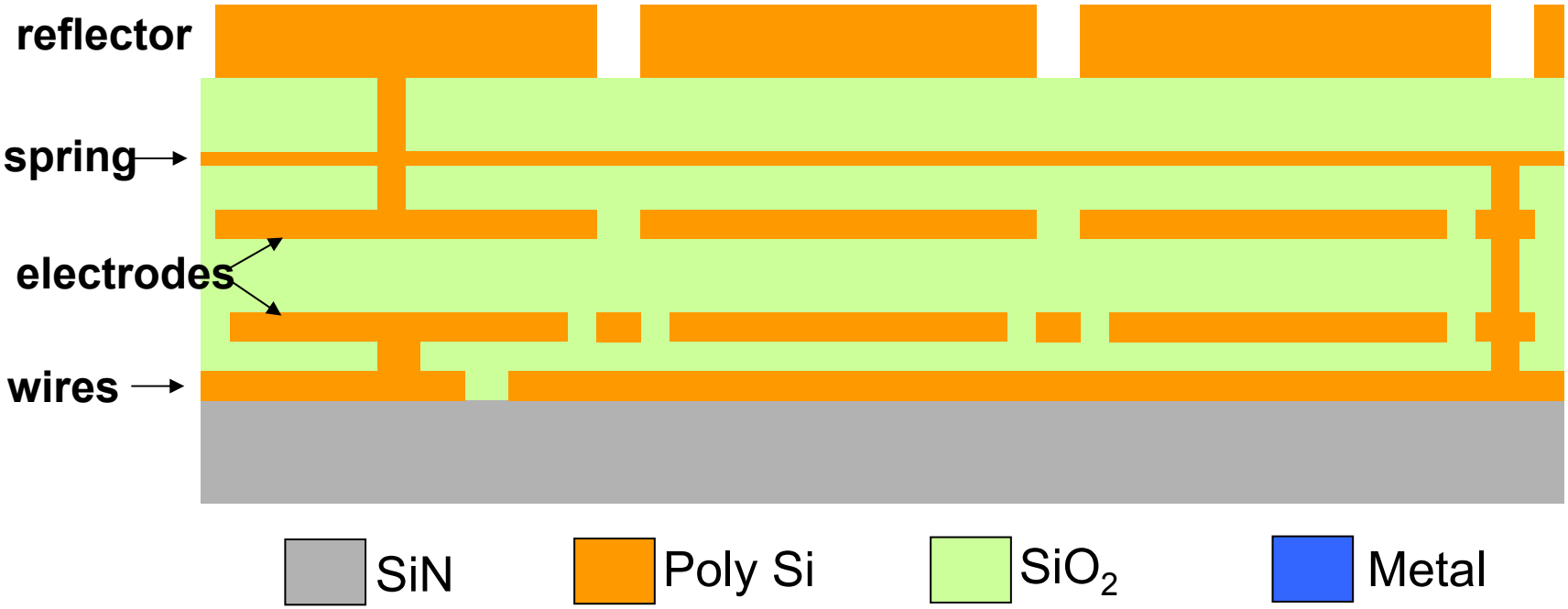
MEMS fabrication process

Poly-Si based MEMS



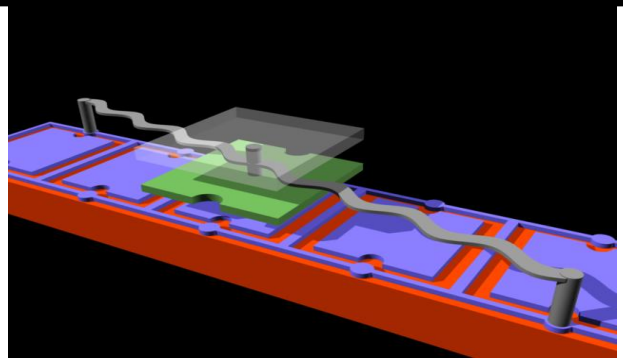
5 structural levels (poly-Si)

4 sacrificial levels (SiO_2)



MEMS fabrication process

Poly-Si based MEMS



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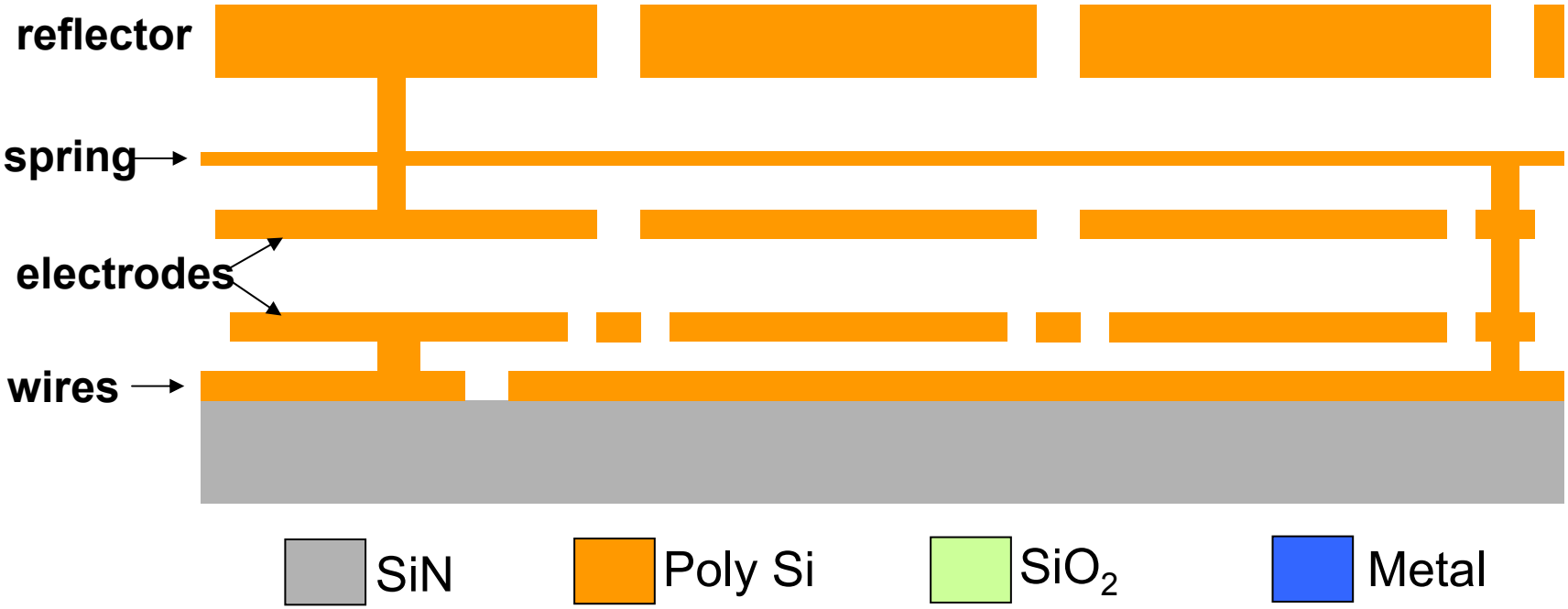
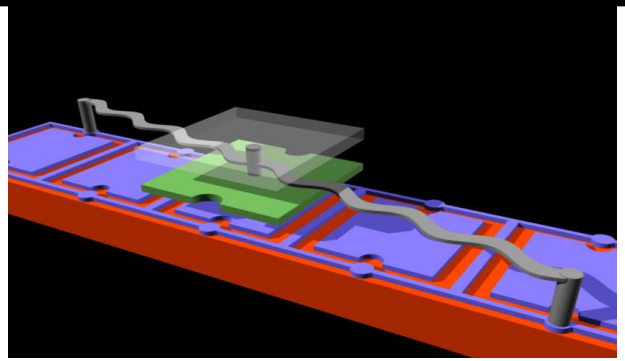
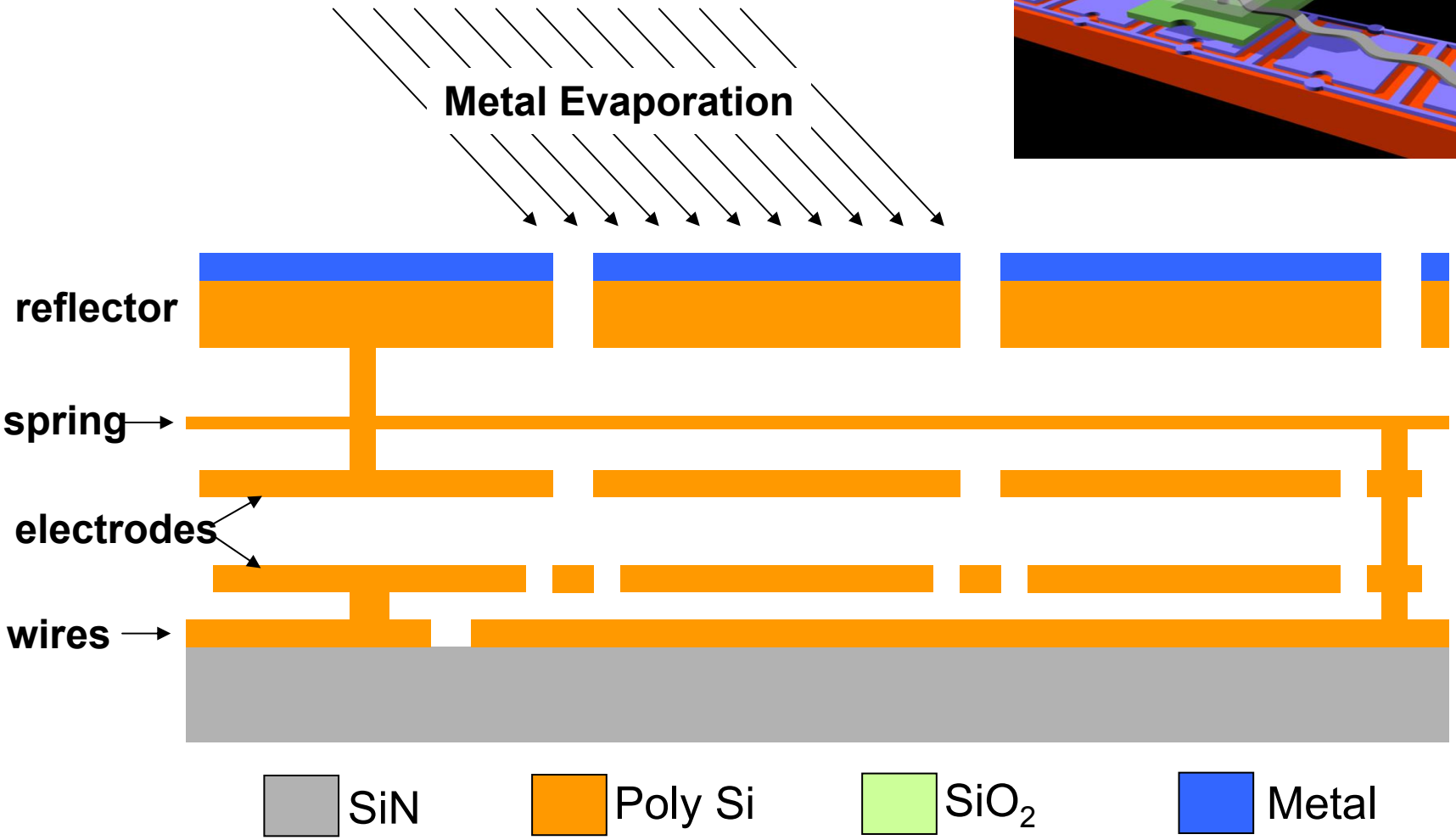


MEMS fabrication process

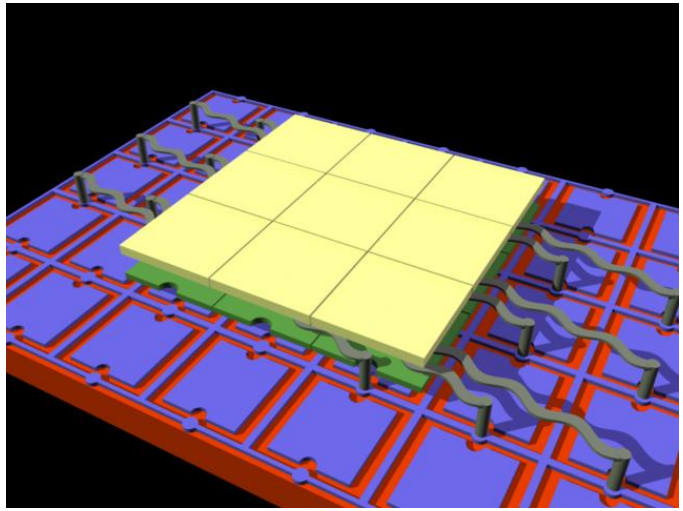
Poly-Si based MEMS





MEMS fabrication process: Lithography

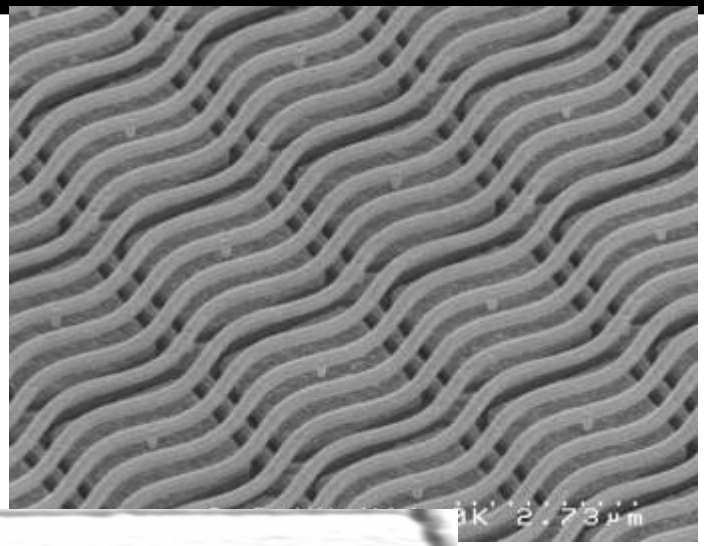
- Smallest possible mirror (3 to 5µm)
- 3 structural + 1 electrical Si levels
- Maximize mirror fill factor
- Maximize force – electrode fill
- Softest possible spring, pure piston motion
  - interleaved beams
  - maximum spring level fill
  - long wavy strain-relieved beams
  - thin spring level Si layer

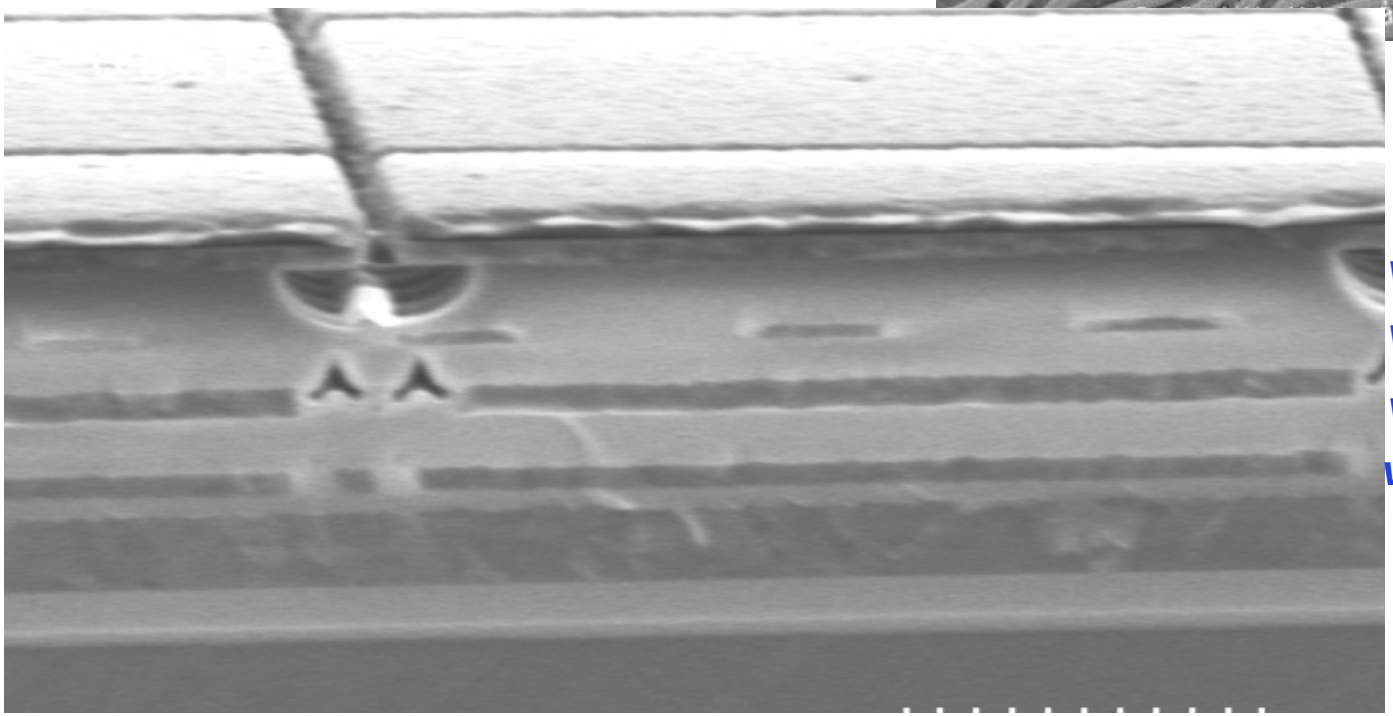


- Lithography Requirements:
  - Via levels from 150 to 220 nm
  - Spring as small as 130 nm
  - Mirror gaps as small as 150 nm
  - Level to Level alignment ~ +/- 50 nm
- Our toolset:
  - SVG (ASML) 193 nm wavelength scanner
  - Alignment measured with BioRad Q7
  - CD measurements with KLA 8100
- CMP required for some levels

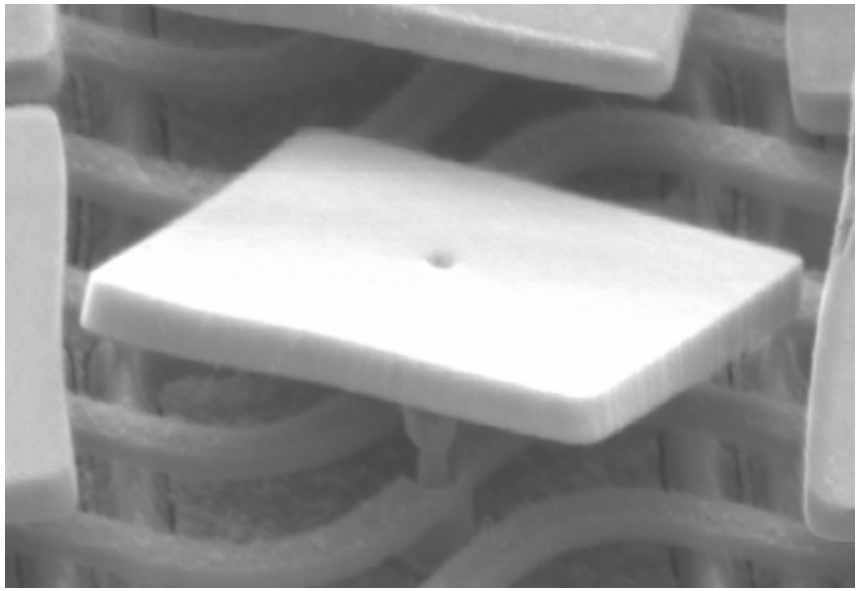
MEMS Crossection

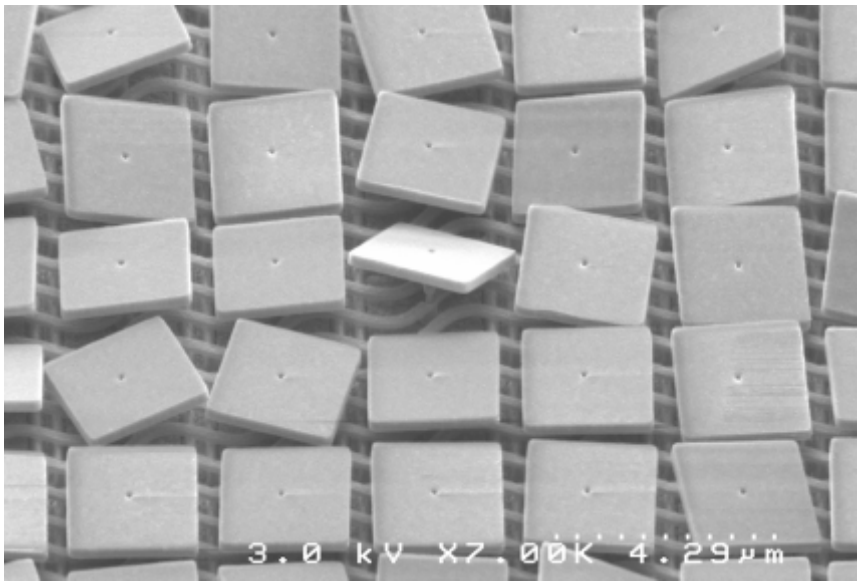
We have fabricated full MEMS micro-mirror arrays:
11 layers process with 130nm critical features and alignment tolerances 30 nm.

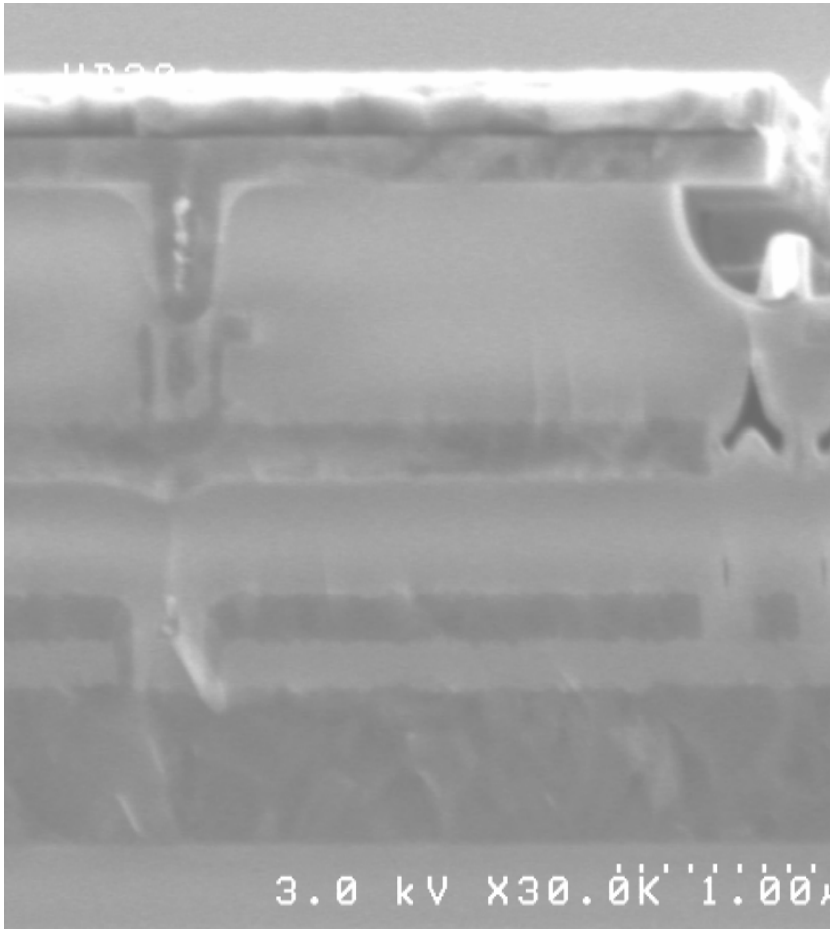




Fabrication issue: Detached mirrors

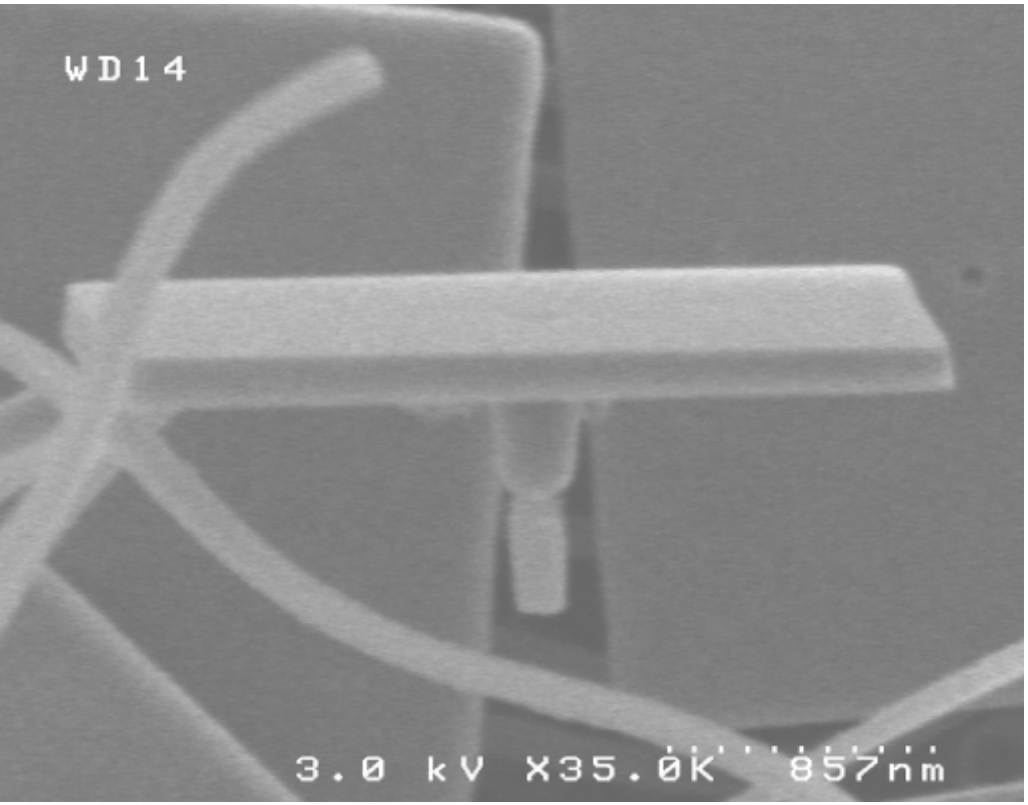


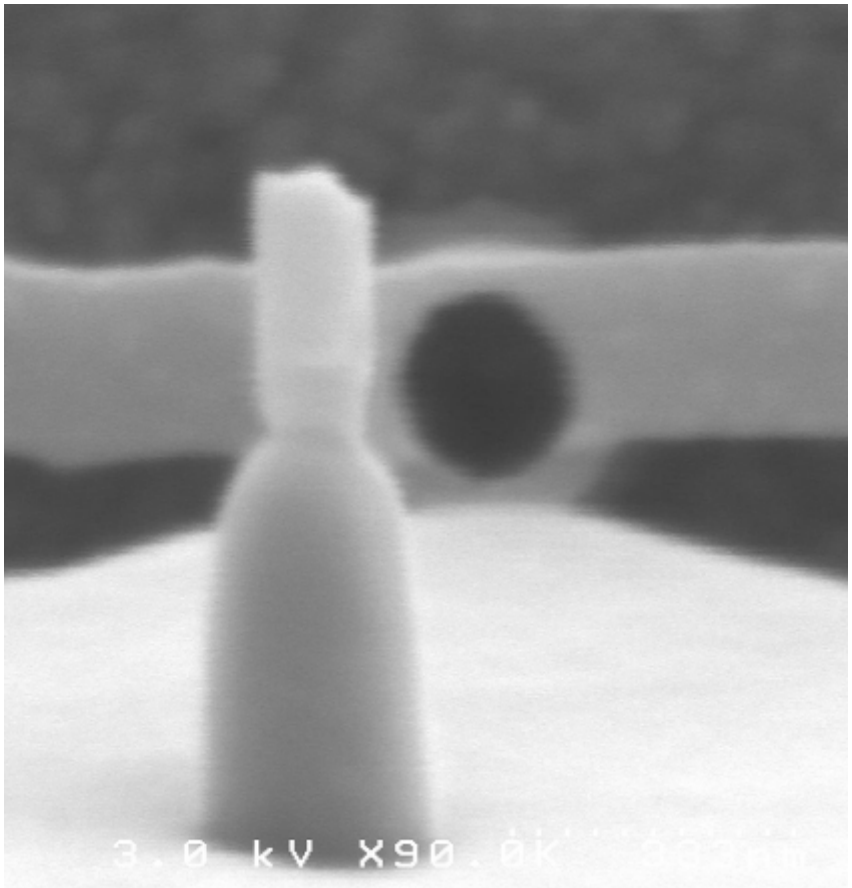




Vias MIRROR – SPRING

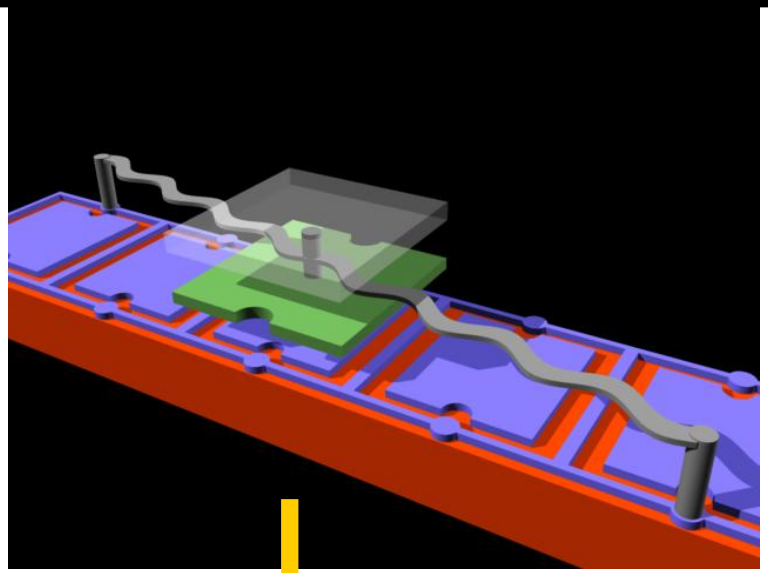
Stacked via issue

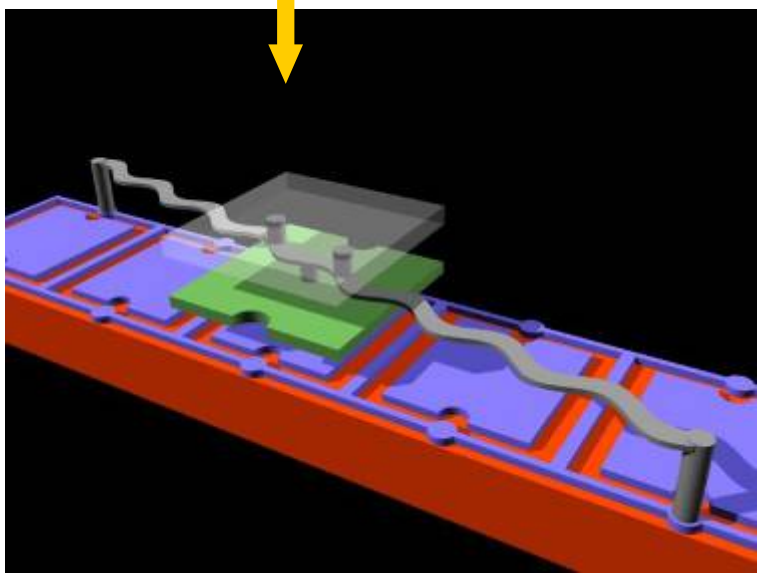


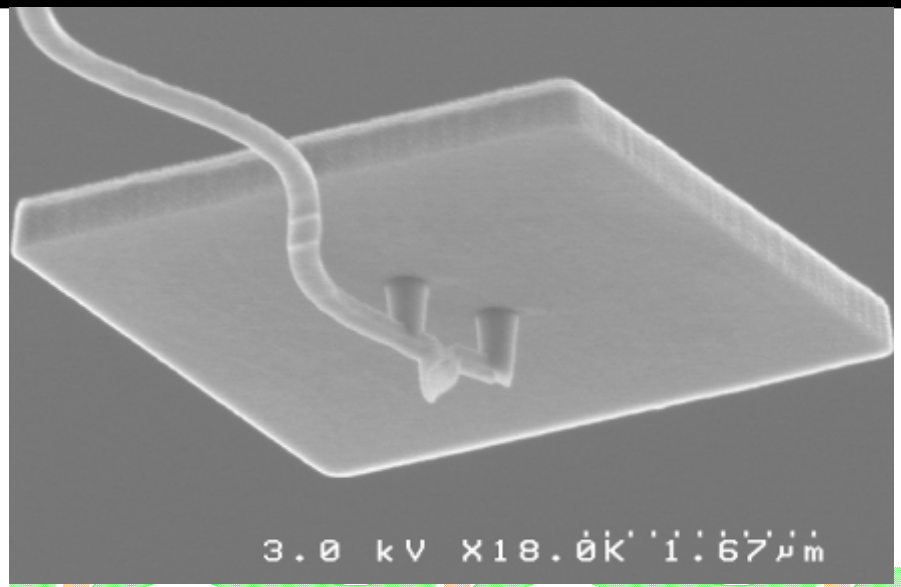


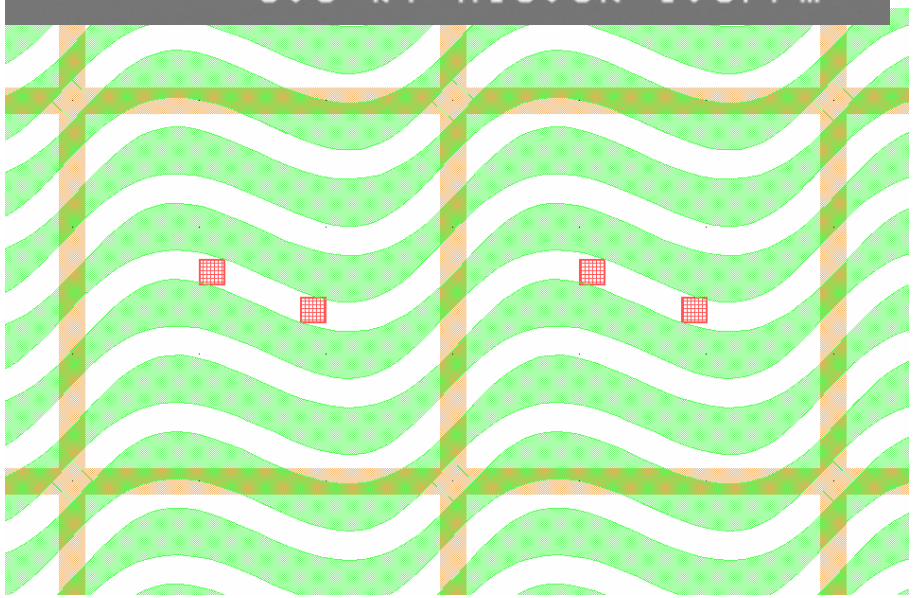
Vias MIRROR – SPRING

New Double Via for Mirror

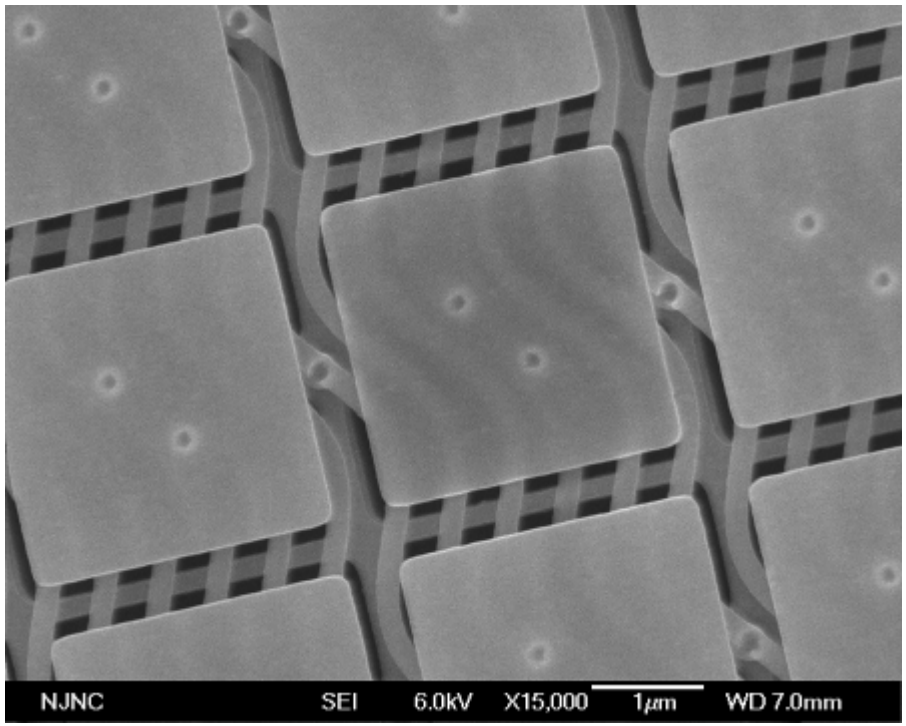


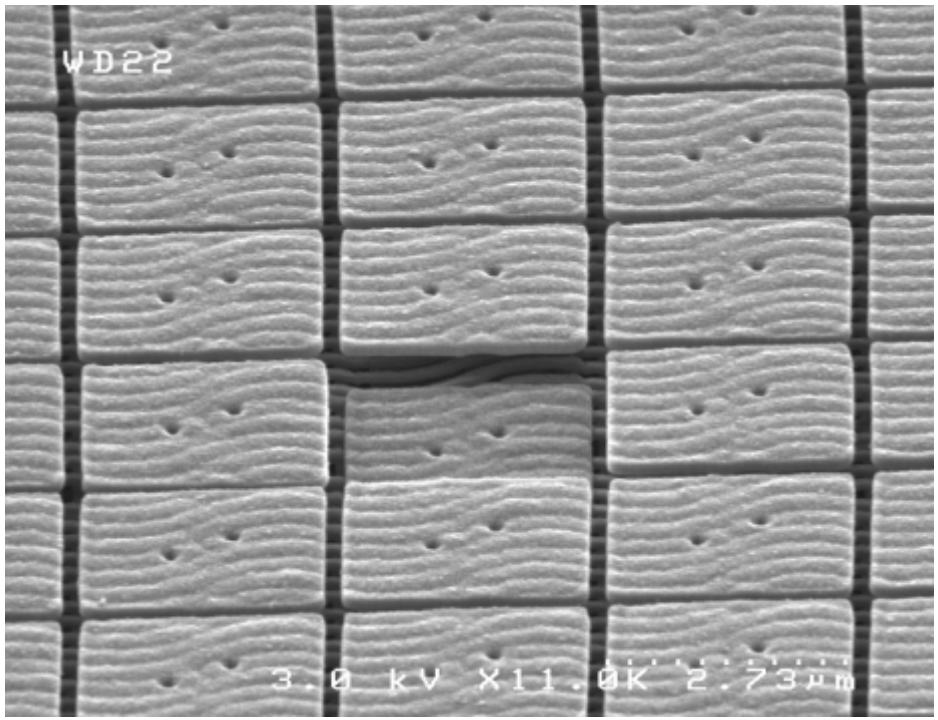


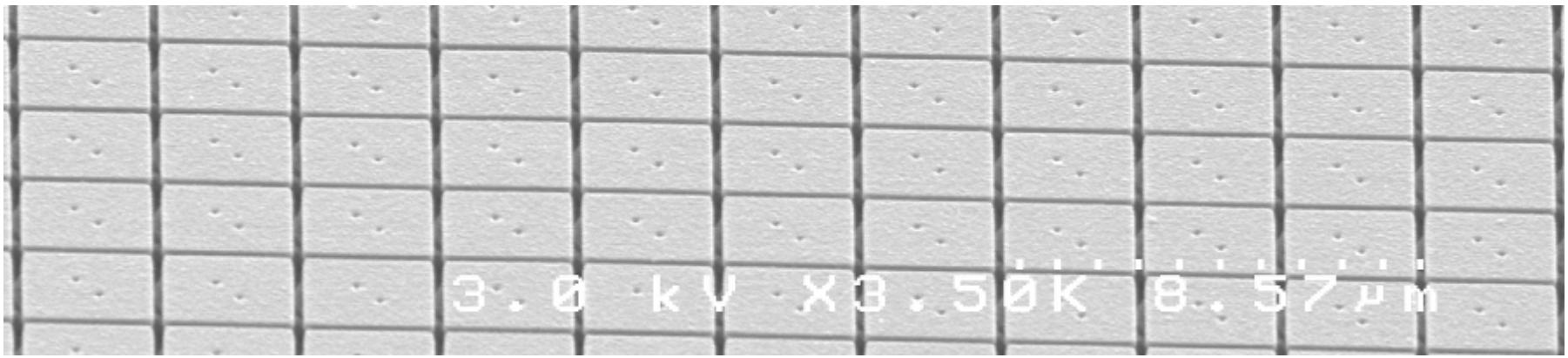




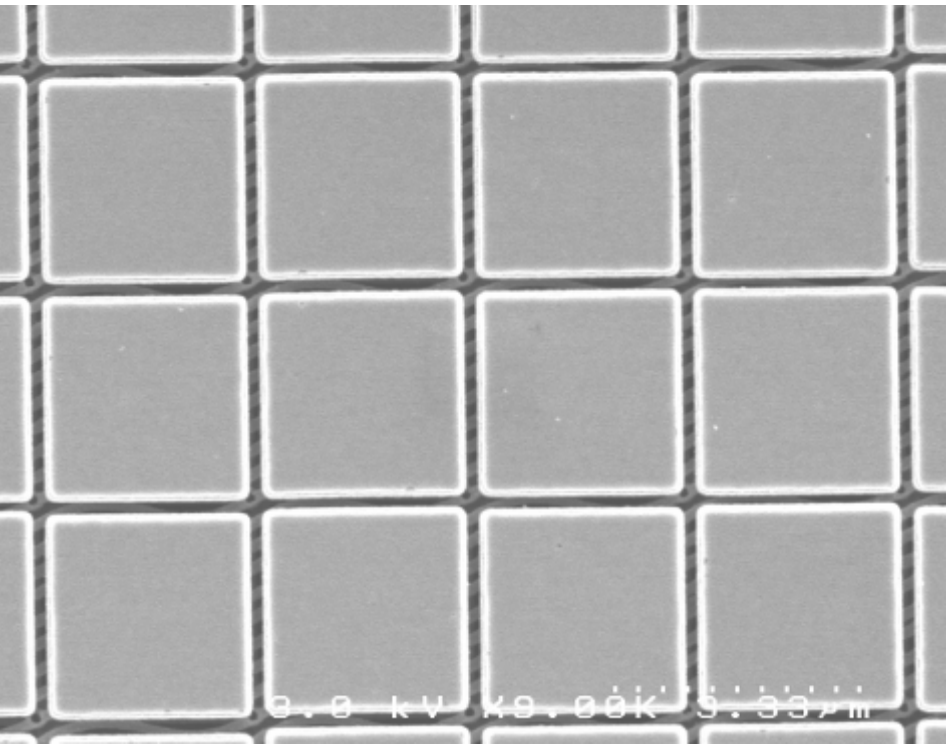
Mirror arrays

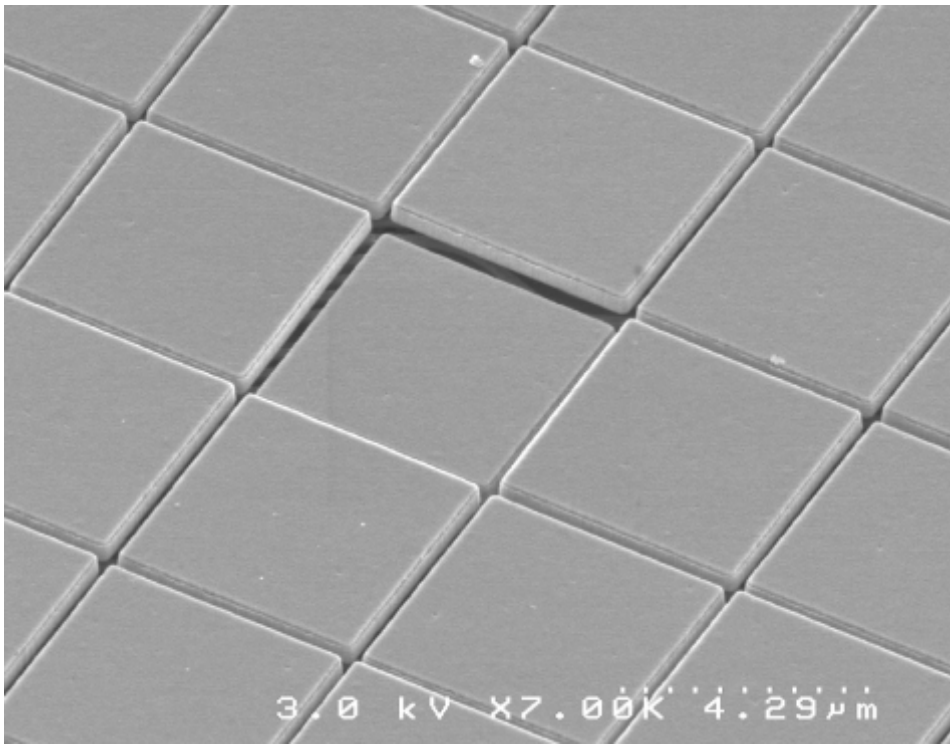


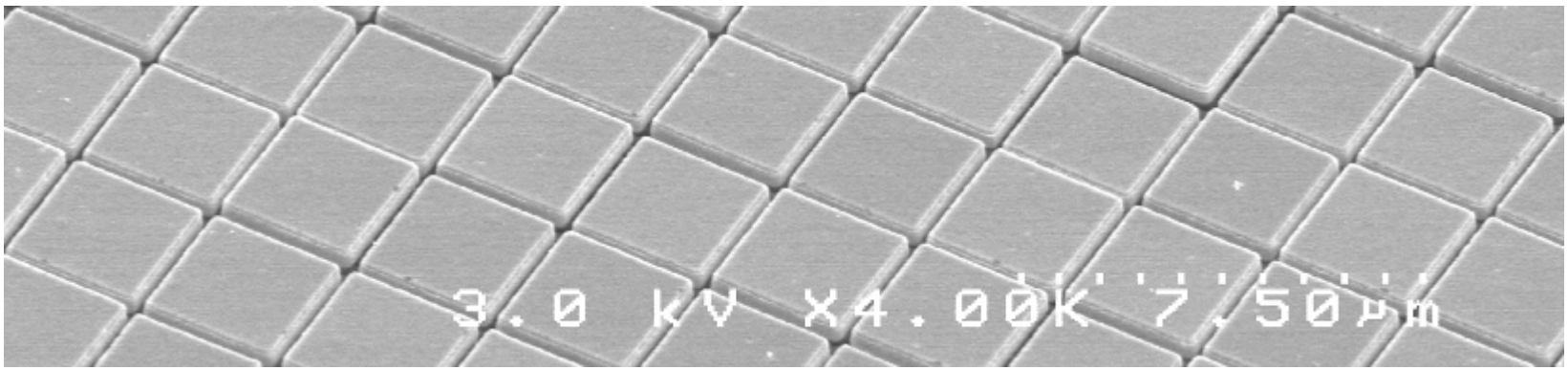




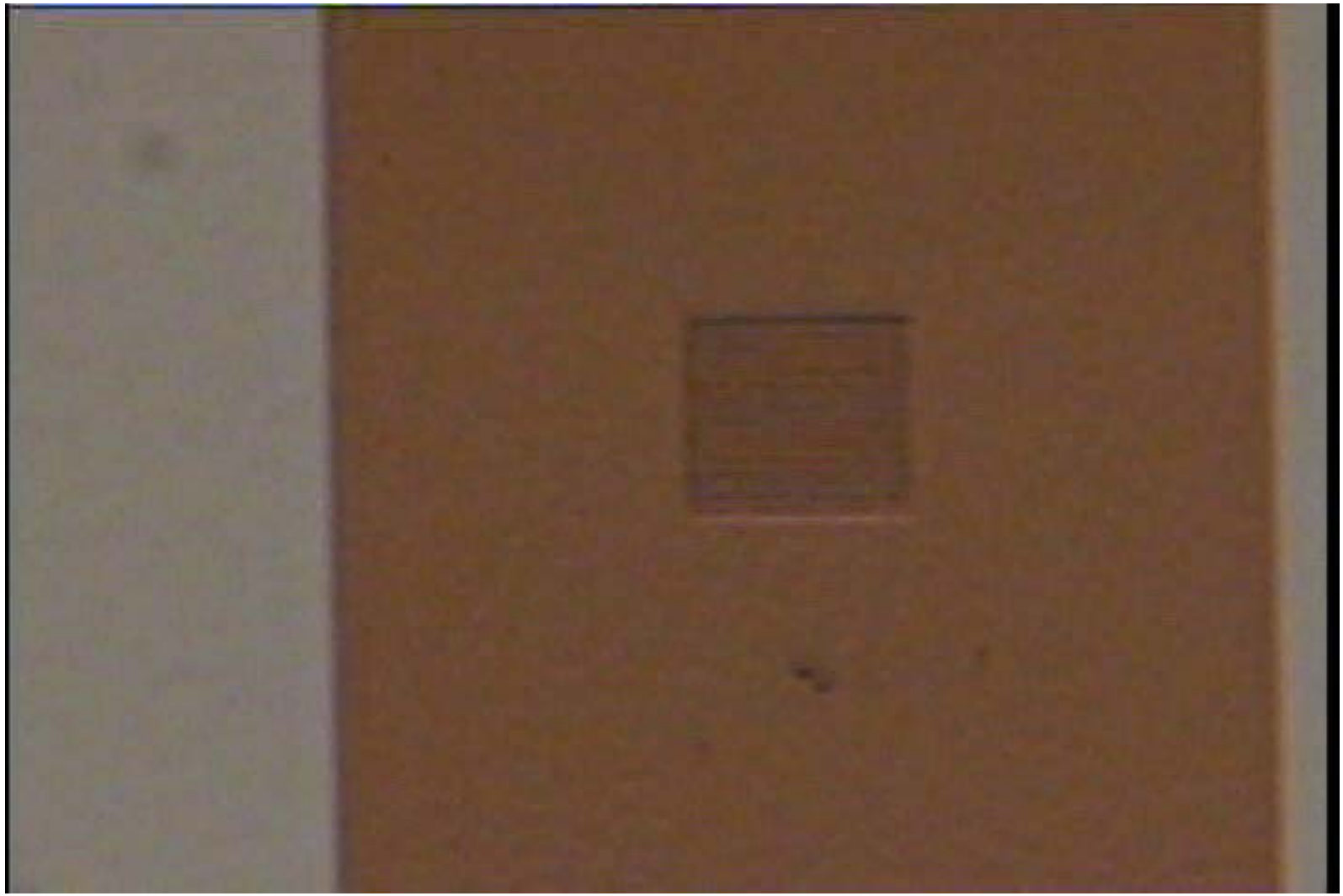
Thick mirrors planarized with CMP





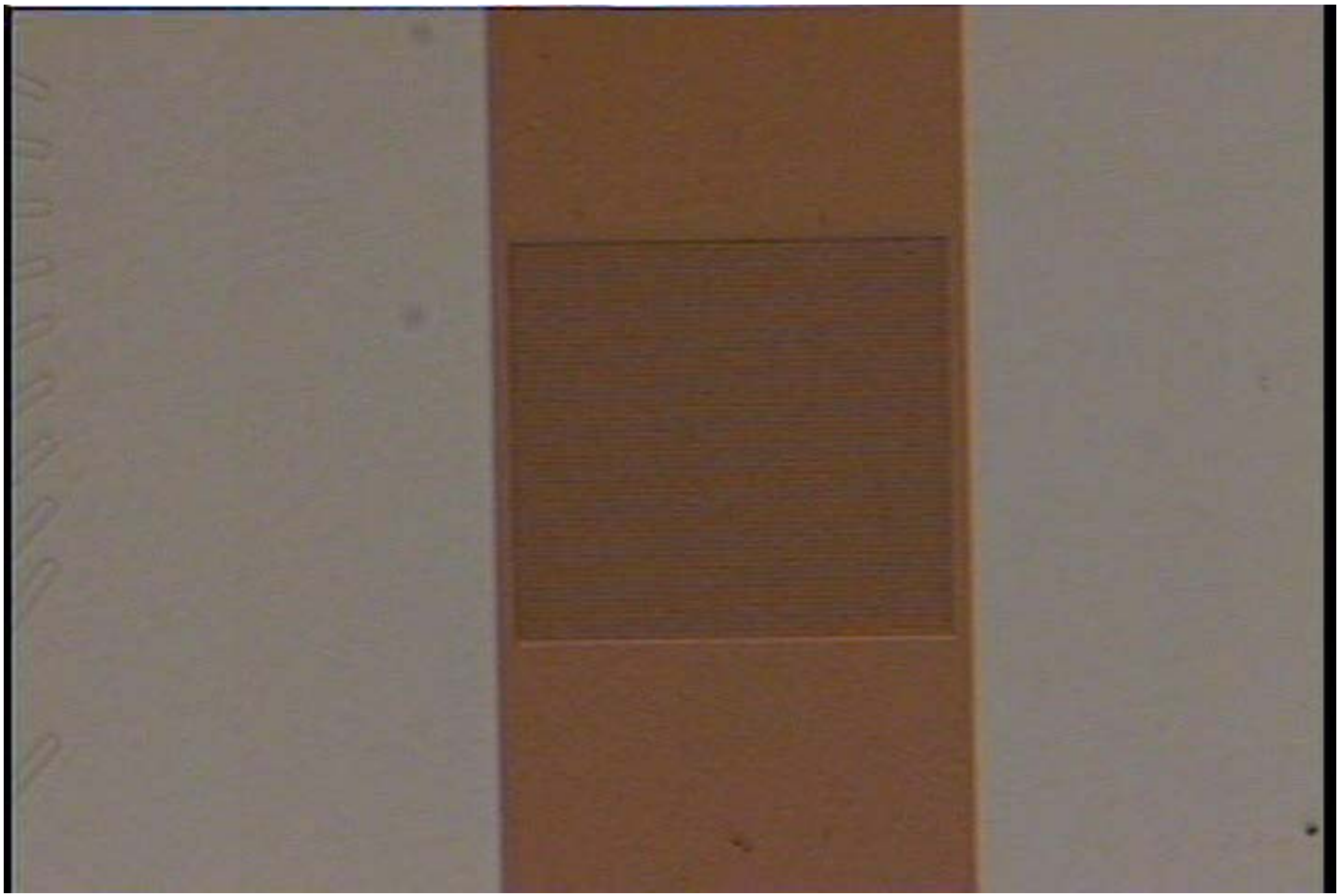


32x32 grating pattern



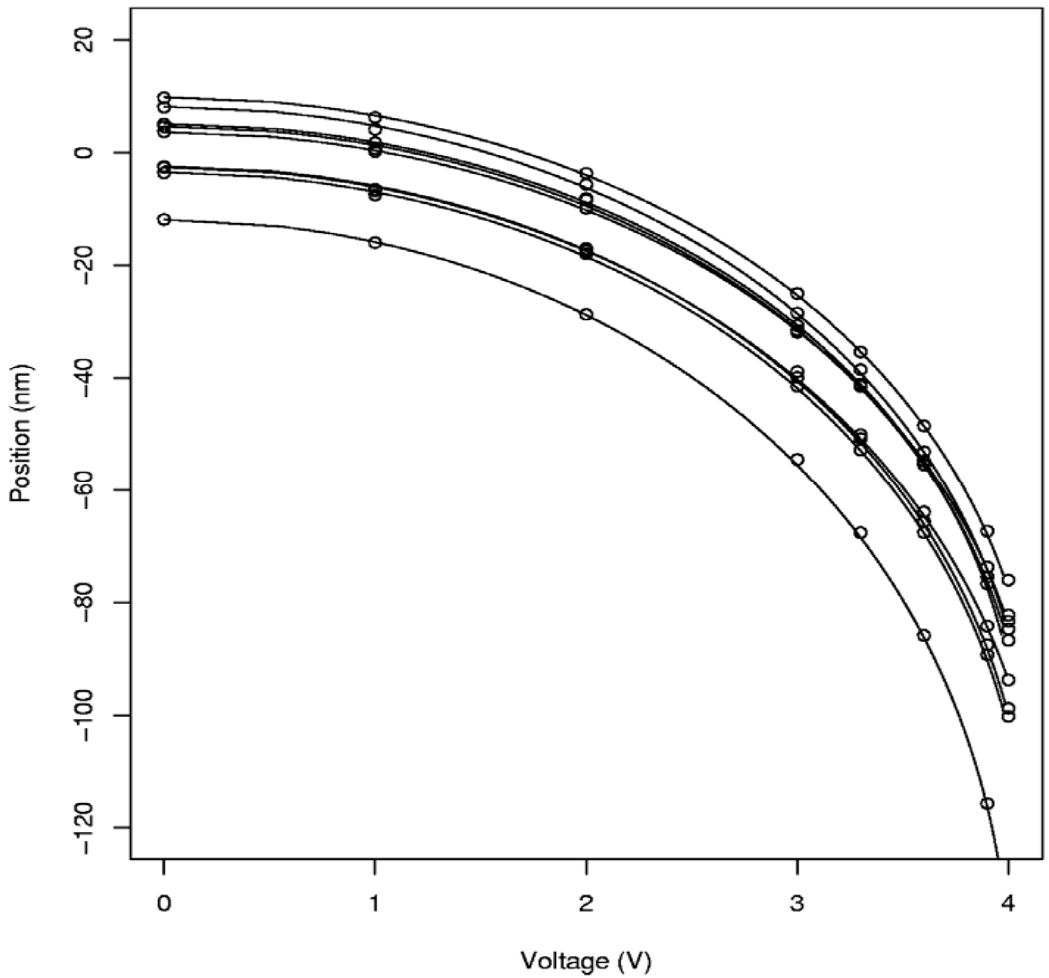
128x128 grating pattern

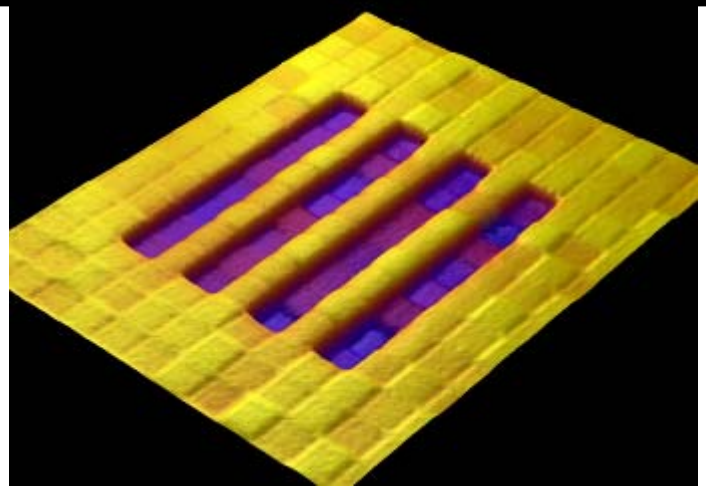
8192 mirrors moving



All moving mirrors are connected in parallel to a single wire

DC actuation curve

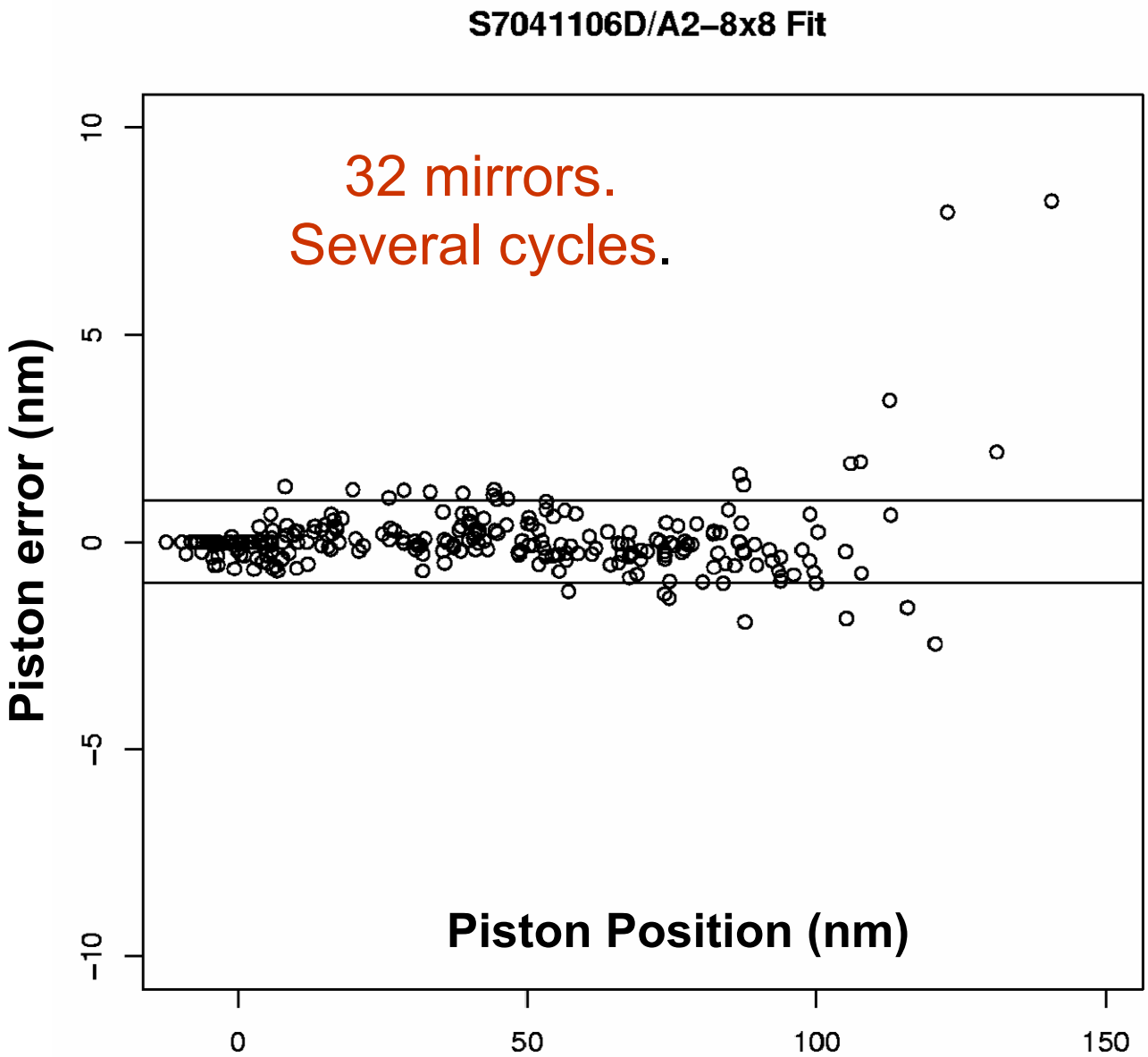




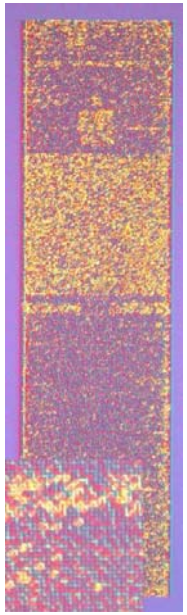
$$V = K\sqrt{(z - z_0)(g - z)^2}$$

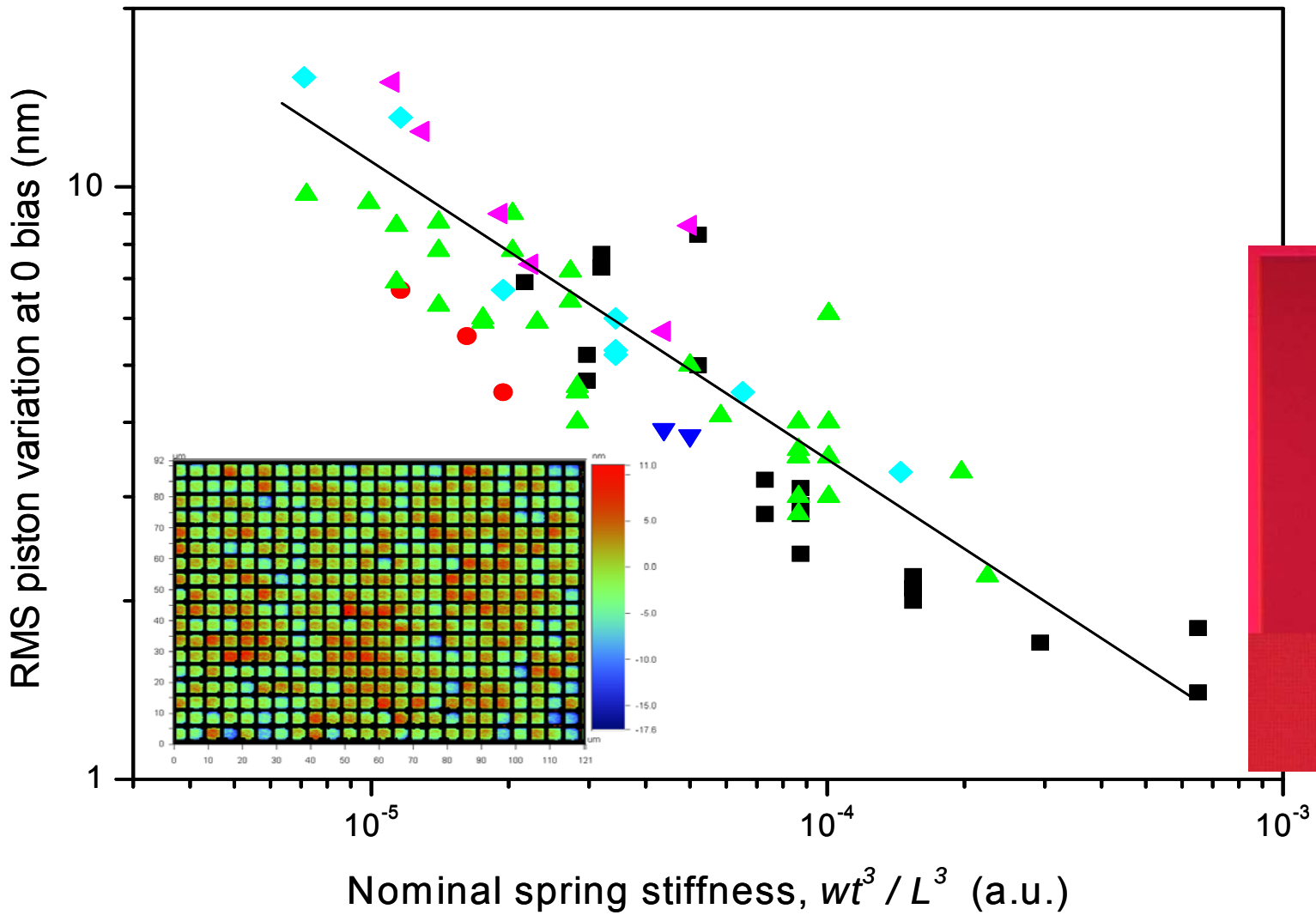
- Idealized parallel plate model with 2 free parameters
- Model explicitly accounts for the measured initial position z_0 of each mirror

Model / motion accuracy

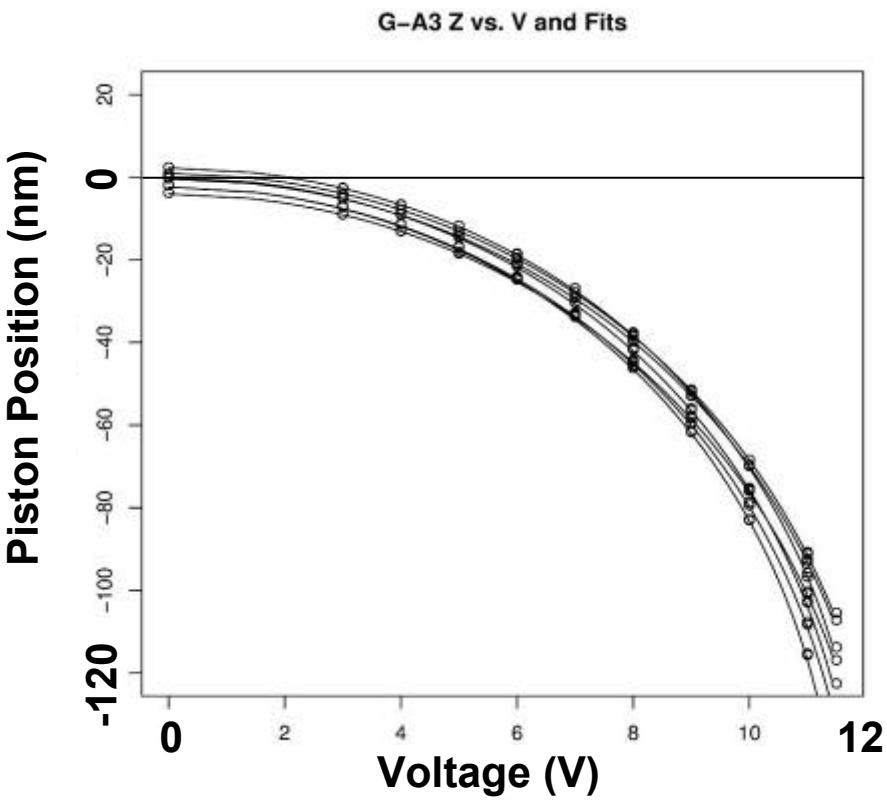


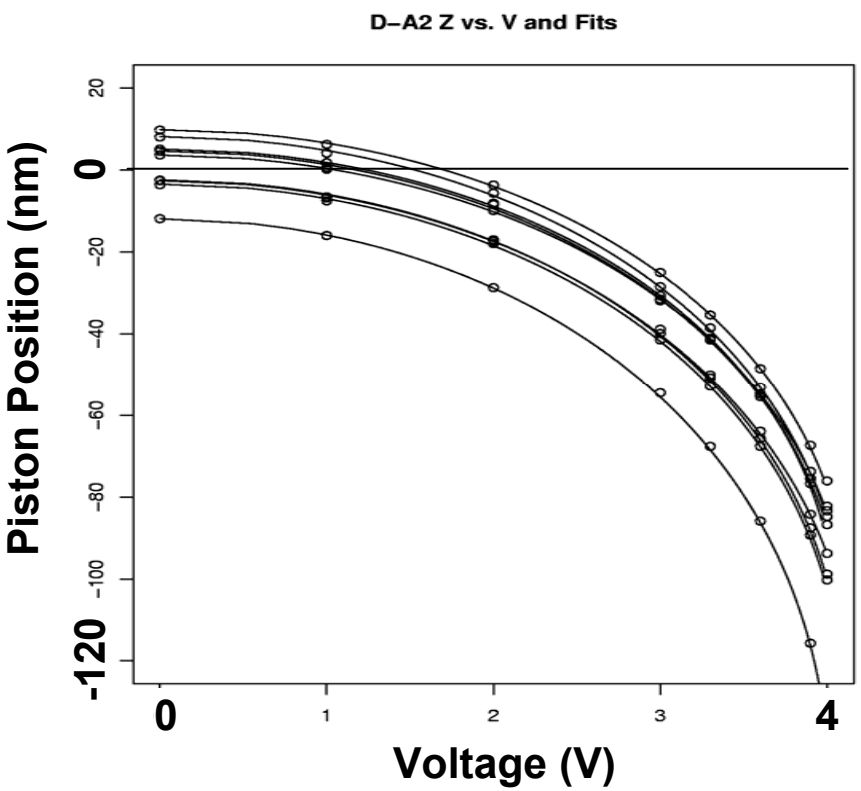
0-Volt piston variation





Different spring stiffness

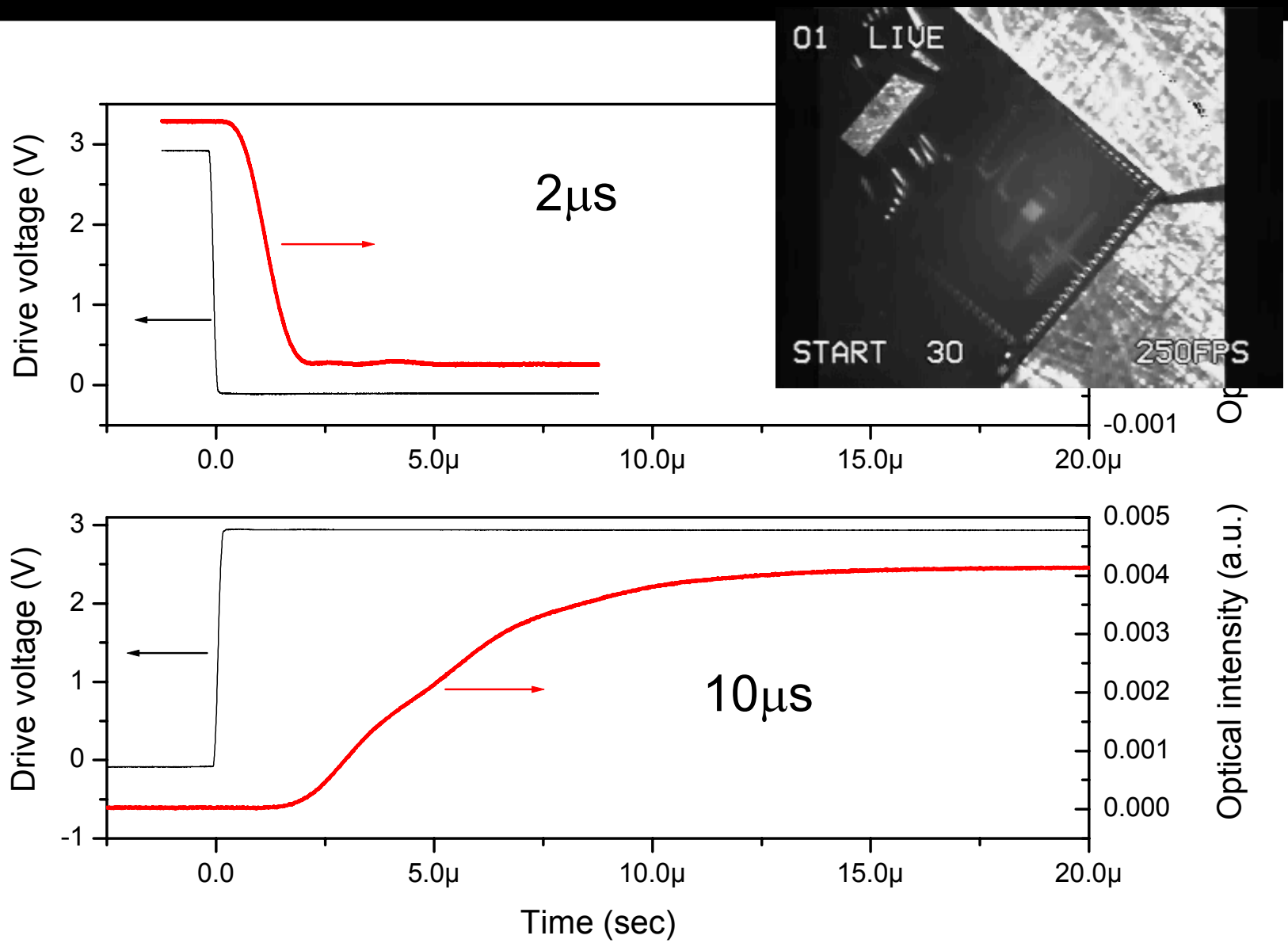




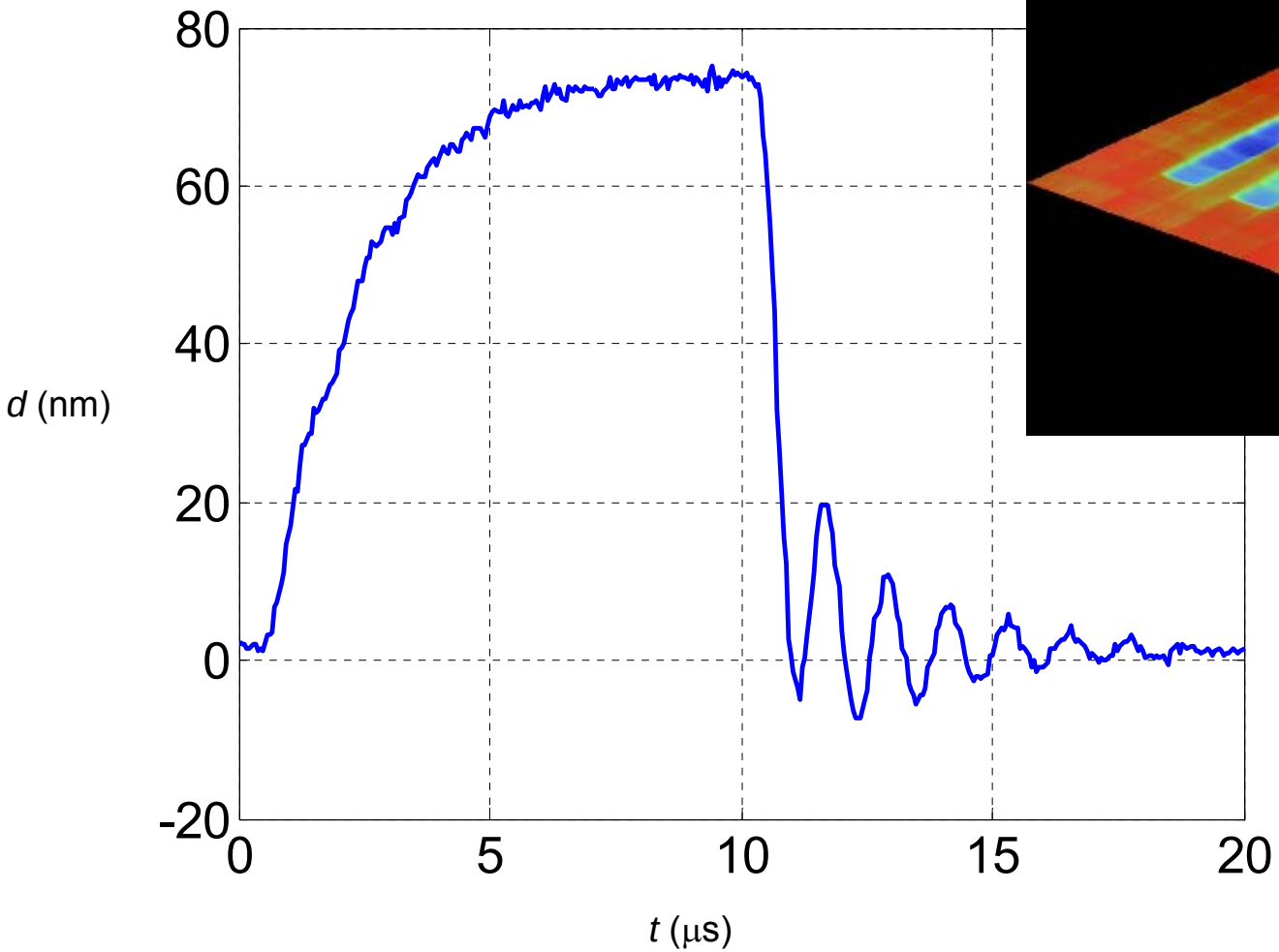
Pitch 5μm
Spring 25μm x 300nm x 180nm
Electrode gap 690nm
V_{sd} = 13V

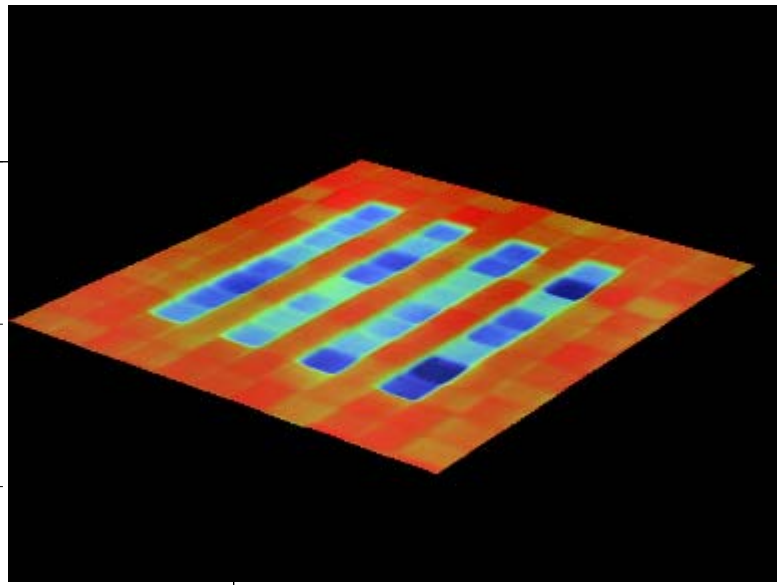
Pitch 3μm
Spring 21μm x 150nm x 110nm
Electrode gap 420nm
V_{sd} = 4.3V

Array dynamic response



Single mirror dynamic response



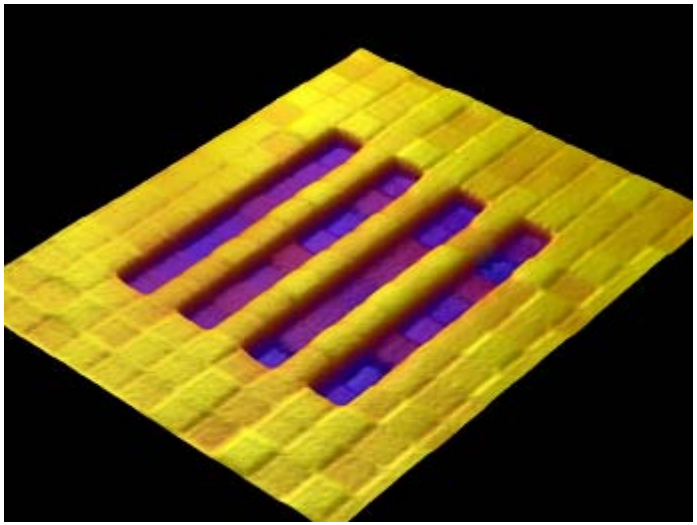


Strobed interferometer measurement

Conclusions and Future work

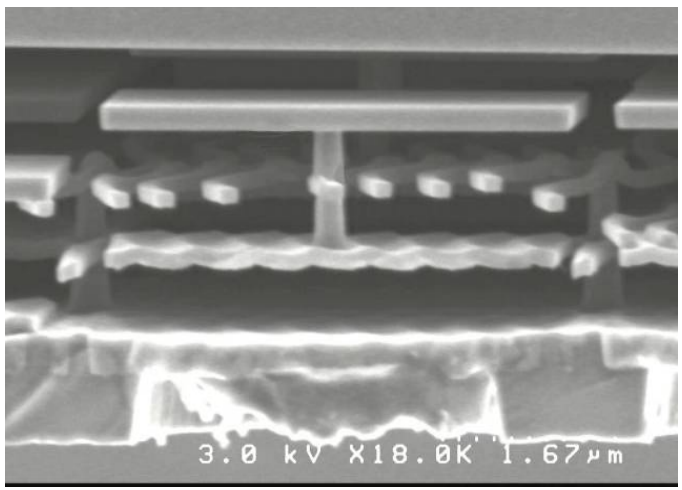
Hi-resolution optical litho for small features, high density -

- High optical and electrical fill factor
- More mechanical Degrees of Freedom (DOF) per unit area
- Large arrays with more DOF per device
- Many layers with accurate overlay



MEMS mirrors for Maskless Lithography SLM -

- arrays of 512x128 mirrors
- 5 structural layers with 30nm alignment
- 3μm and 5μm devices
- 130nm mechanical features 100nm thick
- 4V actuation
- 10μs response time (100KHz)
- fill factor 92%
- reflectivity 88%
- position accuracy ~ 1nm



Future work -

- Understand and improve uniformity
- Hybrid integration with electronics
- Scale to high pixel count (target 10M)

Residual Tilt Analysis

$$K_{rot}\theta = \delta \cdot K \cdot z$$

assuming misalignment δ=50nm, piston motion z=0.1μm

λ=193nm

Straight beam

$$\theta \sim \frac{18 \cdot \delta \cdot z}{L^2} \sim \frac{9 \cdot 10^{-2}}{L^2} \mu m^2 rad$$

pitch=5μm	L=10 μm	L=15 μm	L=20 μm
$\theta \cdot l / \lambda$	1/27	1/36	1/109

pitch=3μm	L=9 μm	L=12 μm	L=15 μm
$\theta \cdot l / \lambda$	1/56	1/65	1/103

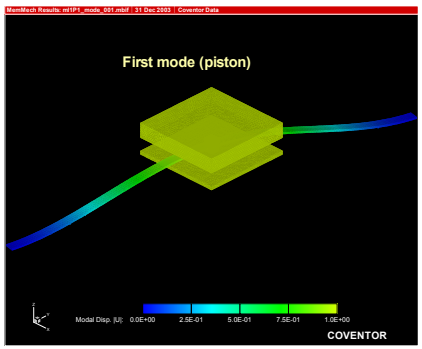
Curved beam
(numerical results)

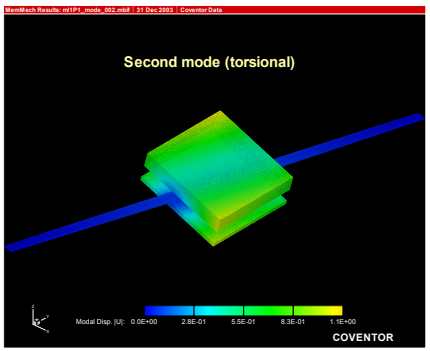
pitch=5μm	L=10 μm	L=15 μm	L=20 μm
$\theta \cdot l / \lambda$	1/61	1/127	1/160

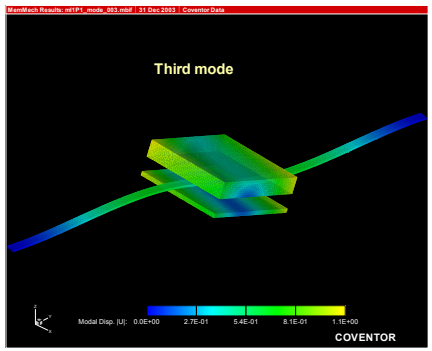
pitch=3μm	L=9 μm	L=12 μm	L=15 μm
$\theta \cdot l / \lambda$	1/64	1/104	1/193

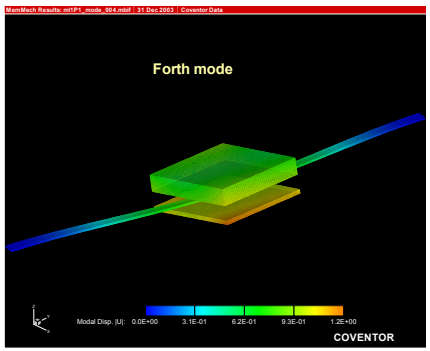
Device resonance modes

[redacted]





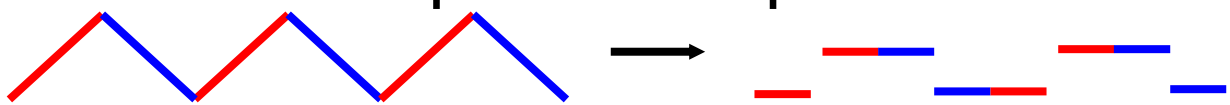


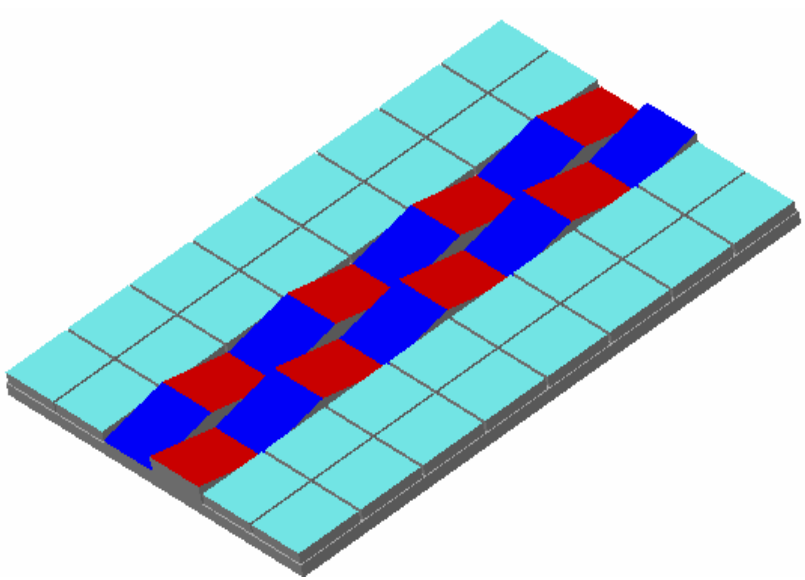


set 1	245 KHz	630 KHz	1.04 MHz	1.3 MHz
set 2	109 KHz	348 KHz	504KHz	704 KHz
set 3	109 KHz	331 KHz	559 KHz	620 KHz
set 4	299 KHz	570 KHz	1.1 MHz	1.6 MHz

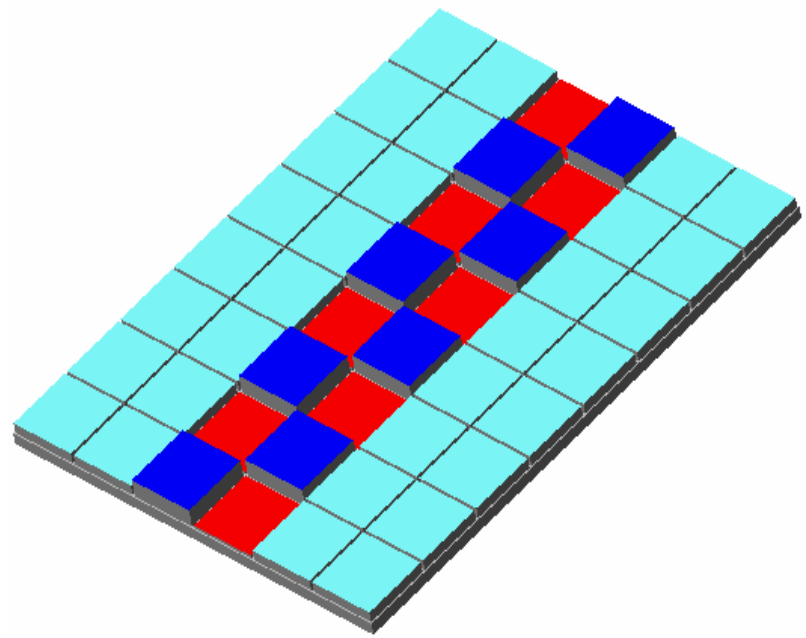
Piston/Tilt Equivalence

- Tilt arrangement and piston arrangement are equivalent except for a ½ pixel shift

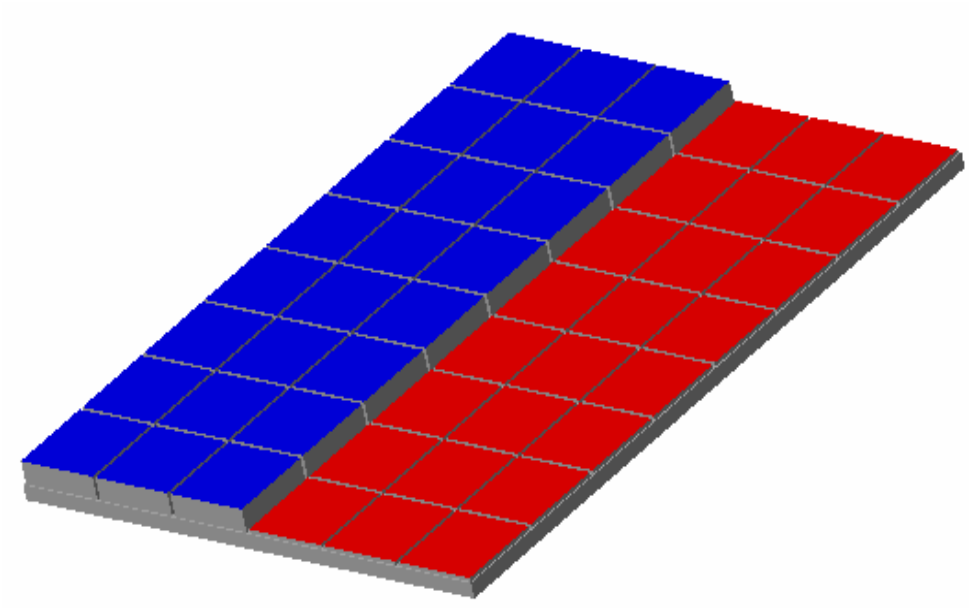




Alternating Horizontal Tilt Mirrors



Checkerboard Piston Mirrors

Alternating Aperture Phase Shifting

- Piston mirrors can employ "strong phase shift" arrangement
- Strong PS can increase DOF and substantially improve minimum feature size
- Smaller NA may be employed
- Adds Complexity:
  - Trim masks (throughput loss) or multiple phases (DOF loss) are required to define IC features
  - Feature size control less straightforward (no Chrome)