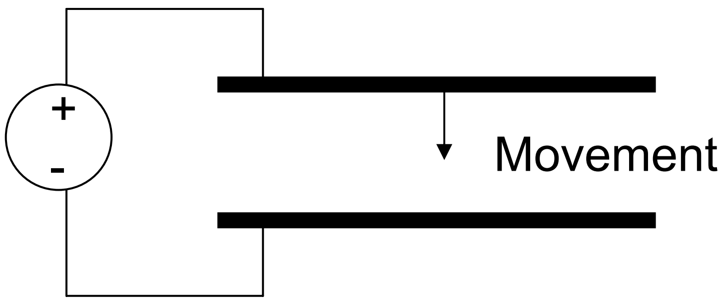
Tema for forelesning

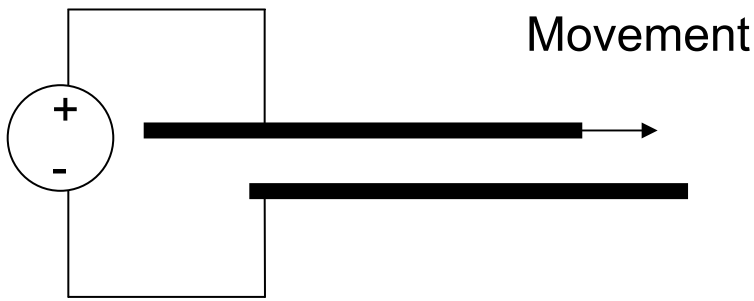
- Elektrostatiske aktuatorer basert på paralellplatekondensatorer
- Eksempler:
  - SINTEF CDOE
  - Texas Instruments DLP teknologi
  - Fraunhofer IPMS analog SLM teknologi

- Elektrostatiske aktuatorer basert på “comb-drives”
- Eksempler:
  - Optisk bølgeledersvitsj
  - Fraunhofer IPMS skannerspeil-teknologi

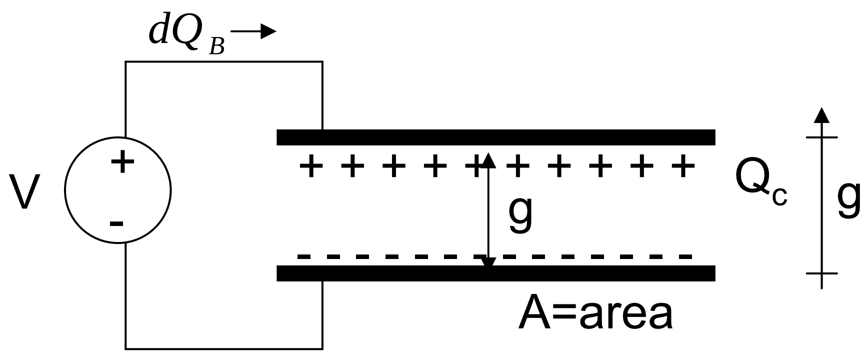
Typical electrostatic actuators used in MEMS

- Parallel-plate capacitor actuator
- Comb-drive actuator





Capacitor: Force between plates



$$C = \frac{Q}{V} \qquad dW = V \cdot dQ \qquad C = \frac{\varepsilon A}{g}$$

$$W_C = \int_0^Q \frac{q}{C} dq = \frac{1}{2}\frac{Q^2}{C} = \boxed{\frac{1}{2} CV^2}$$ Energy stored in capacitor

Force is in the direction which <u>lowers</u> the <u>total energy</u>: $F = -\frac{dW_T}{dg}$

Total energy is battery plus capacitor: $W_T = W_C + W_B$ where $W_B = Q_B V$

Charge balance: $-dQ_B = dQ_C = dCV$ (What leaves battery accumulates at capacitor)

Force on plates at a <u>constant voltage</u> becomes:

$$F = -\frac{dW_T}{dg} = -\frac{dW_C + dW_B}{dg} = -\frac{V^2}{2}\frac{dC}{dg} + V\frac{d(CV)}{dg} = \frac{V^2}{2}\frac{dC}{dg} = \boxed{-\frac{\varepsilon A V^2}{2g^2}}$$

Linear elastic spring

- Euler-Bernoulli beam equation:

$$EI\frac{\partial^4 u}{\partial x^4} = F$$

- Hooke's law:

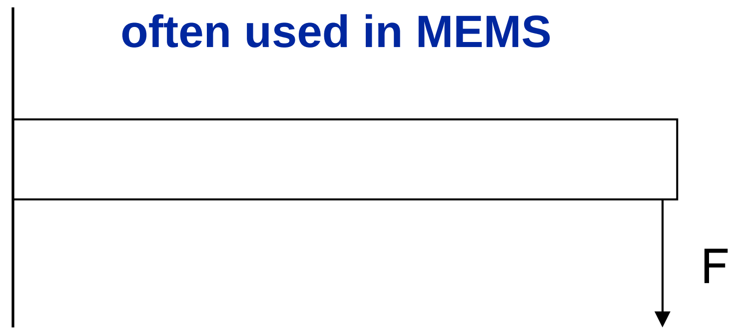
$$F = ku$$

- Spring constant for beam with load F at beam tip:

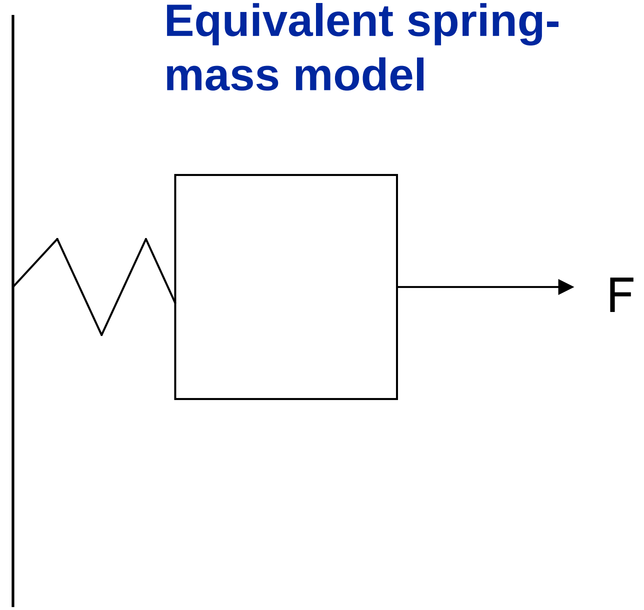
$$k = \frac{Ewt^3}{4L^3}$$

E – Young's modulus
w – beam width
t – beam thickness
L – beam length

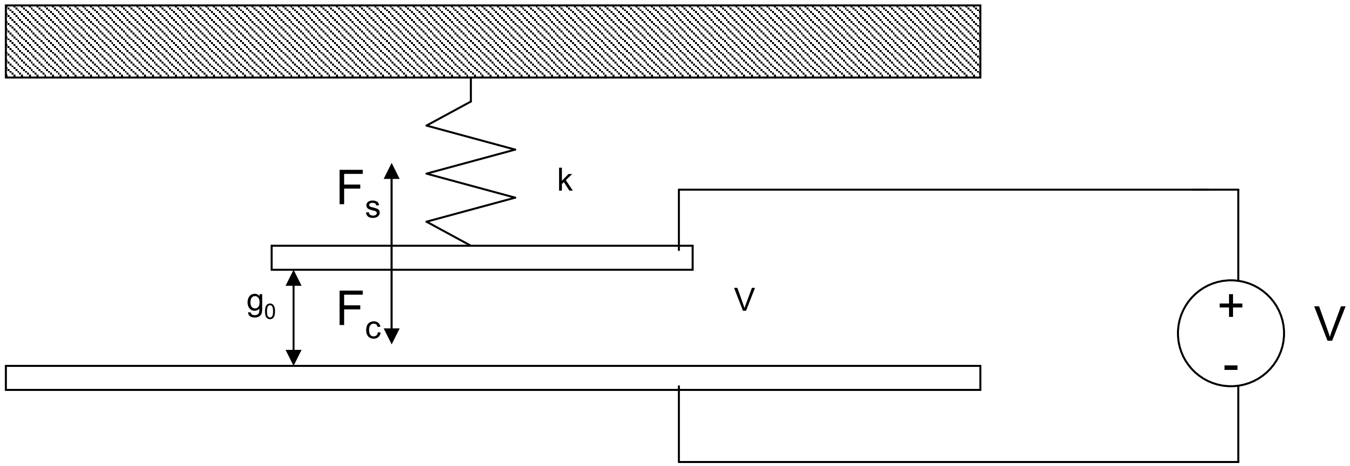
Cantilever beam often used in MEMS



Equivalent spring-mass model



Parallel plate capacitor with linear spring



- Consists of two parallel conductive plates where one plate is held by a spring
- A voltage V pulls the plates together, counterbalanced by the linear spring

$$F_c = \frac{\varepsilon A V^2}{2g^2} \qquad F_s = k(g_0 - g)$$

$$F_{net} = \frac{-\varepsilon A V^2}{2g^2} + k(g_0 - g)$$

Pull-in of parallel capacitor plates with linear spring

What happens when capacitor plates get too close?

$$F_{net} = \frac{-\varepsilon A V^2}{2g^2} + k(g_0 - g)$$

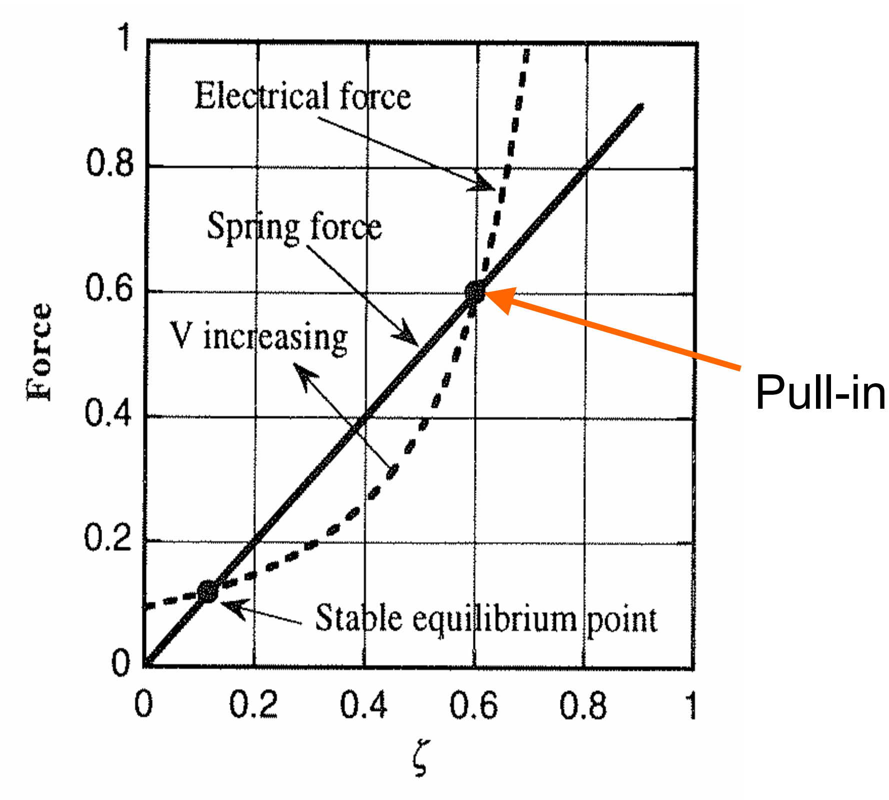
When the electrical force exceeds the spring force, pull-in occurs

- Stable and unstable equilibrium:

$$\frac{\partial F_{net}}{\partial g} = \frac{\varepsilon A V^2}{g^3} - k$$

- STABLE if $\partial F/\partial g < 0$
  a smaller gap gives a decrease in net force, equilibrium at $F_{net}=0$

- UNSTABLE if $\partial F/\partial g > 0$
  a smaller gap increases the net force, plates are pulled together until g=0



Pull-in of parallel plates with linear spring

- By gradually increasing the actuation voltage, pull-in occurs at:

$$\frac{\partial F_{net}}{\partial g} = 0 \quad \text{and} \quad F_{net} = 0$$

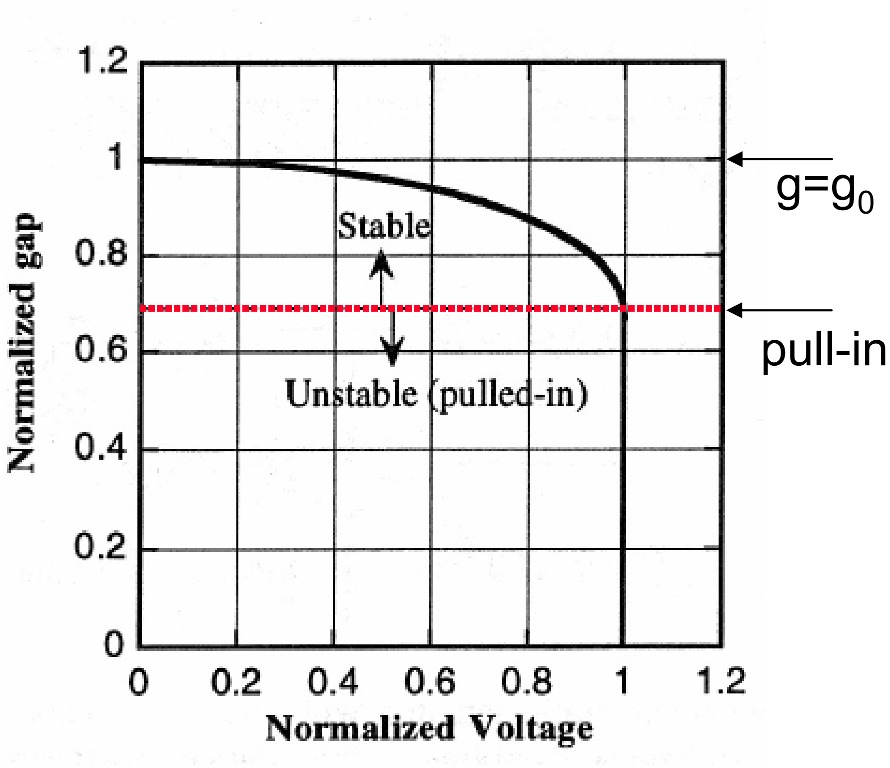
$$\Downarrow \qquad\qquad \Downarrow$$

$$k = \frac{\varepsilon A V^2}{g^3} \qquad\qquad k(g_0 - g) = \frac{\varepsilon A V^2}{2g^2}$$

$$g_{PI} = 2/3 g_0$$

$$V_{PI} = \sqrt{\frac{8kg_0^3}{27\varepsilon A}}$$

Gap vs. voltage

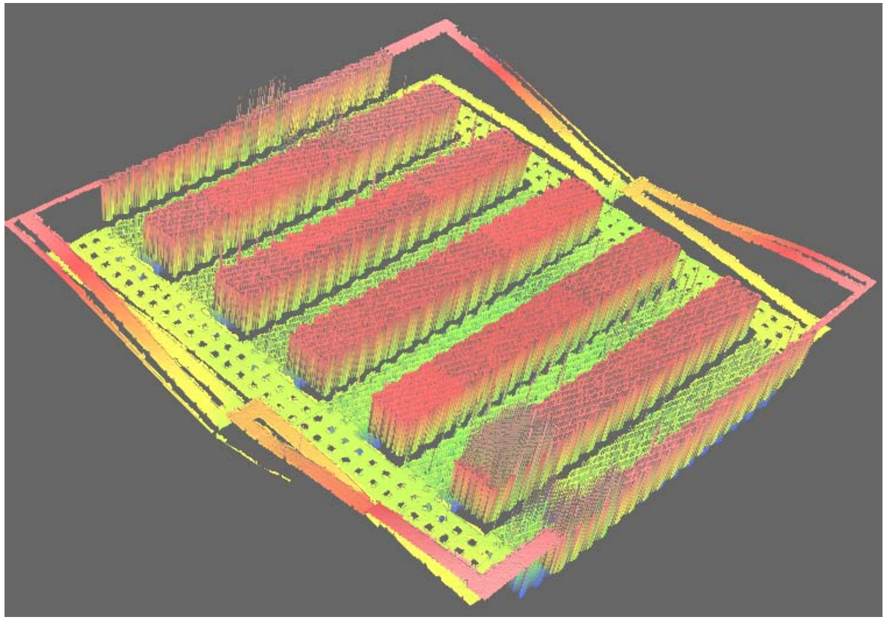


- Parallell plates, linear spring elastic force

- Normalized gap g/g_0
- Normalized voltage V/V_{PI}

SINTEF CDOE

- Configurable diffractive optical element - CDOE



Our aim is to measure *gas concentration* using a *micromechanical infrared filter*

The figure shows an old, established infrared sensing method for measuring gas concentration

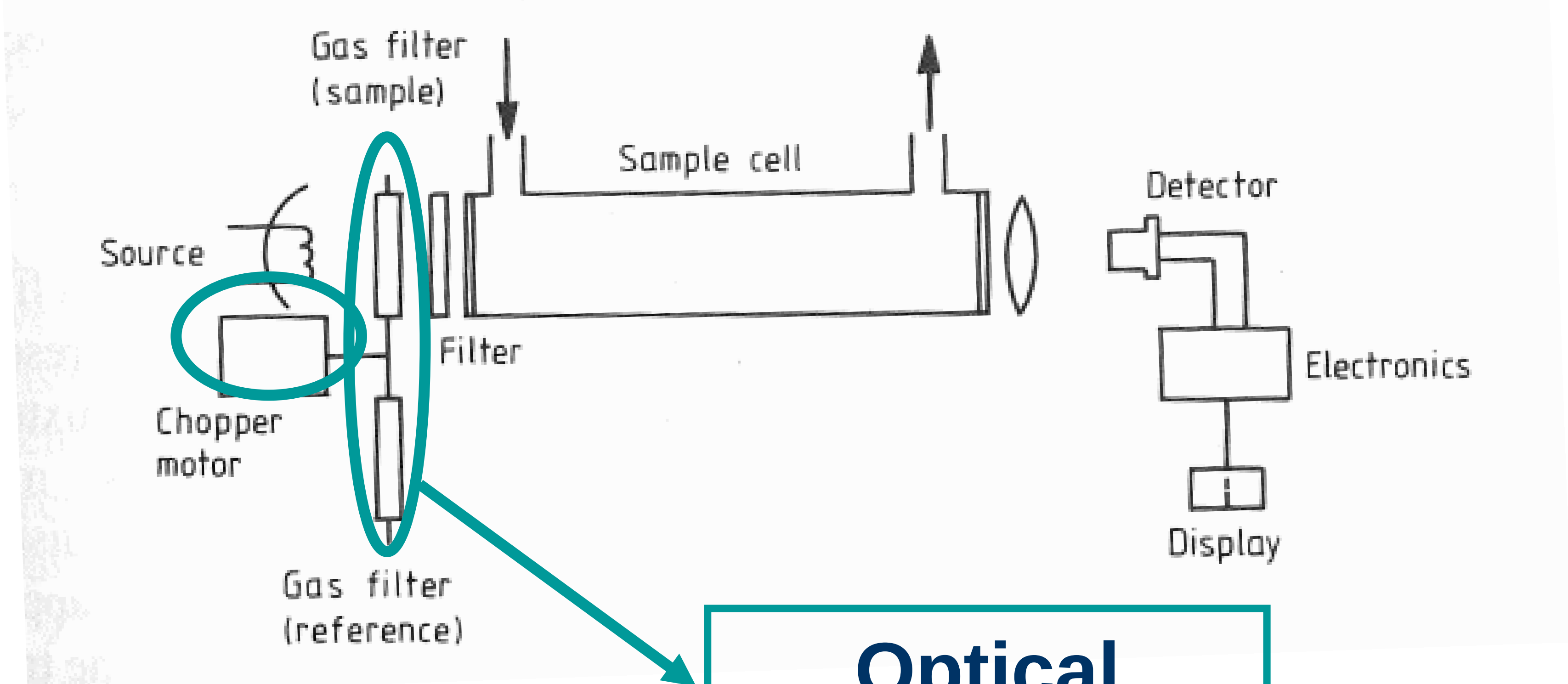
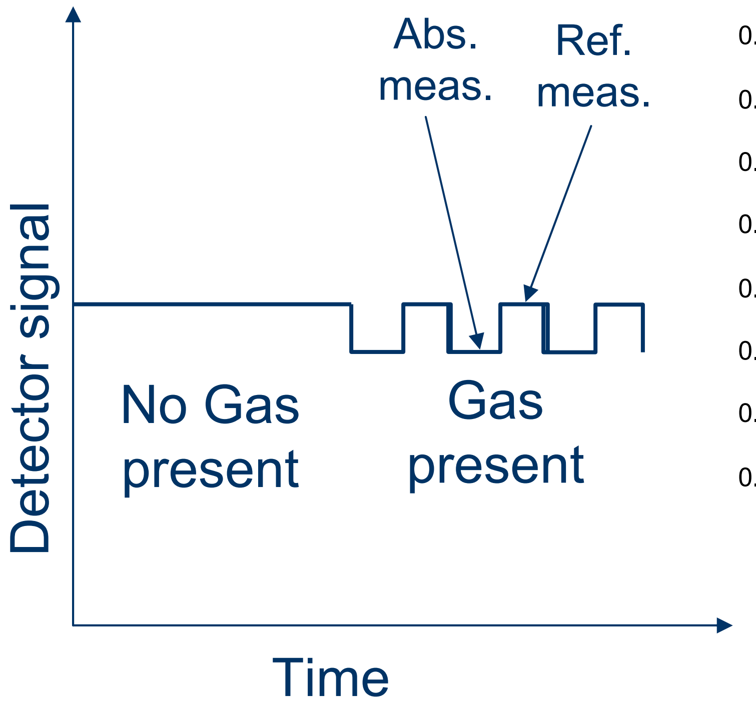


Image taken from Moseley et al, ”Techniques and mechanisms in gas sensing”

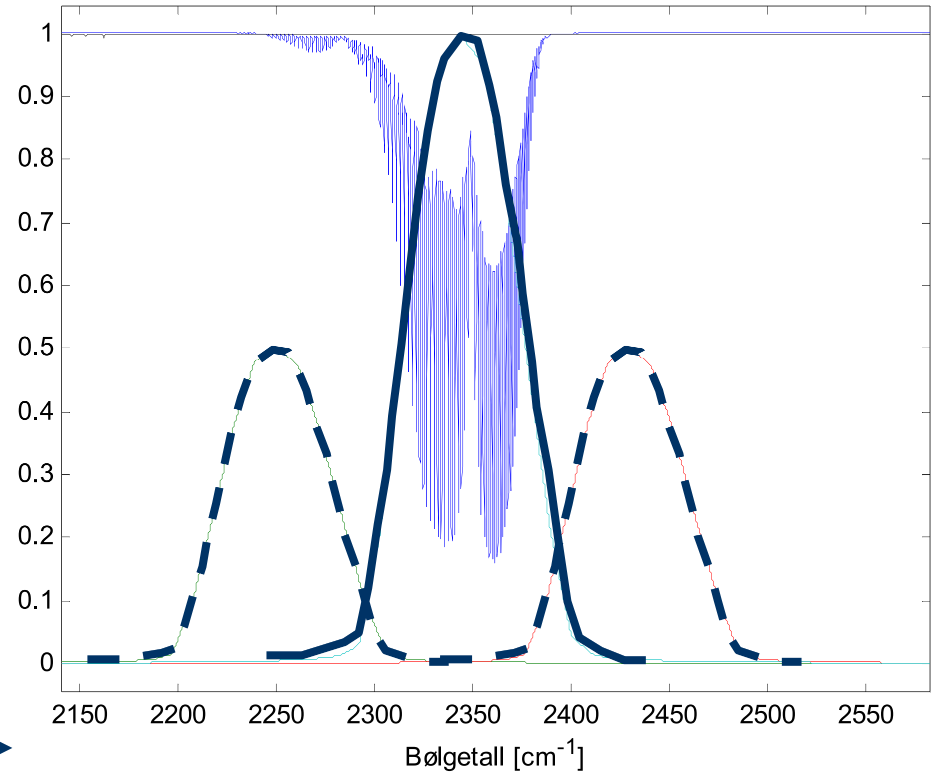
Optical MEMS device

Reference measurements **must be made in one or more wavelength bands outside the absorbing region**

- Example: Carbon dioxide absorption
- Single detector
- Alternating filter

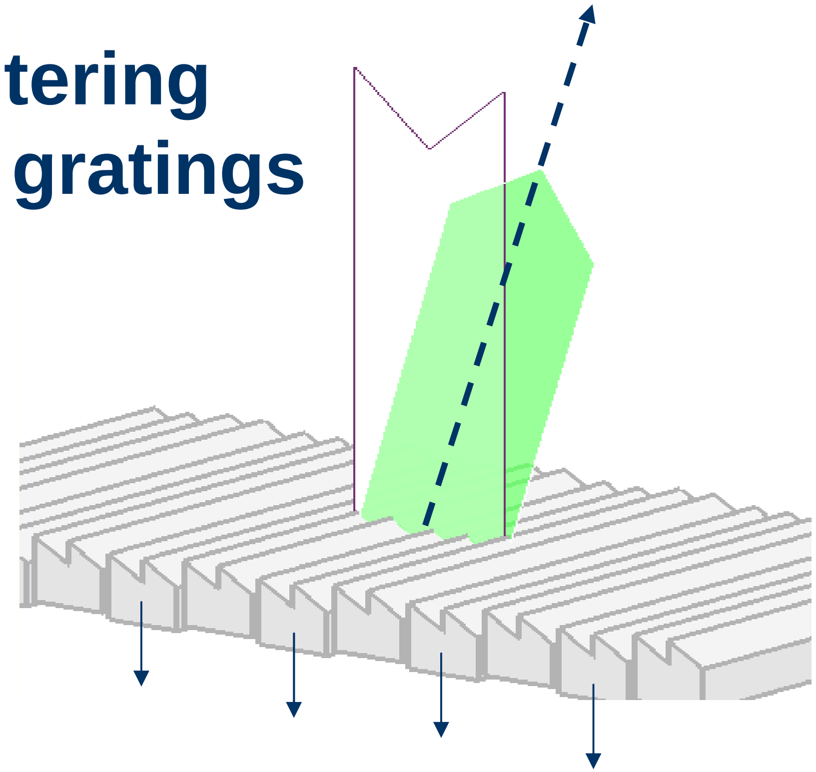


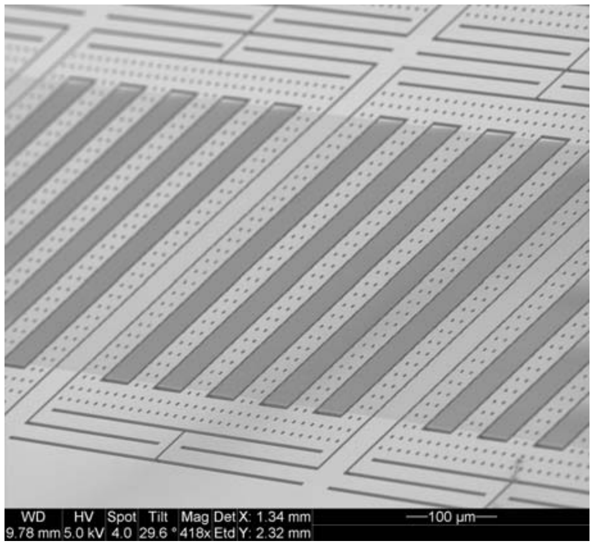
Infrared transmittance spectrum of CO_2



Design concept: Optical filtering with Modulated diffraction gratings

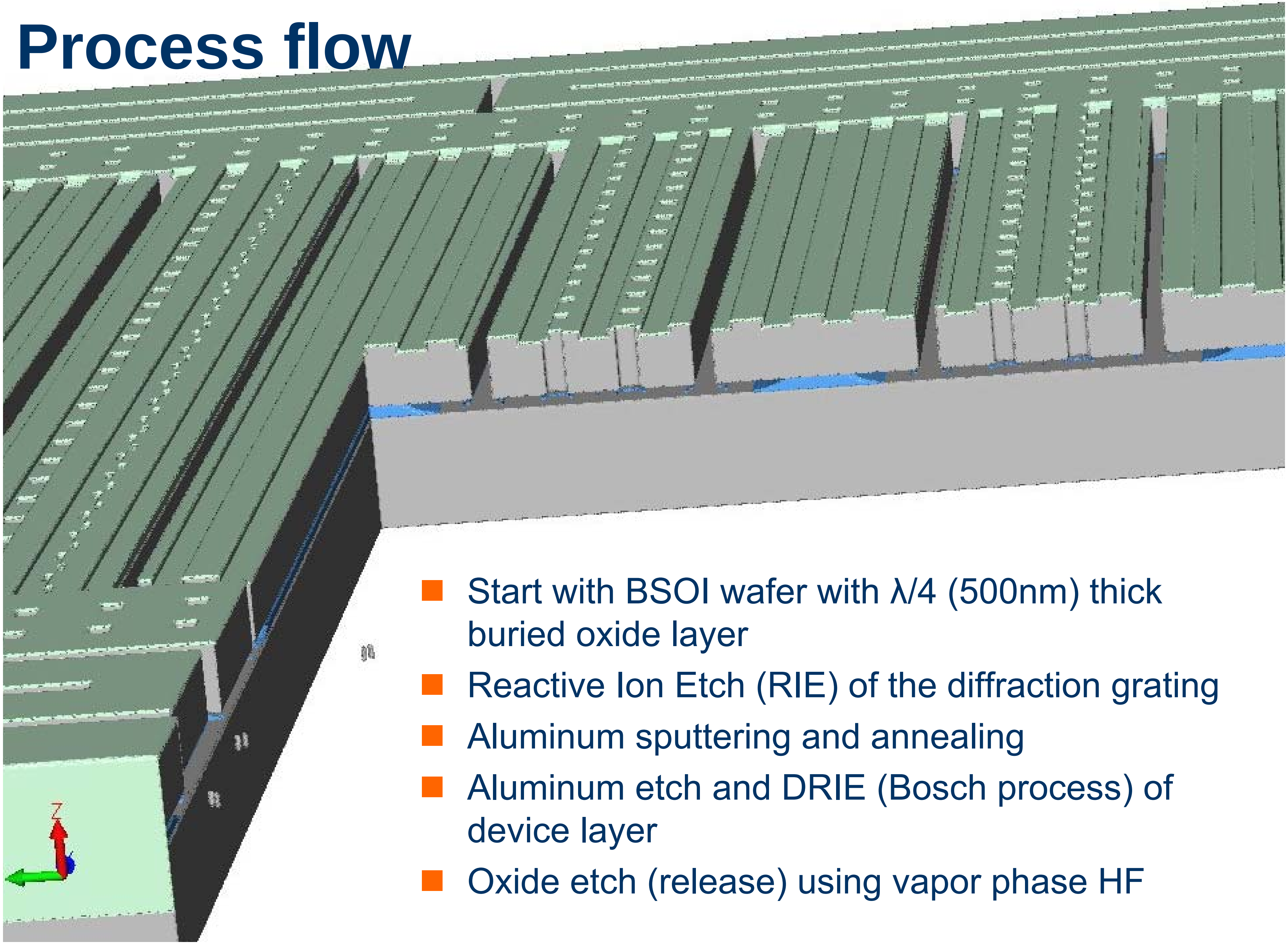
- Shine white light (broadband IR) onto a diffraction grating
- Collect the light diffracted into a chosen angle
- Change the color and intensity of the light by electromechanical modifications of the grating shape





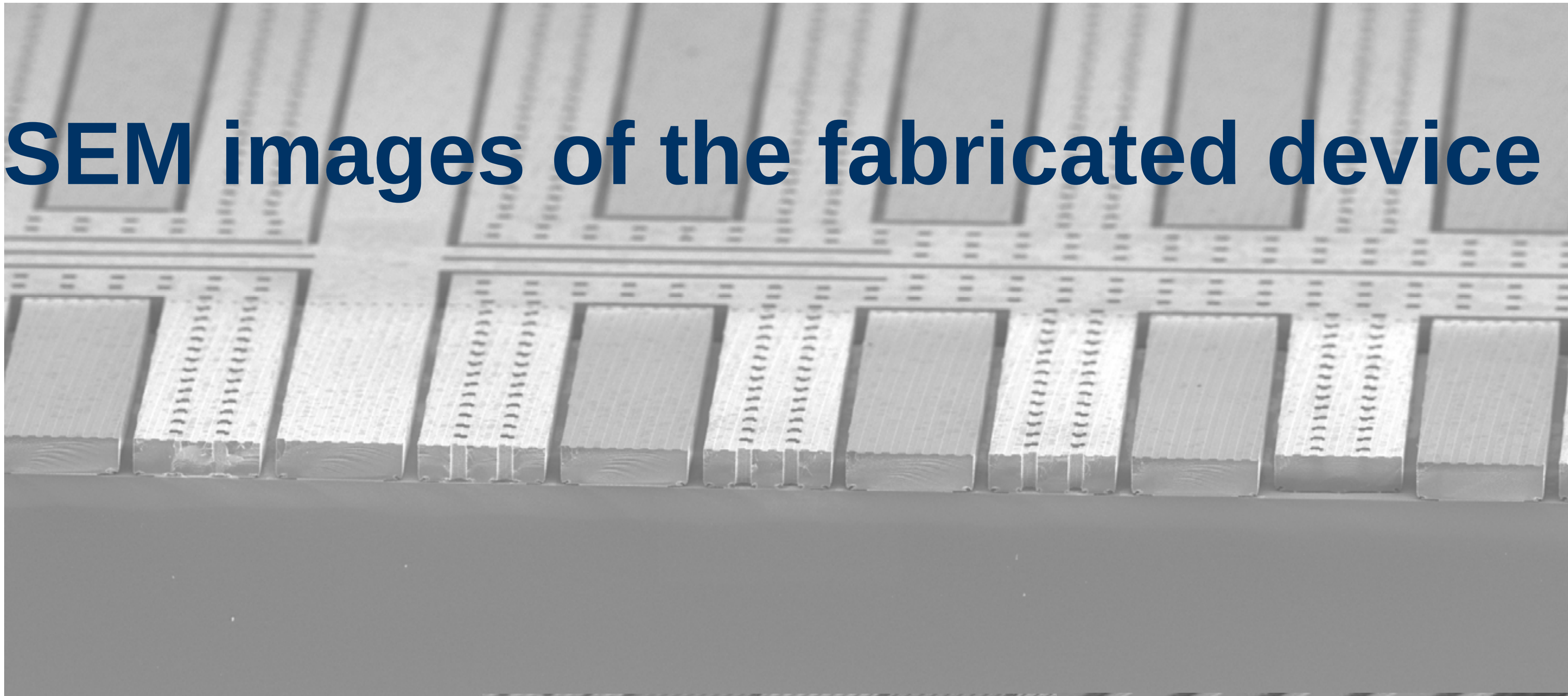
- Design objective:
  - Electromechanically simple
  - No position feedback
  - No calibration
  - No drift
  - Robust
  - Low-cost

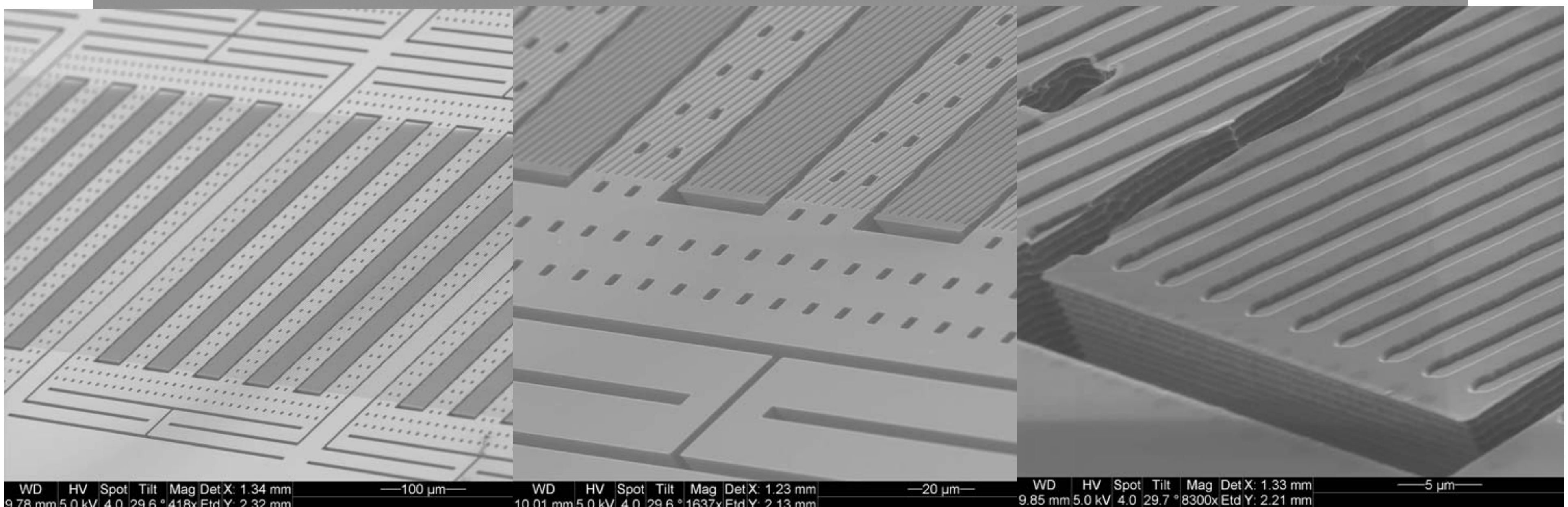
Process flow



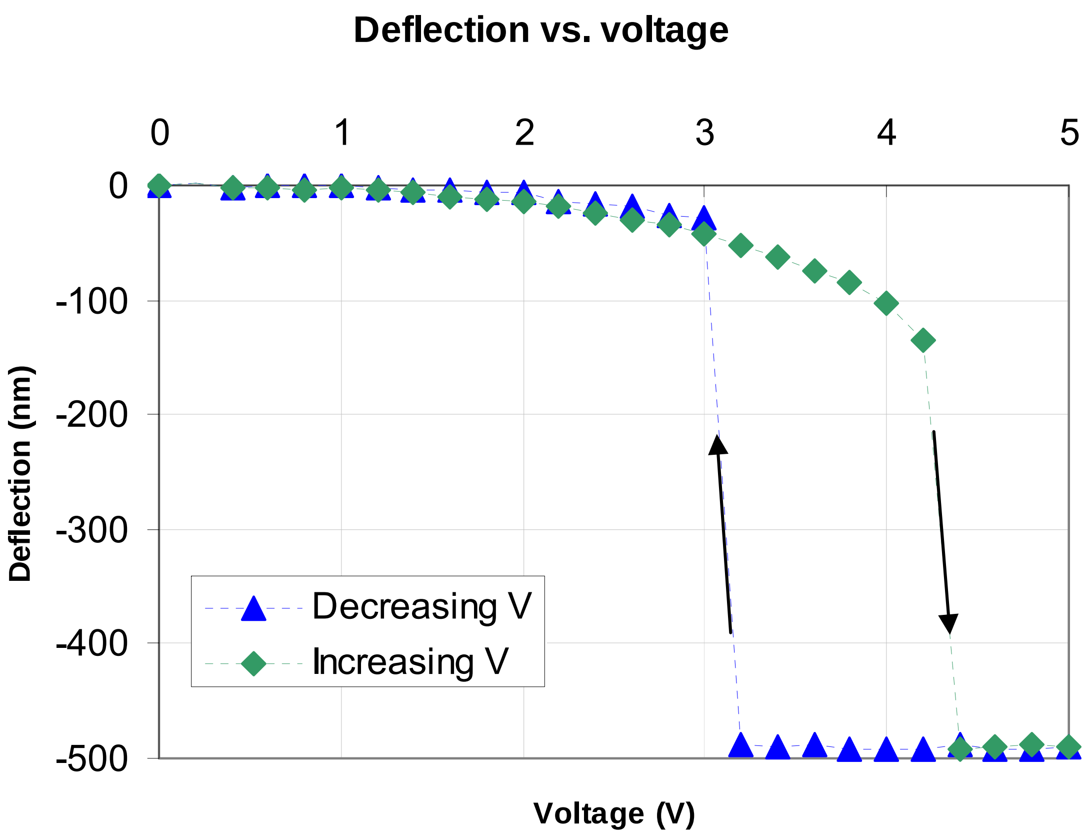
- Start with BSOI wafer with λ/4 (500nm) thick buried oxide layer
- Reactive Ion Etch (RIE) of the diffraction grating
- Aluminum sputtering and annealing
- Aluminum etch and DRIE (Bosch process) of device layer
- Oxide etch (release) using vapor phase HF

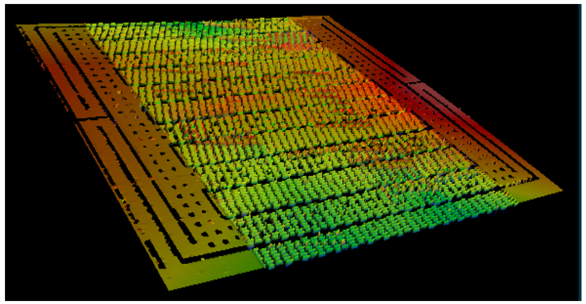
SEM images of the fabricated device



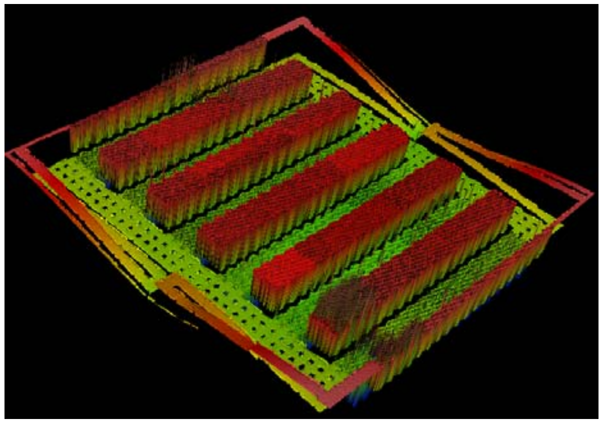


Actuation characteristic



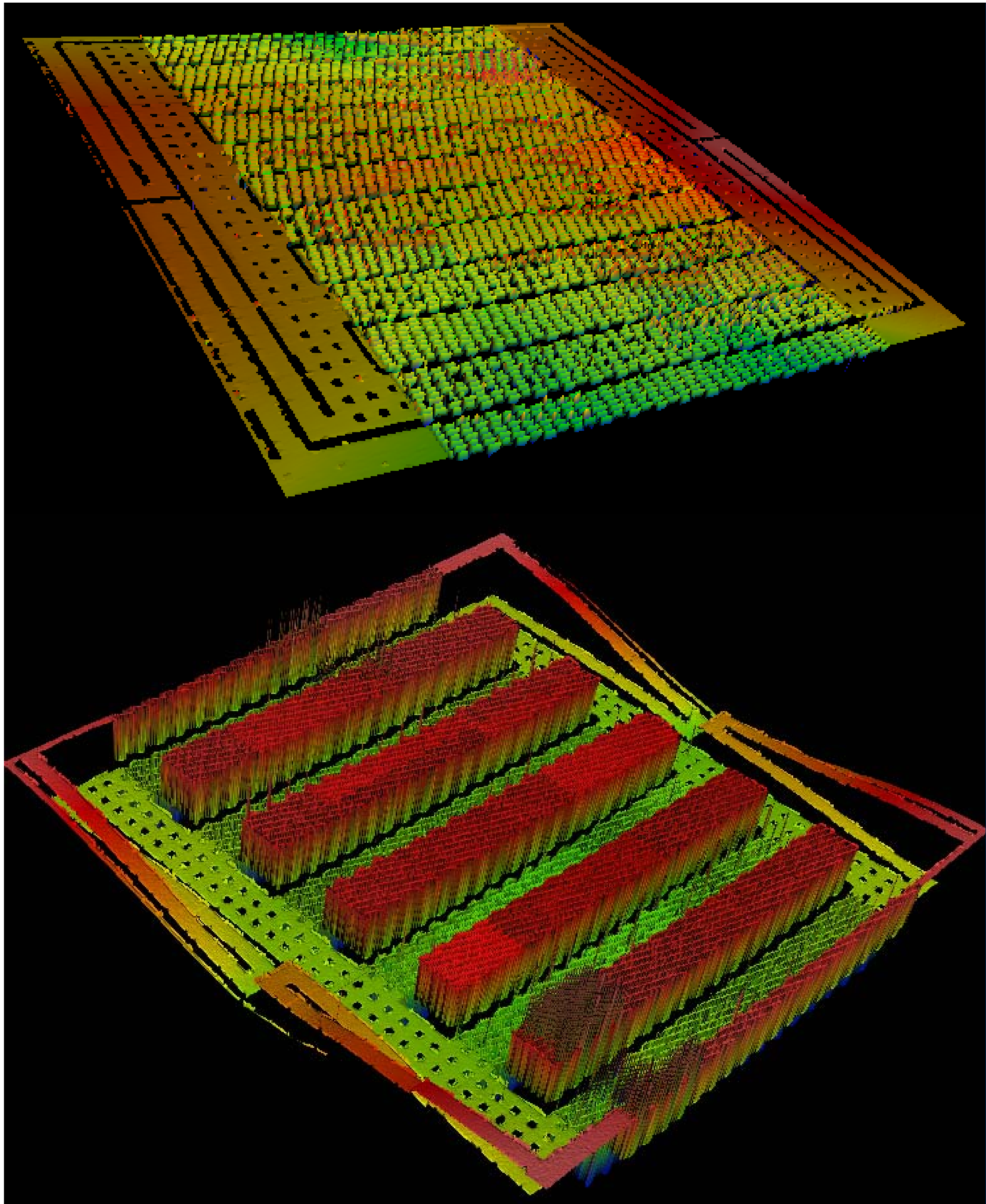


Idle (0V)



Fully actuated (5V)

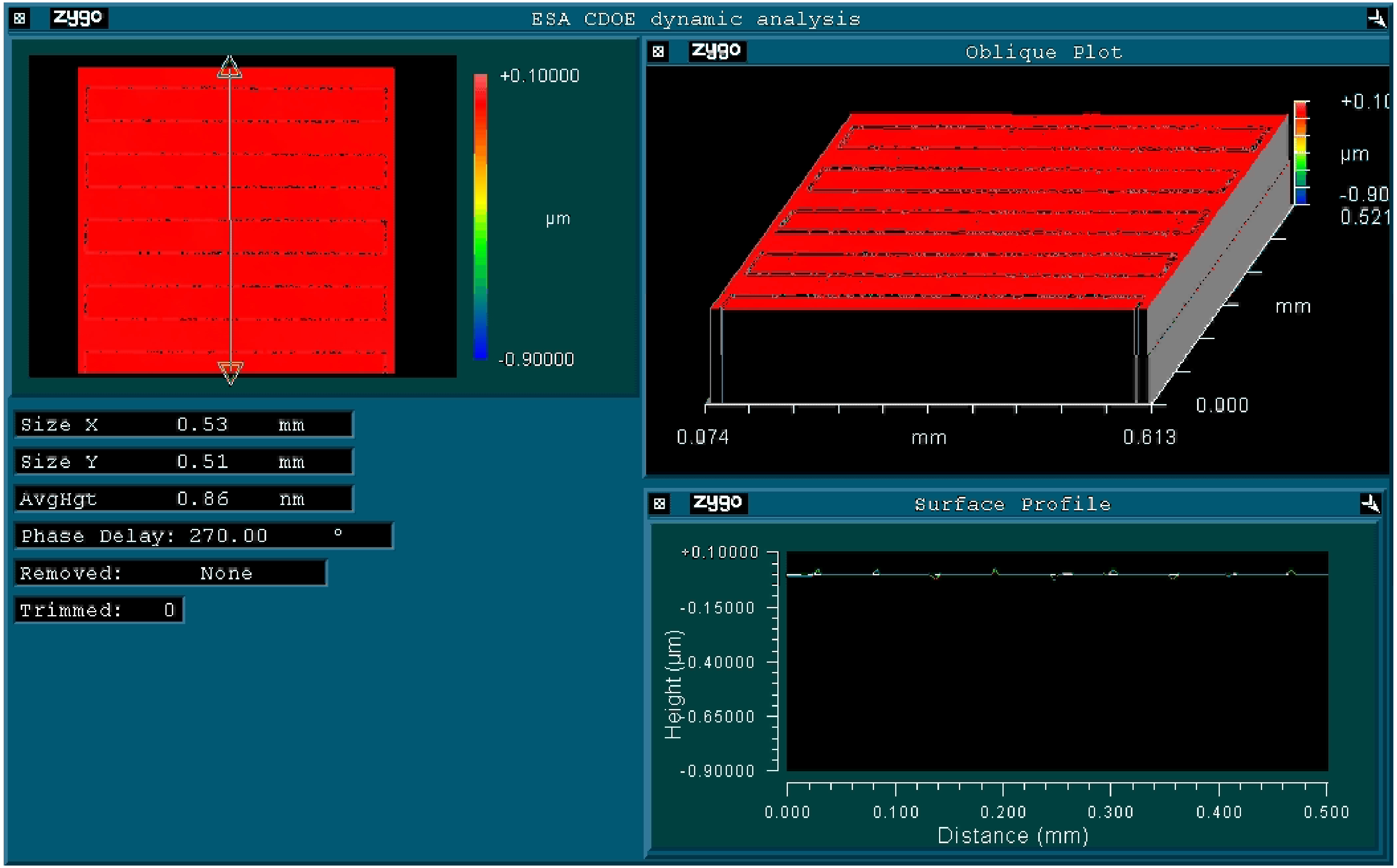
- Bistable operation with snap-down at 4.2V
- Hysteresis due to pull-in effect



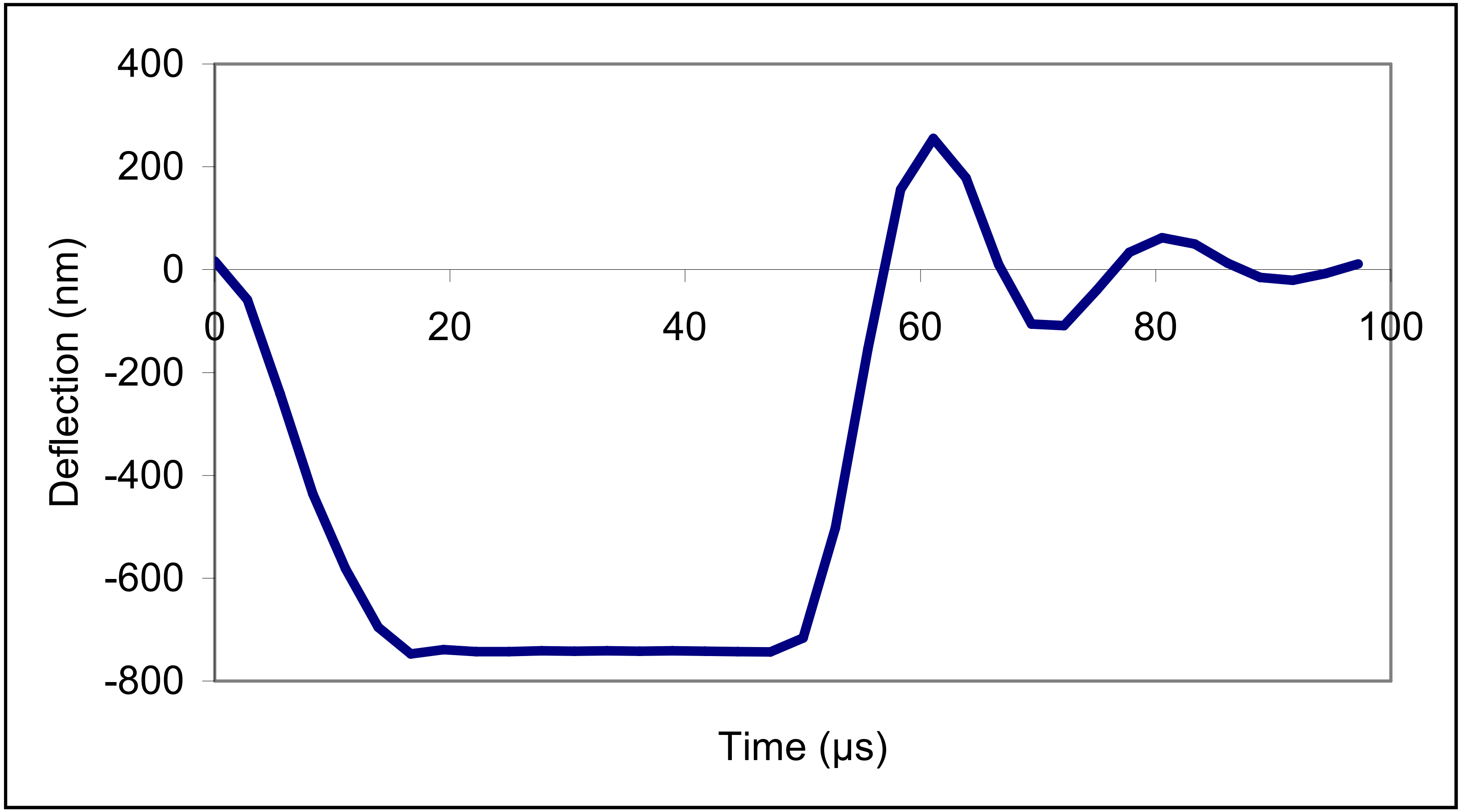
0V

5V

Dynamic actuation

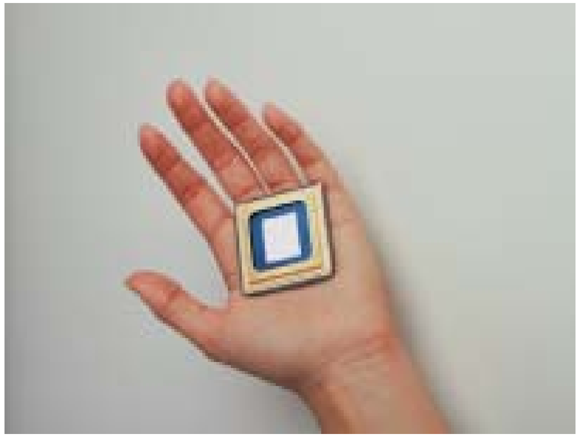


Dynamic actuation (10kHz square wave)



Electrostatically actuated mirror-array

- Array of micro mirrors (e.g. 1280x1024 SXGA)
- Produced by Texas Instruments



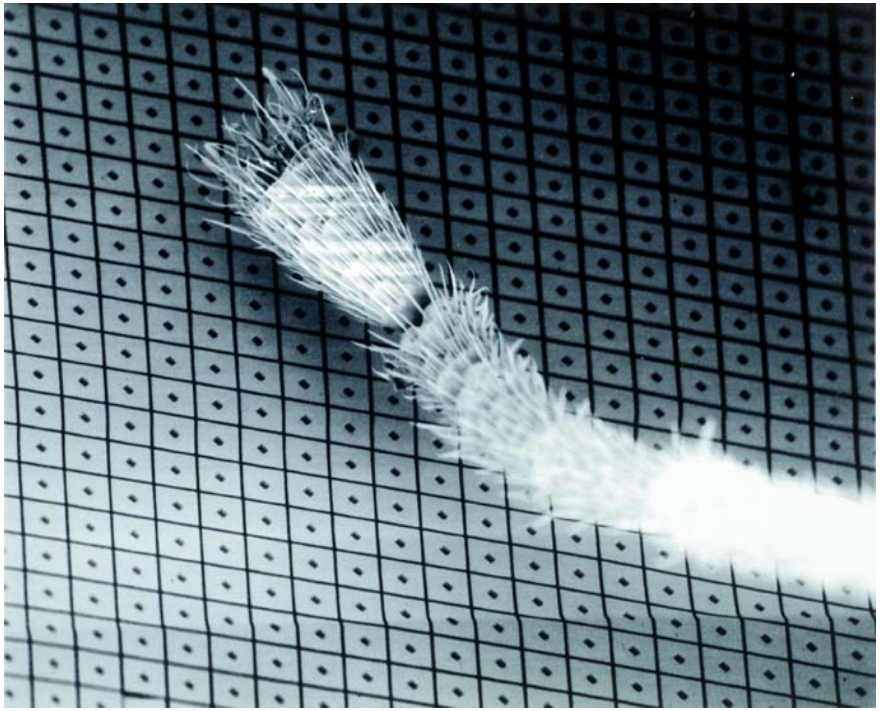
- “Digital Micro mirror Device”
- “Digital Light Processing”

- Used in projectors, TVs, movie theaters
- Digital images

DLP
A TEXAS INSTRUMENTS TECHNOLOGY

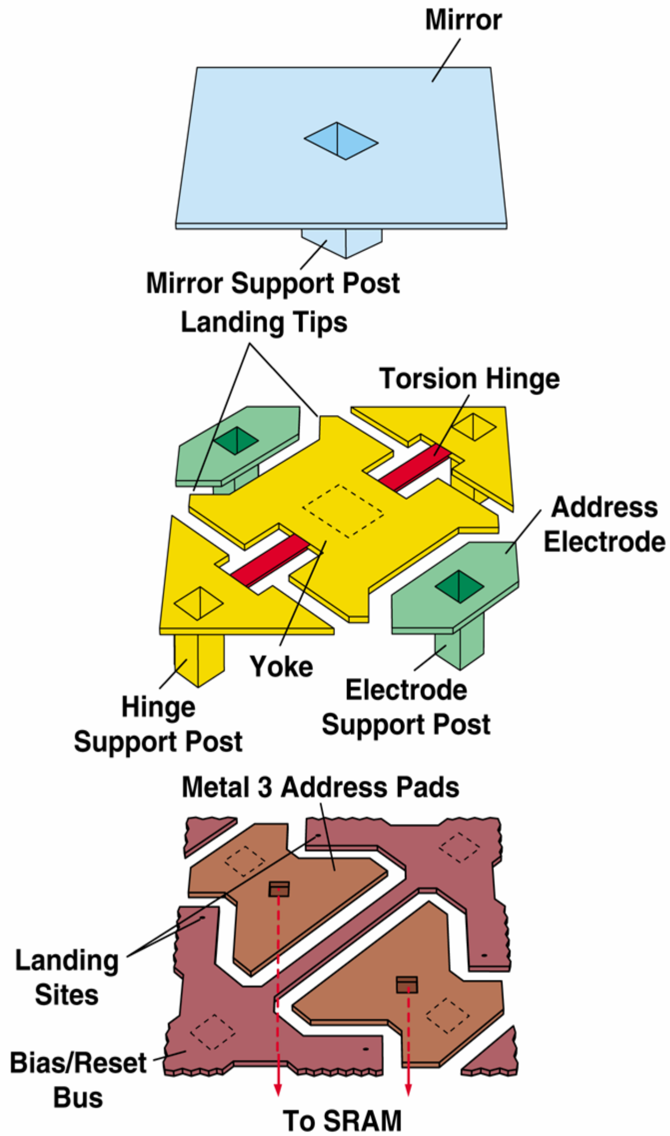
Dimensions of micro mirror array

- Size of mirror: 16μmx16μm, 14μmx14μm, smaller and smaller
- Gap between mirrors 1 μm
- Switch more than 50000 times pr second
- Vacuum packed



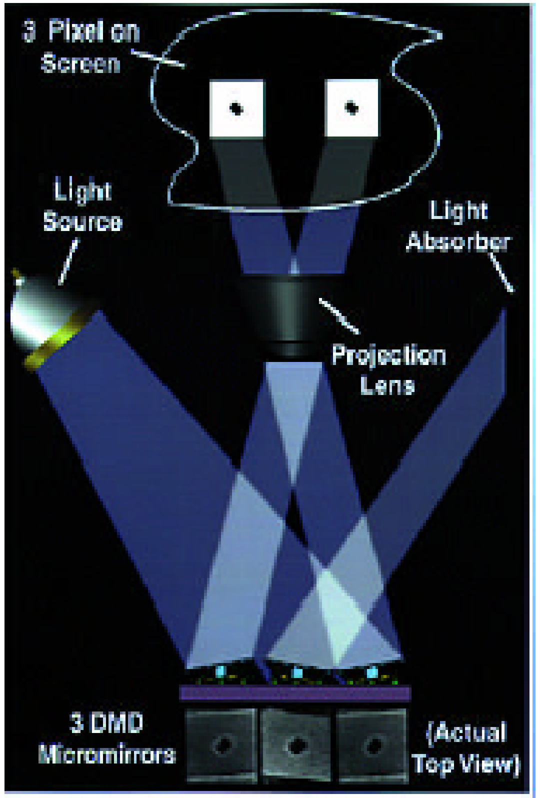
Mirror tilting

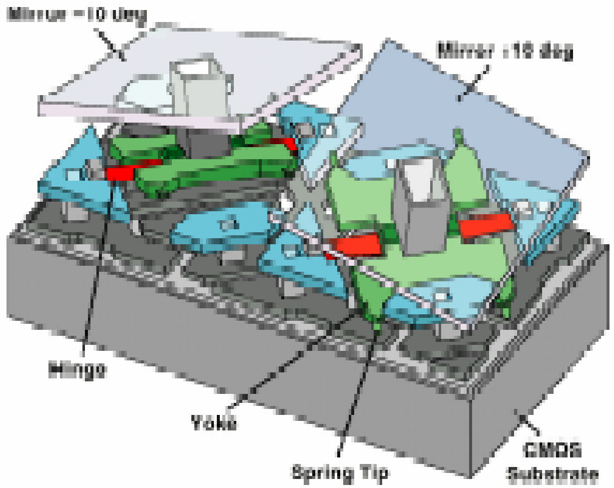
- Mirror made in reflective aluminium
- Mirror sits on top of Yoke
- Yoke can tilt, supported by torsion hinges
- Yoke can be attracted to left or right electrode by electrostatic forces
- Every electrode for every mirror at the silicon surface can be accessed separately
- The voltage between mirror and electrode is large enough to cause pull-in
- Yoke is mechanically stopped by landing tips (no electric contact)

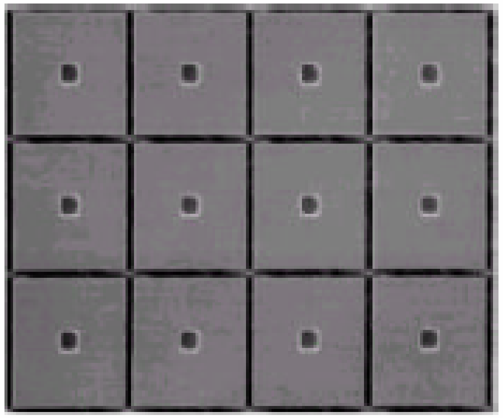


Principle of Image Projection

Electrostatic On-Off Control of Mirror Array



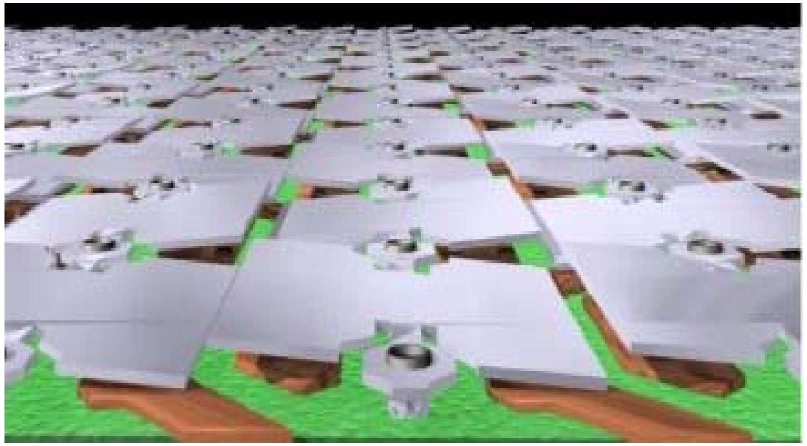


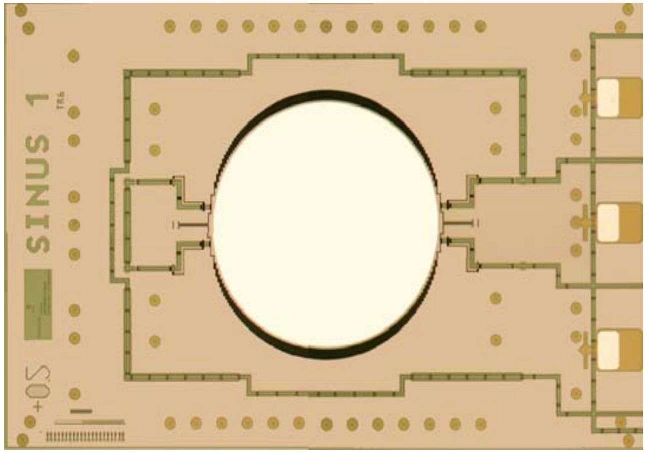


Hiroshi Toshiyoshi Hiroshi@ee.ucla.edu

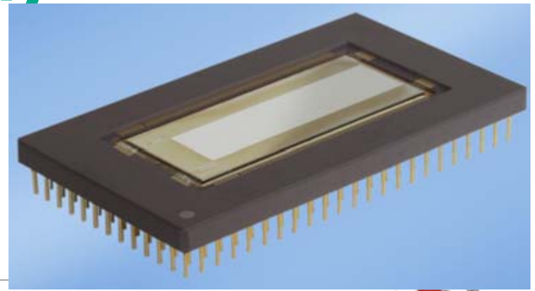
Innhold

- FoU ved Fraunhofer Institut für Photonische Microsysteme (IPMS)
- Mikrospeilmatriser med opptil 1 million adresserbare speil
- Store mikroskannerspeil opptil 3mm i diameter

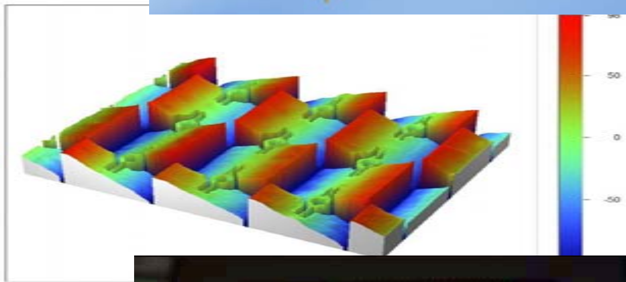




Spatial Light Modulators (SLM)

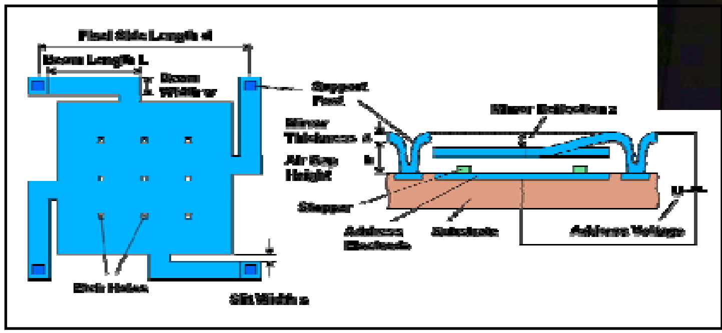


- **Micro Mirror Arrays as programmable mask**
  - Microlithography
  - PCB Printing
  - Mask Inspection
  - Structured Illumination

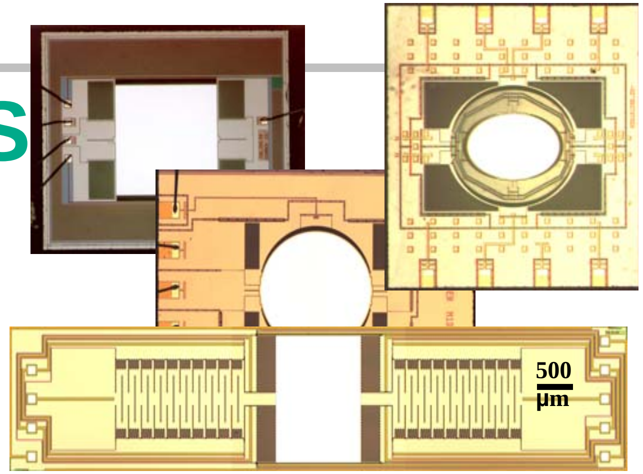


- **Micro Mirror Arrays as Wave Front Corrector**
  - Adaptive Optics
  - Ophthalmology
  - Microscopy
  - Astronomy
  - Laser Pulse Shaping

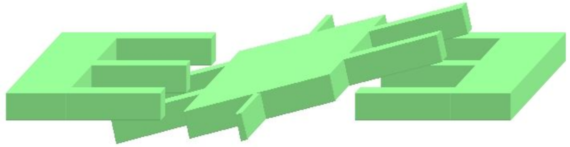
- **Technical Parameters**
  - 16 µm pitch
  - 2048 x 512 pixel
  - 2 kHz frame rate



Micro Scanner Devices (MS



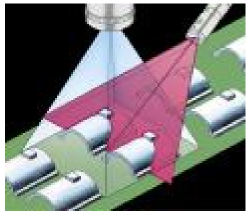
- **Technical Parameters**
  - 1D and 2D, rotational
  - Translational
  - Frequencies: 0.2 kHz … 35 kHz
  - Mirror diameter: 0.5 mm … 3.0 mm
  - Deflection angle: up to +/- 34°
    (136° optical scan range)
  - Mirror flatness: better than $\lambda/10$



- **Applications**
  - Bar Code Reading
  - Laser Projection
  - Endoscopes
  - Pattern generation (Laser printers, Direct writing, Laser marking, Direct Prototyping)
  - Metrology (Grating spectrometer, LIDAR, Triangulation, Confocal Microscopy)

www.spiegel.de

www.microvision.com



www.sukhamburg.de

www.intermec.com

Fraunhofer

IPMS
Fraunhofer Institut Photonische Mikrosysteme

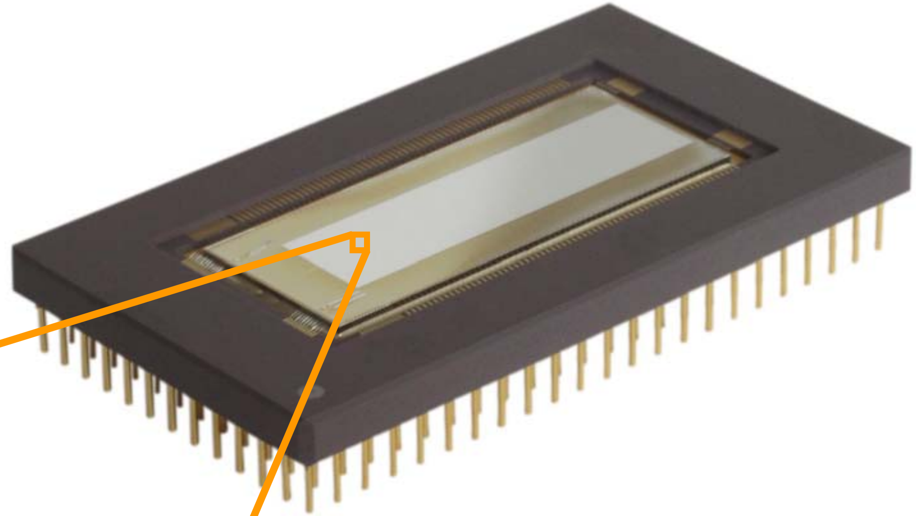
Thor Bakke

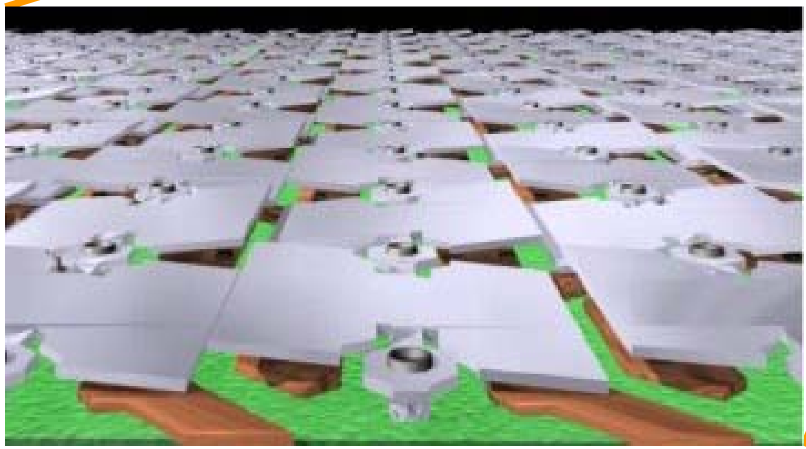
The Fraunhofer Megapixel SLM

- Image generating device in the Sigma 7500 photo-lithographic mask writer

MICRONIC LASER SYSTEMS

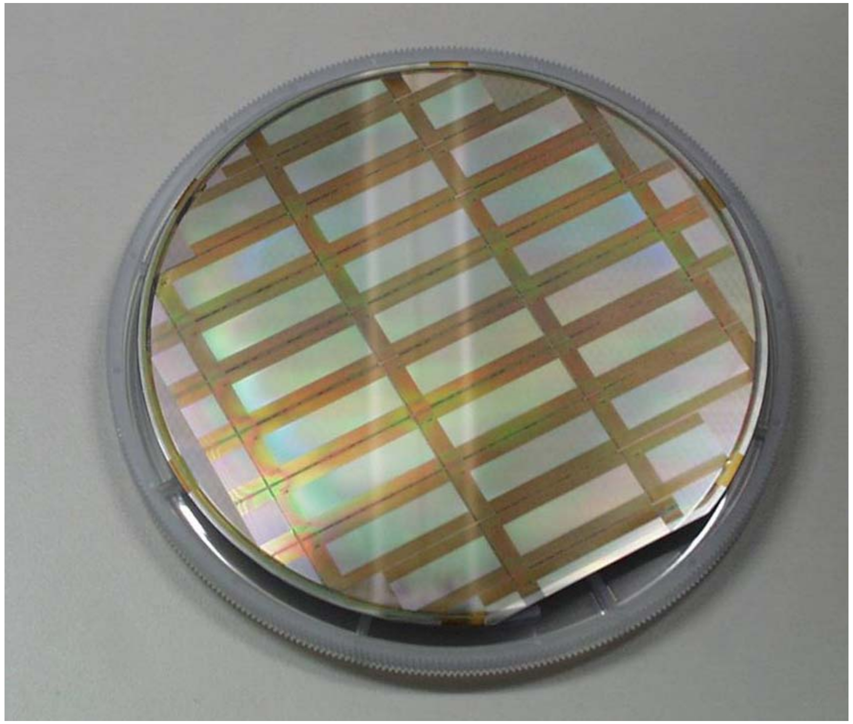
IPMS
Fraunhofer Institut Photonische Mikrosysteme



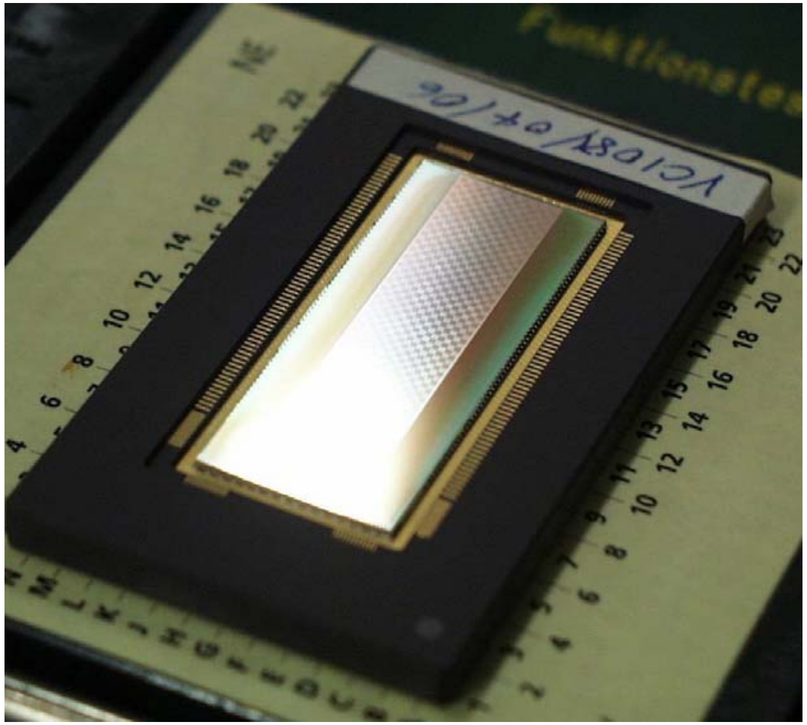


- 512 x 2048 tilt mirrors
  - Monolithically integrated on 35V CMOS circuit
  - individually addressable
- 16µm mirror pitch
- 2kHz frame rate
- 64 gray levels

The Fraunhofer IPMS 1MegaPixel SLM



Wafer with SLM's
(16 per 6 inch wafer)

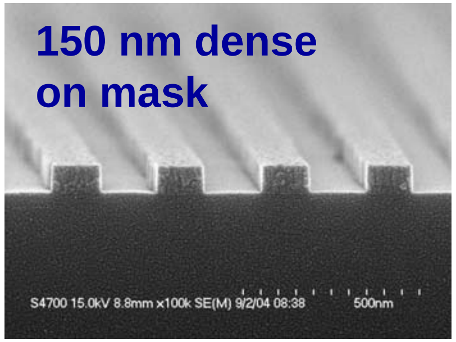


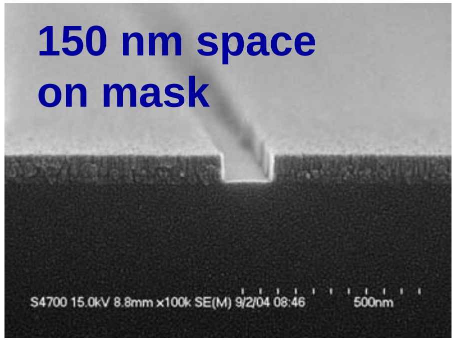
Addressed SLM
Chequerboard

Sigma 7500 Maskwriter

Unique <u>SLM-based</u> mask writer

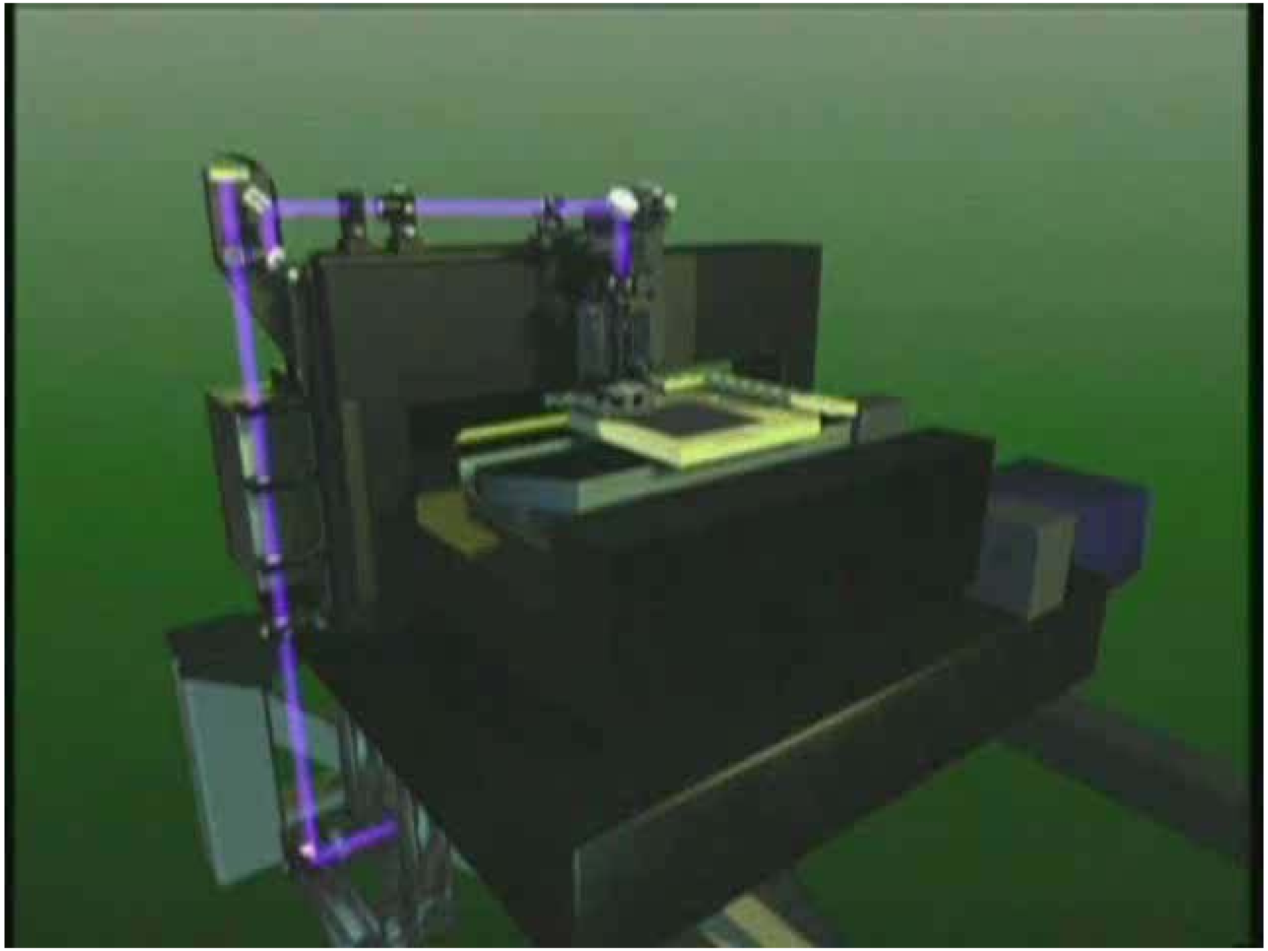
- Quick turn-around and cost-effective production of 65 nm and 45 nm node reticles
- Binary and phase shift masks
- Minimum main feature
  - 220nm
- Address grid
  - 1.25nm
- CD uniformity
  - Global (3σ) <5.5 nm
- Registration
  - Global (3σ) <12 nm
- Write time: <3 hours (6” mask)





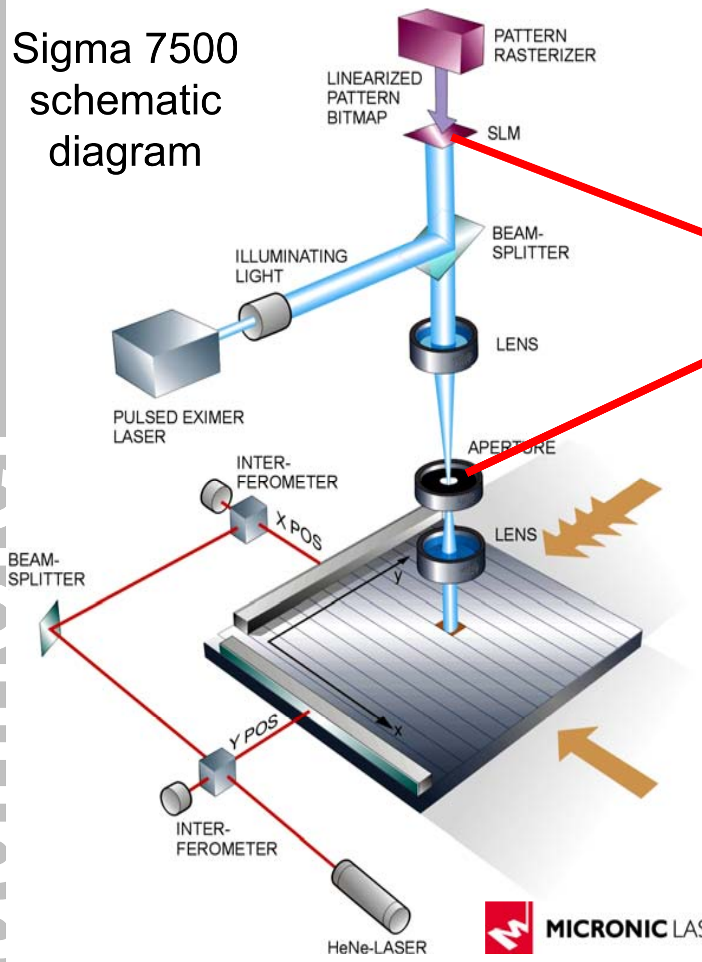
MICRONIC LASER SYSTEMS

Sigma 7500 Maskwriter (cont.)



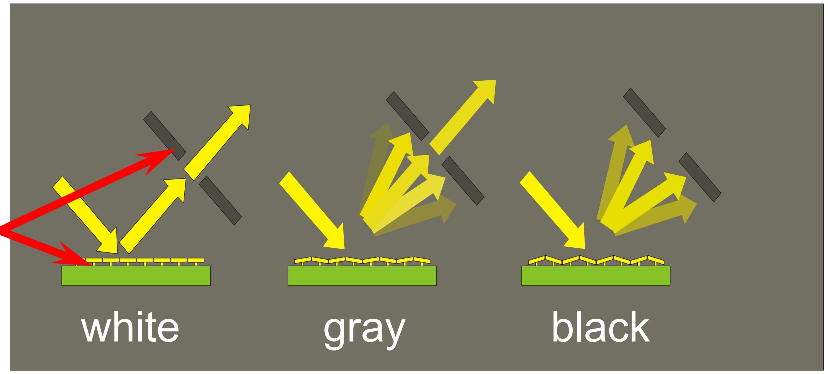
SLM: Principle of Operation

Sigma 7500 schematic diagram

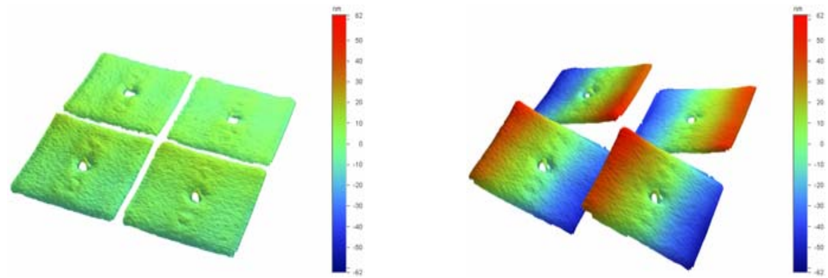


MICRONIC LASER SYSTEMS

- **operation wavelegth 248nm**



Diffraction and spatial filtering



- white pixel
- black pixel for deflection = $\lambda/4$ (62 nm)
- **true gray levels for 0 < deflection < $\lambda/4$**

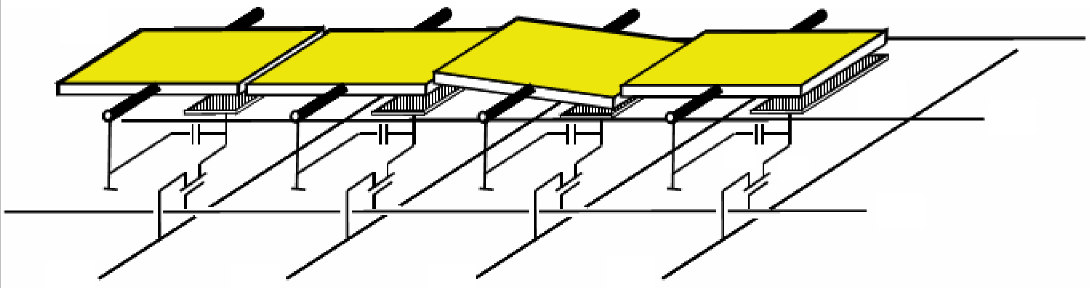
Fraunhofer

TÜV CERT DIN EN ISO 9001 Zertifikat: 09 100 5263

Fraunhofer IPMS Institut Photonische Mikrosysteme

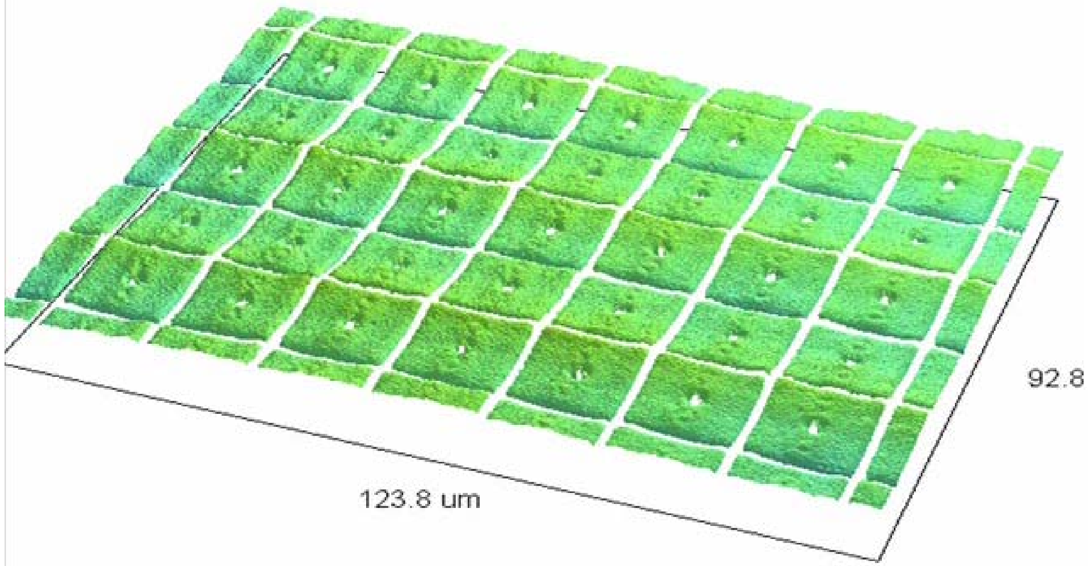
Thor Bakke

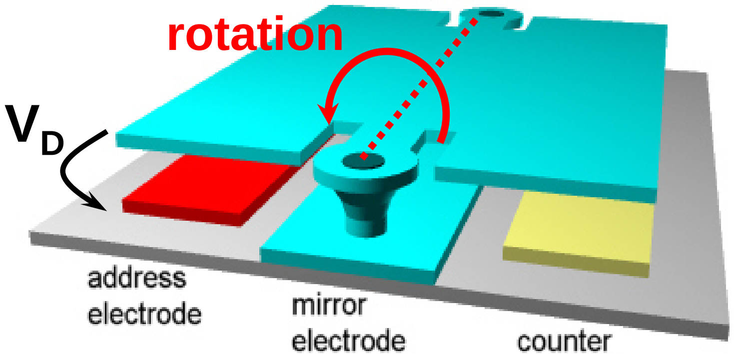
SLM: Principle of Operation (cont.)



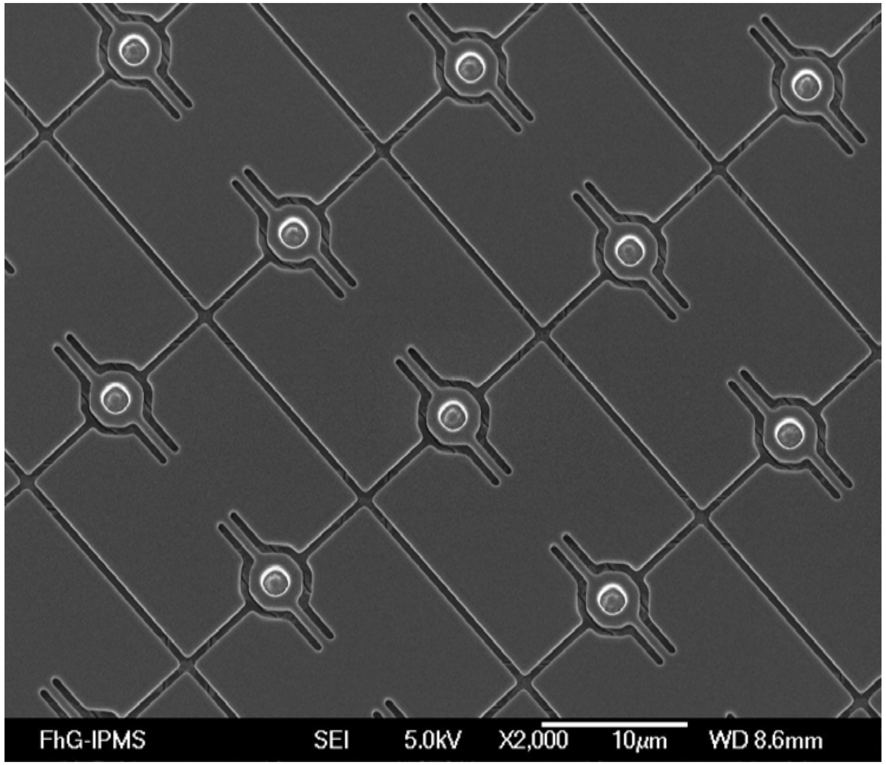
Matrix addressing of analog array

- Matrix-addressed CMOS circuit stores an analog voltage for each mirror





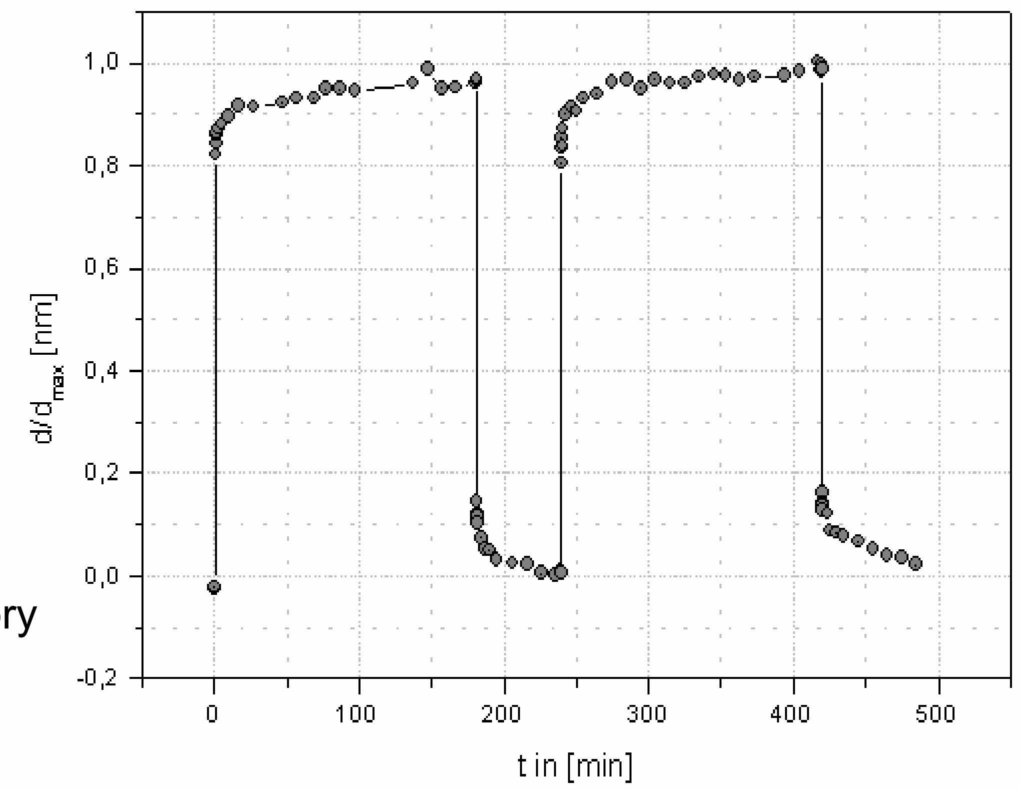
Current Technology 1-Level Mirrors



- Mechanical element (spring) and optical element (mirror) are formed by one layer
  - Selection of the mirror material is a compromise between optical properties (reflectance) and mechanical properties (elasticity)
- Limited optical fill factor (~75%)
- CMOS compatible process

Current Technology 1-Level Mirrors

- The current 1-level mirrors are made of an aluminium alloy:
  - Reflectance @ 248nm ~80%
  - Polycrystalline Structure
  - Mechanical creep due to grain boundary sliding
- Problem: drift of deflection
  - Pattern dependent memory effect
  - Elaborate calibration procedure was implemented for high performance operation in the Sigma 7500 system



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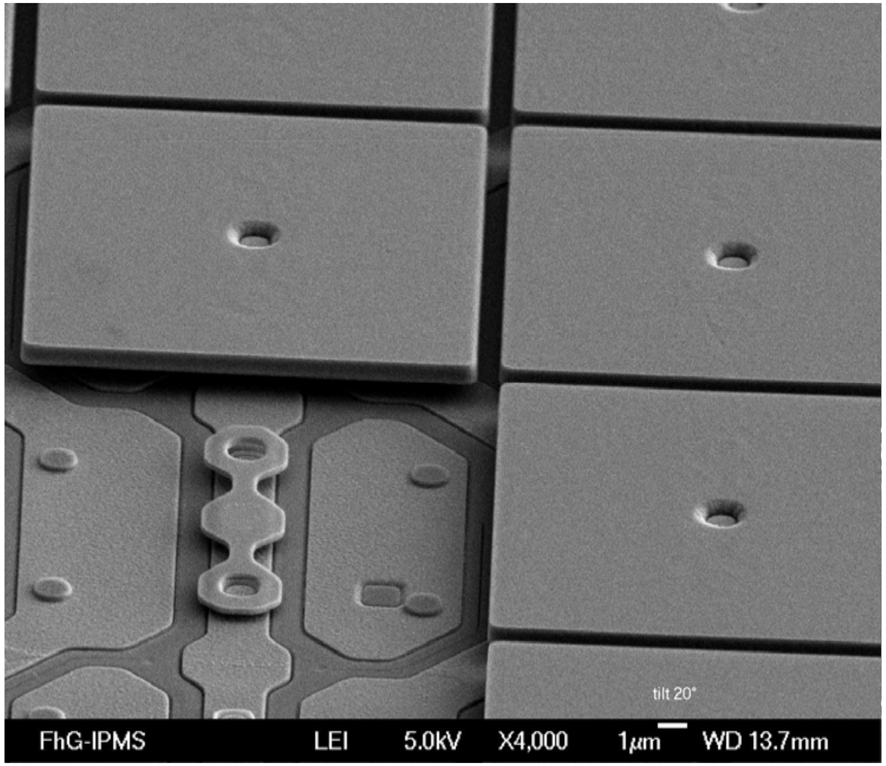
Thor Bakke

New 2-Level Mirrors

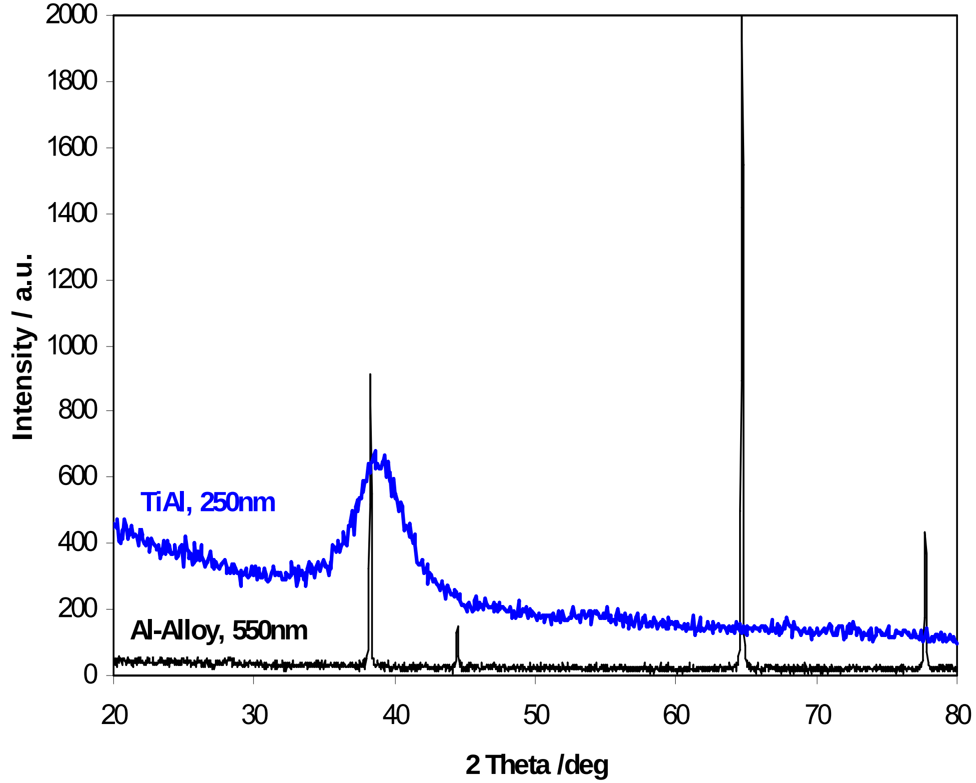


- Higher optical fill factor (~95%)
  - Spring is hidden under the mirror plate
- More degrees of freedom in actuator design
  - Thin and soft spring for operation at low voltage
  - Thick and stiff mirror plate gives low deformation
- Different materials for mirror and spring gives optimum optical as well as mechanical properties

M. Friedrichs, et al., IEEE Optical MEMS, Aug. 2006

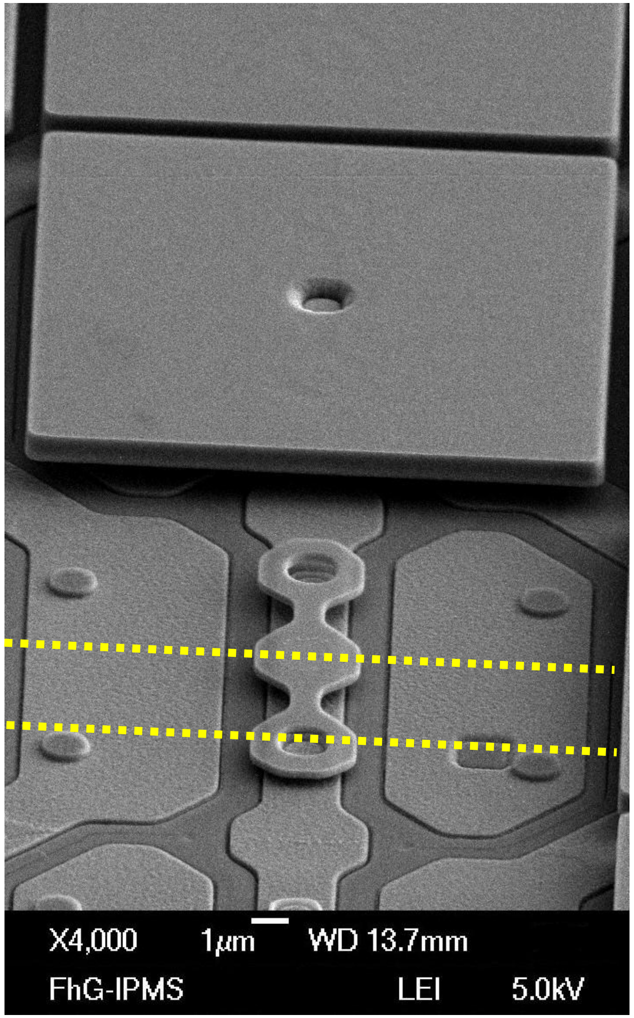
New 2-Level Mirrors with TiAl Springs

- Aluminium alloy for the mirror plate
- TiAl Alloy as spring material
  - Room temperature sputter deposition
  - CMOS compatible
  - Dense Film
  - High melting point (1460°C)
  - Amorphous Structure
  - No grain boundary sliding
  - Highly elastic

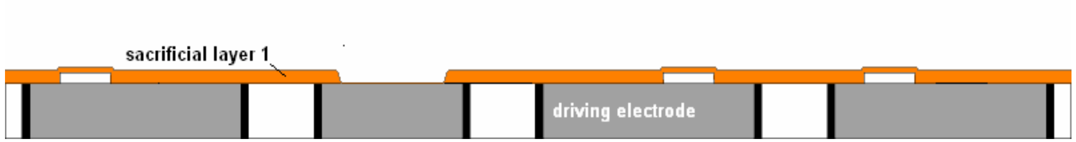


M. Friedrichs, et al., IEEE Optical MEMS, Aug. 2006

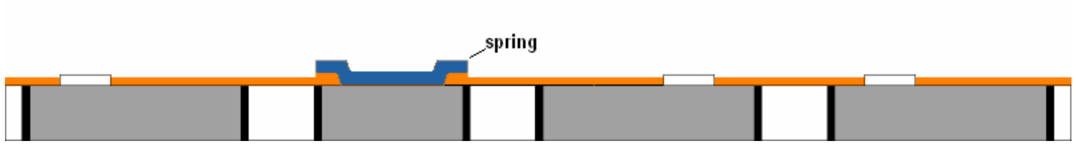
Fabrication



- Spin on first sacrificial polymer and cure
- Structure support holes for springs (O_2 RIE)



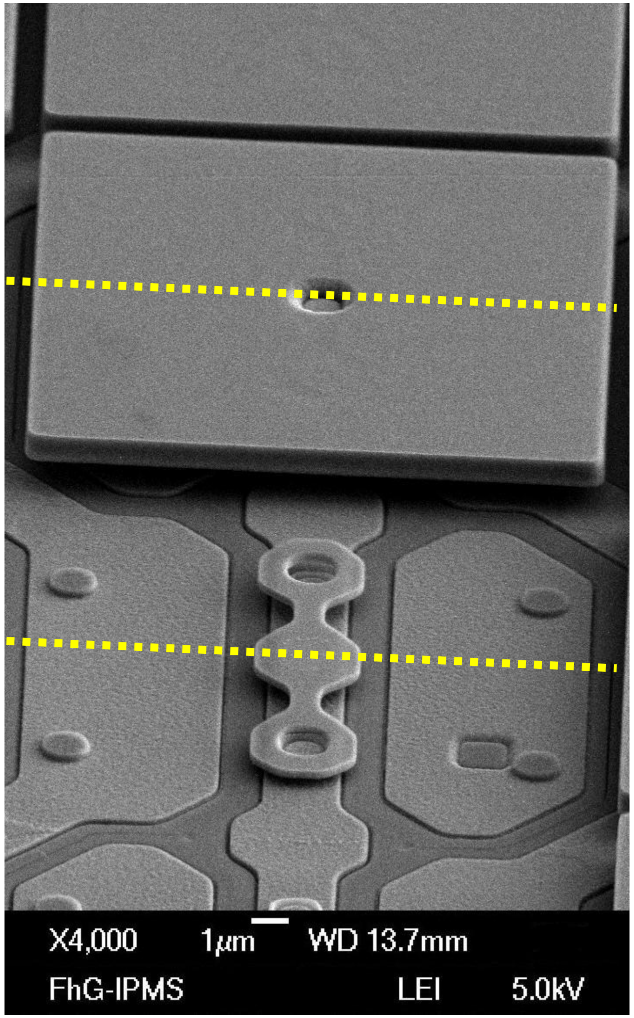
- Sputter deposition TiAl spring alloy
- Structure torsional springs



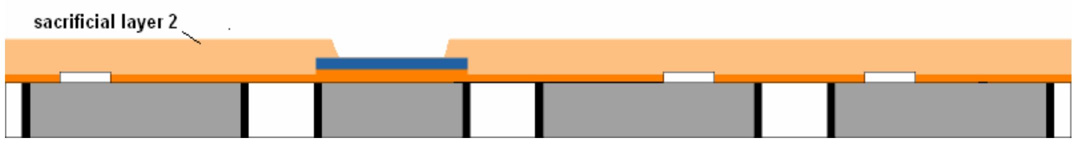
- Spin on second sacrificial polymer and cure

M. Friedrichs, et al., IEEE Optical MEMS, Aug. 2006

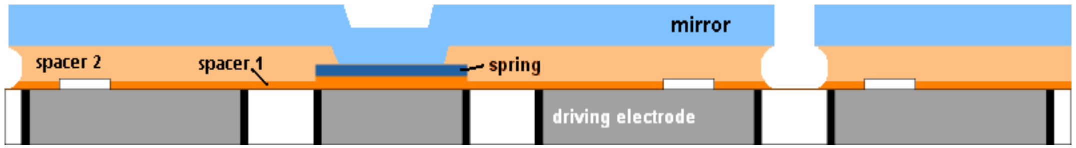
Fabrication



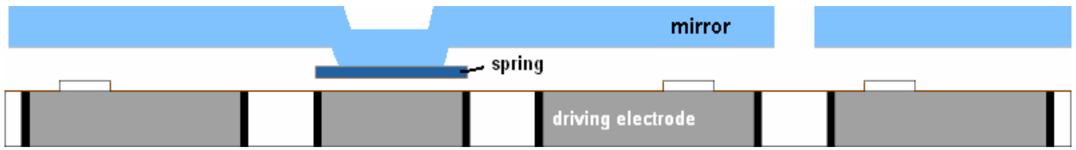
- CMP
- Structure support holes for Mirrors (O_2 RIE)



- Sputter deposition aluminium mirror alloy
- Structure mirror plates

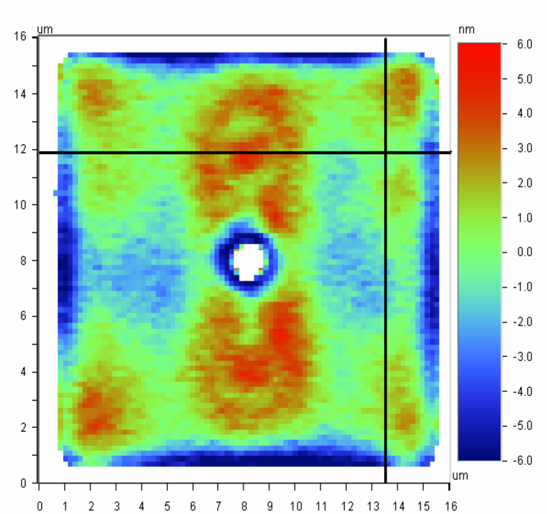


- Etch sacrificial layer (O_2 / CF_4)

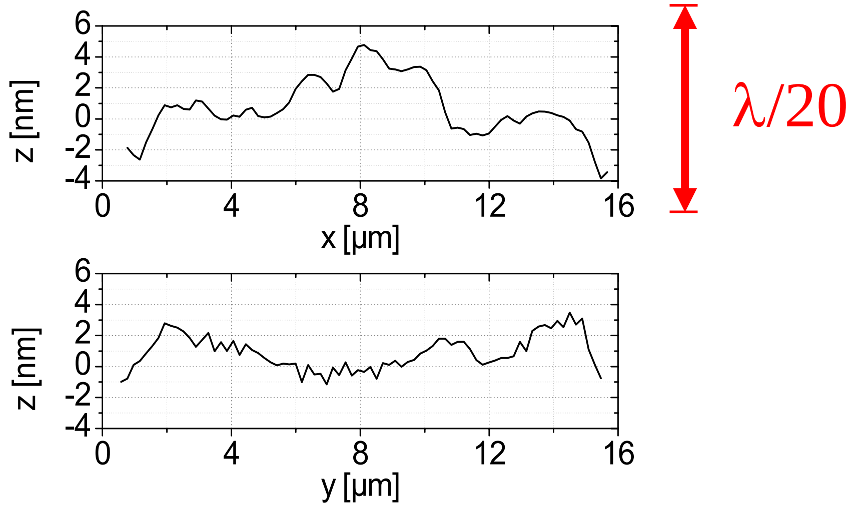


M. Friedrichs, et al., IEEE Optical MEMS, Aug. 2006

Results: Mirror Planarity

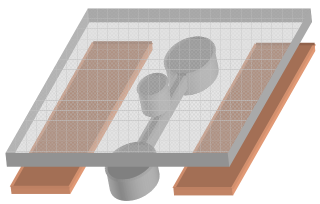


Mirror topography on a λ/20 scale

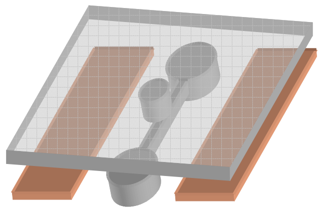


Spring thickness	Mirror RMS Planarity	Planarity spread	Spread of initial deflection
200nm	1.9 nm	0.9 nm	**2.4 nm**
250nm	2.4 nm	1.1 nm	**2.6 nm**

Statistics of two chips with different spring thickness



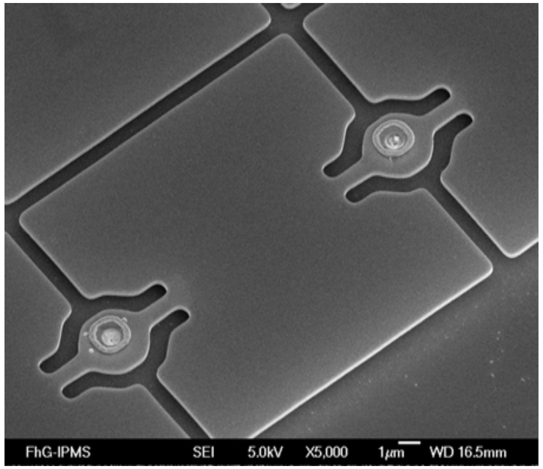
Zero initial deflection



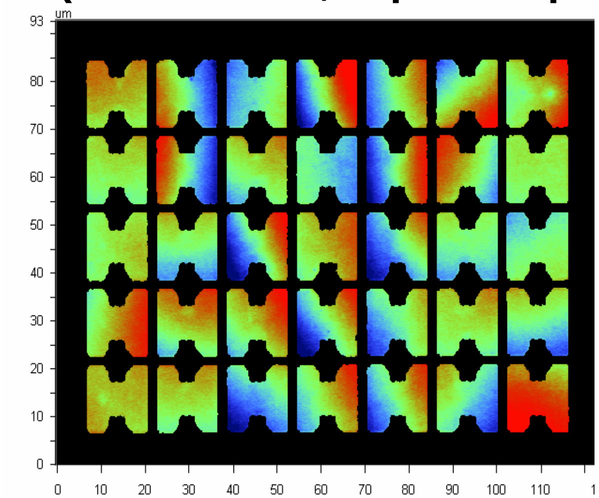
High initial deflection

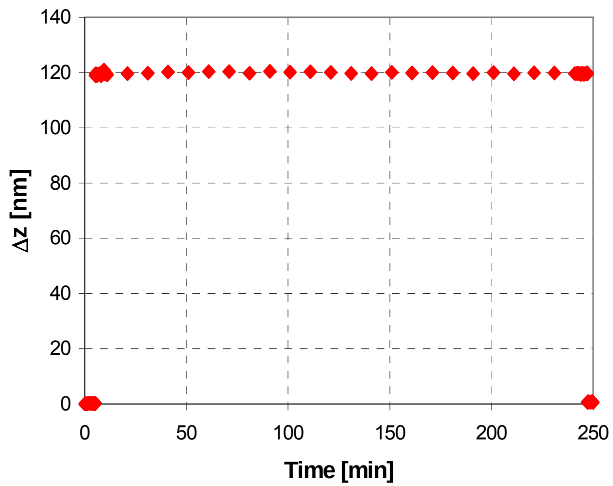
M. Friedrichs, et al., IEEE Optical MEMS, Aug. 2006

Monocrystalline silicon micromirrors



Monocrystalline silicon mirrors
(300nm thick, 16µm x 16µm)





Static deflection 4 hours: Drift free

Parameter	Average (92 mirrors)
RMS mirror planarity (σ_{OOP})	1.27 nm
Peak-to-valley (cosine fit)	0.34 nm

Exceptional planarity

B. Völker et al., MME’05

Thor Bakke

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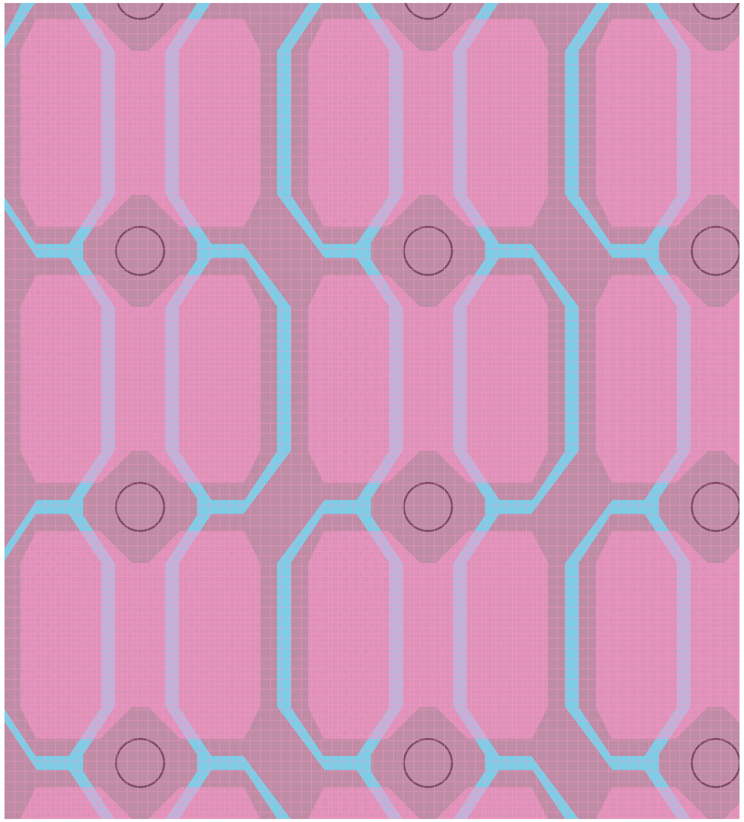
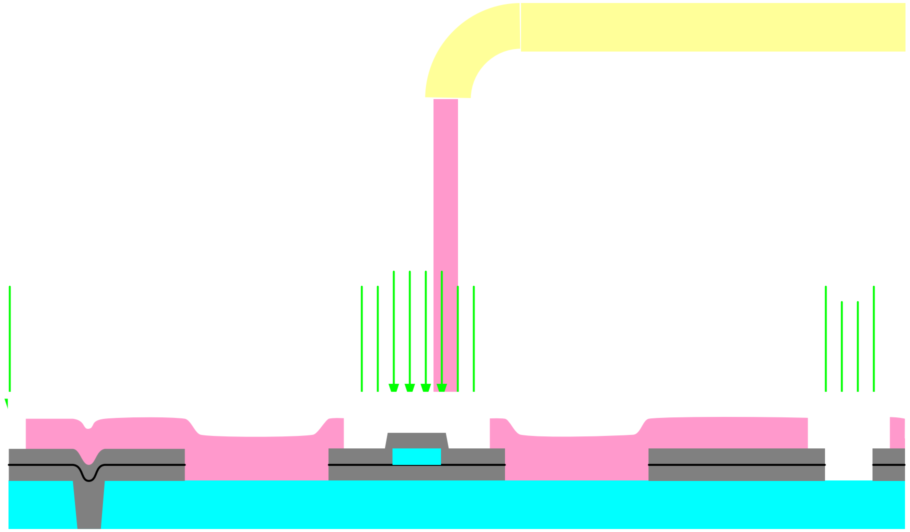
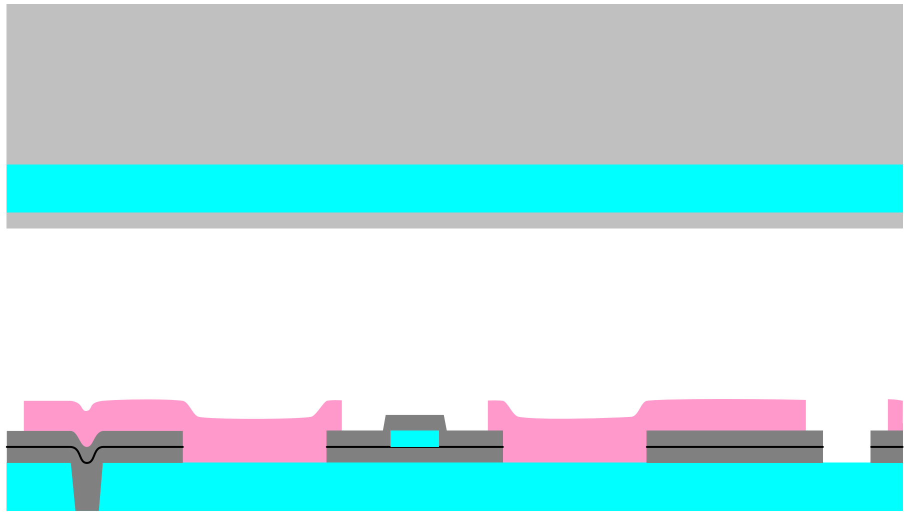
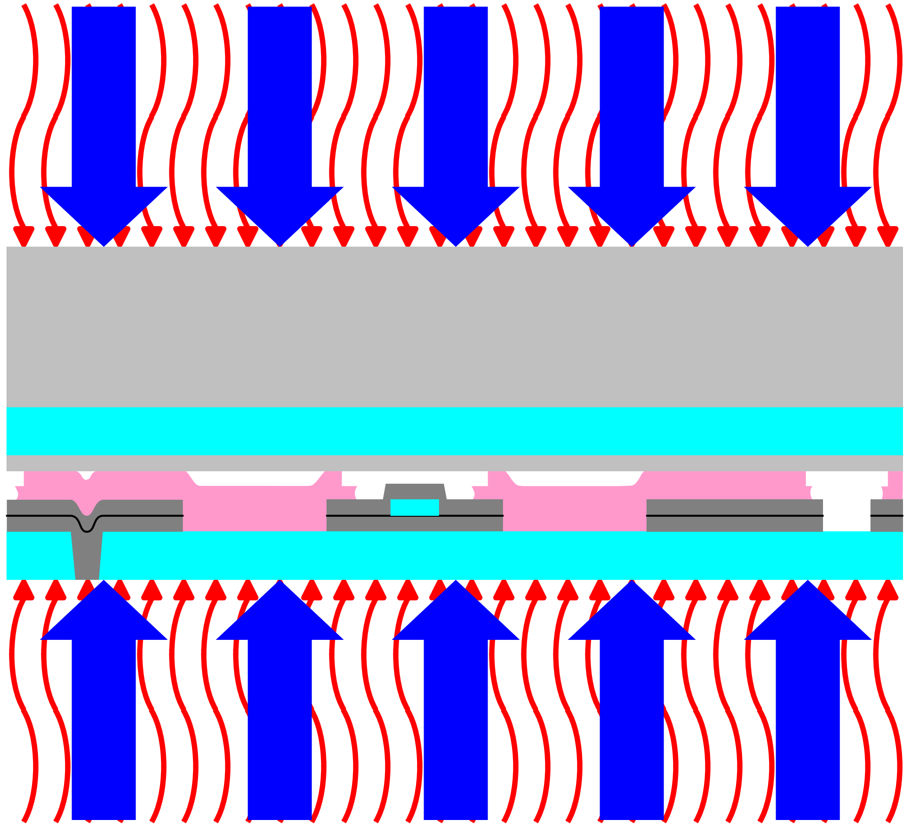
Challenge: Integration of monocrystalline silicon micromirrors and CMOS

- Method: Silicon layer transfer by wafer bonding
- Requirements to the bonding process:
  - Low temperature (<450°C)
  - Sufficient bonding strength to allow substrate removal and post processing of the MEMS structures
  - Bonded layer should be thermally stable up to ~200°C
  - High dimensional control of bond layers (i.e. gap thickness)
  - Fully compatible with a CMOS manufacturing environment
- Chosen solutions:
  - Adhesive bonding with a reflowable polymer
  - Low temperature direct bonding to polished SiO_2 (PECVD-TEOS)









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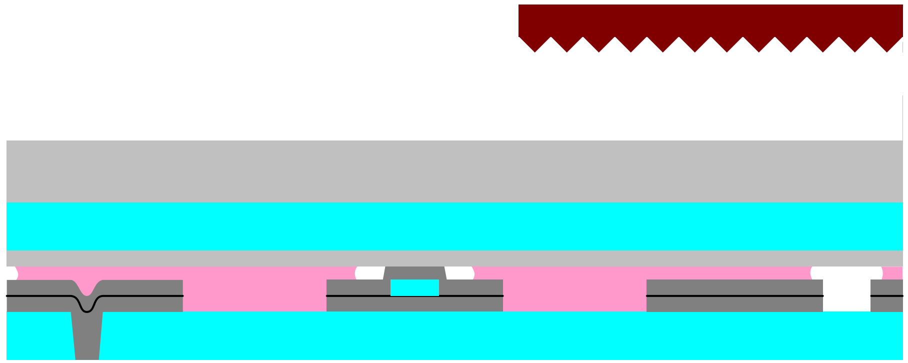

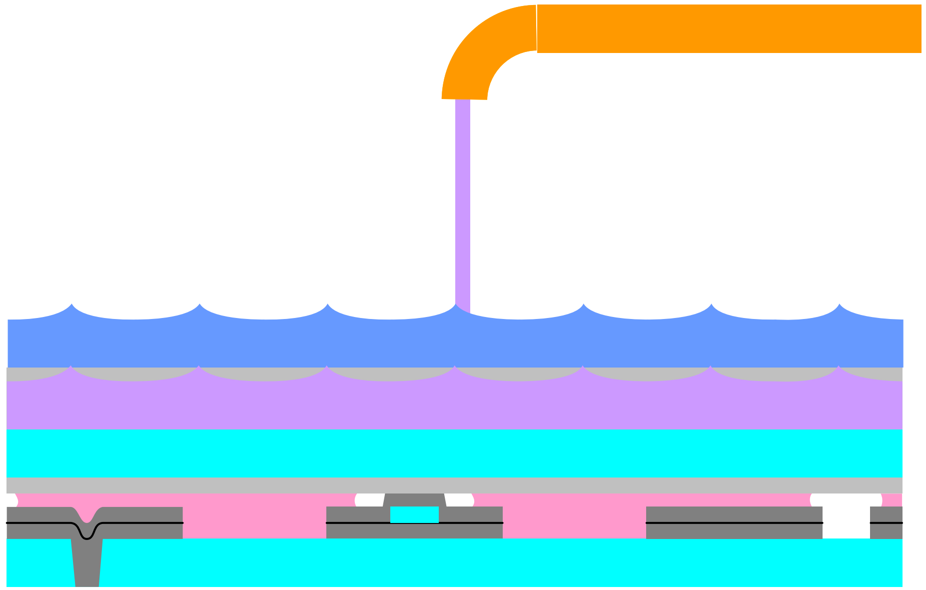

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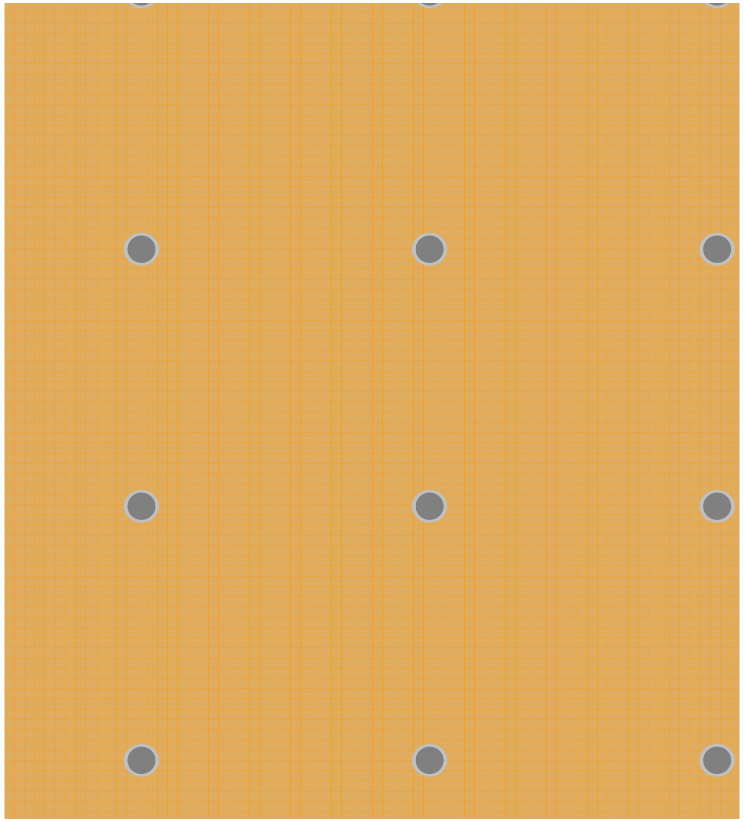
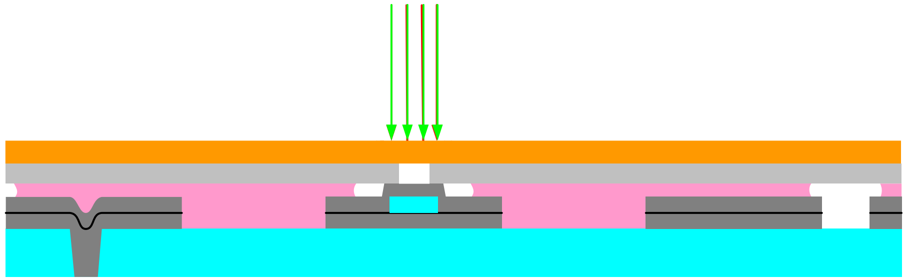
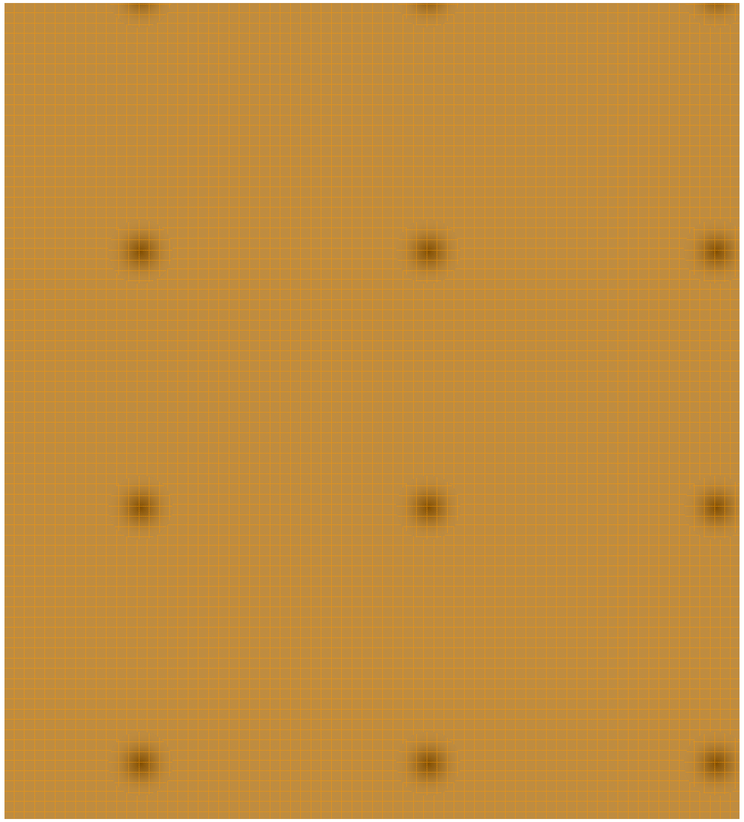
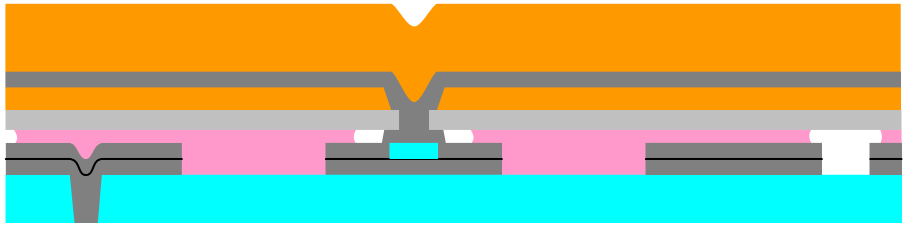
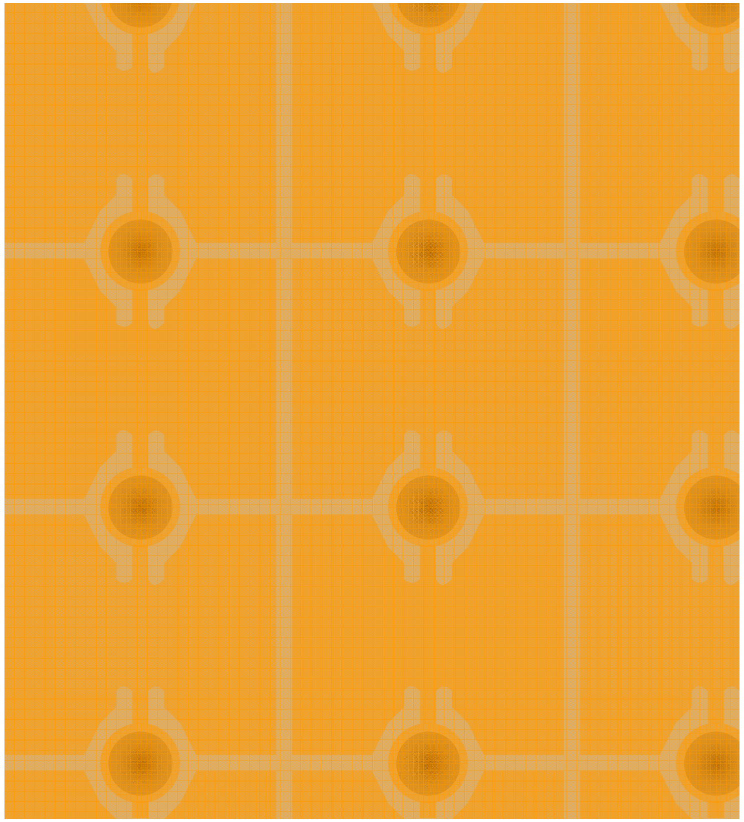
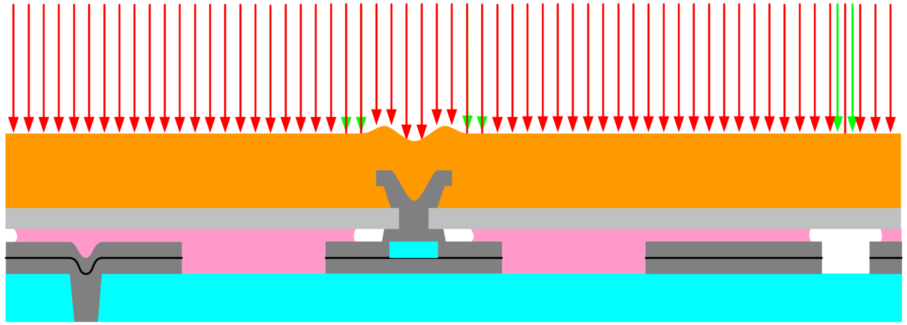


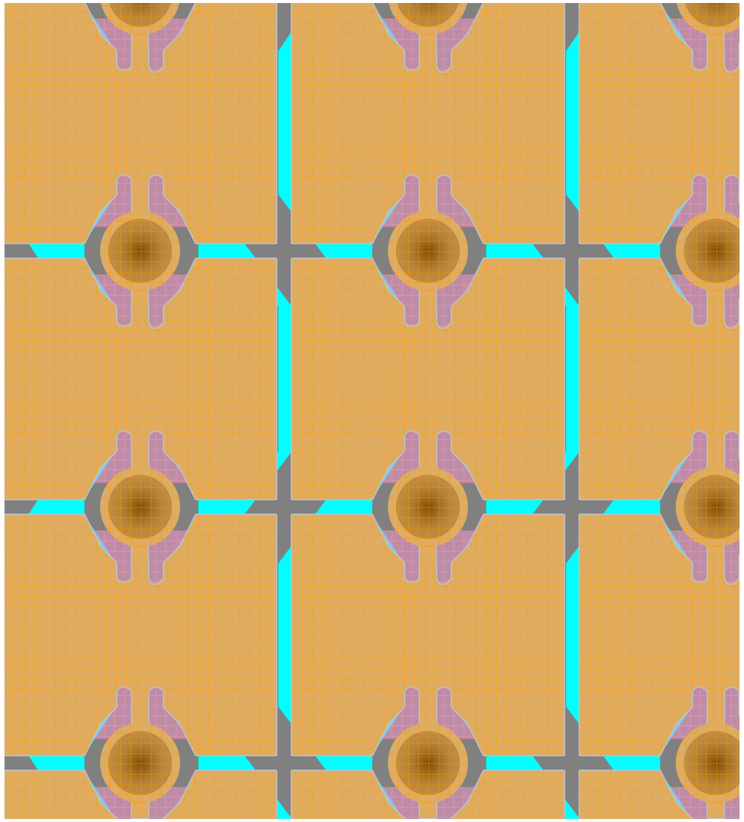


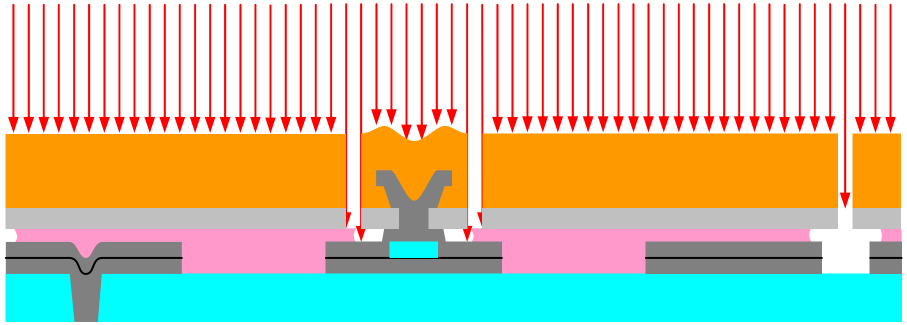




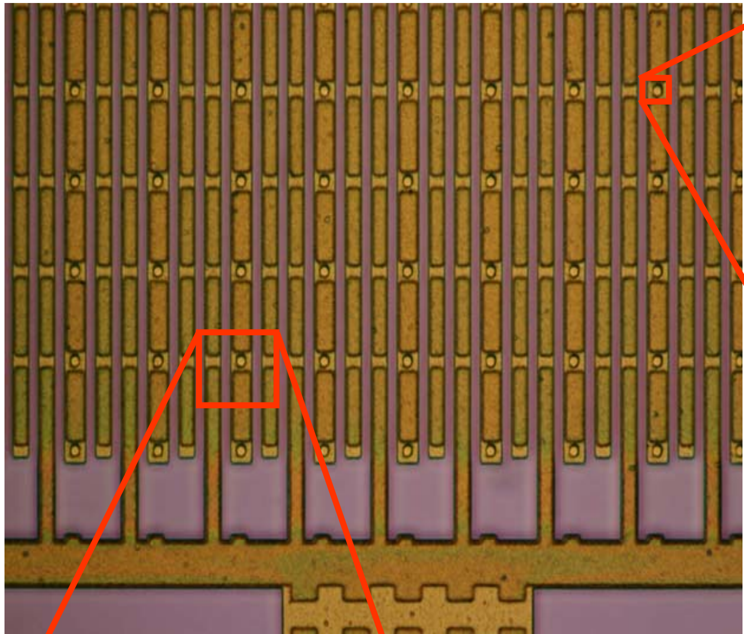


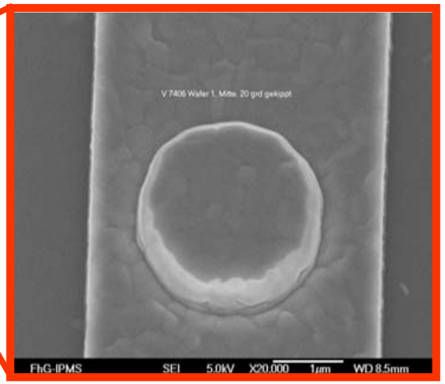






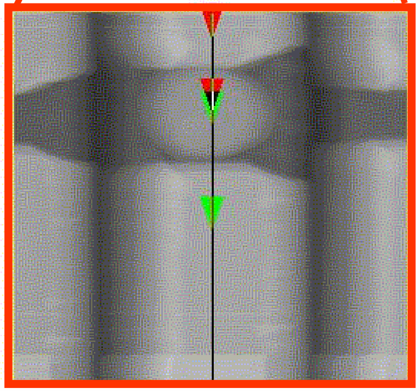
Structured bonding layer

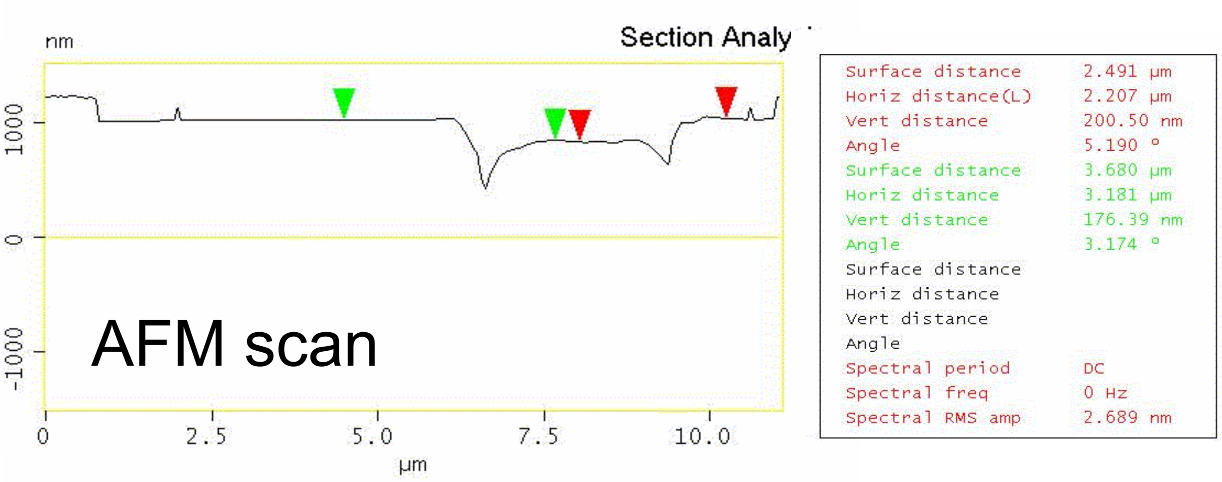




- Adhesive removed on top of mirror posts
- 150-200nm thicker PMGI than mirror posts

- Structuring the bond layer ensures accurate electrode/mirror spacing





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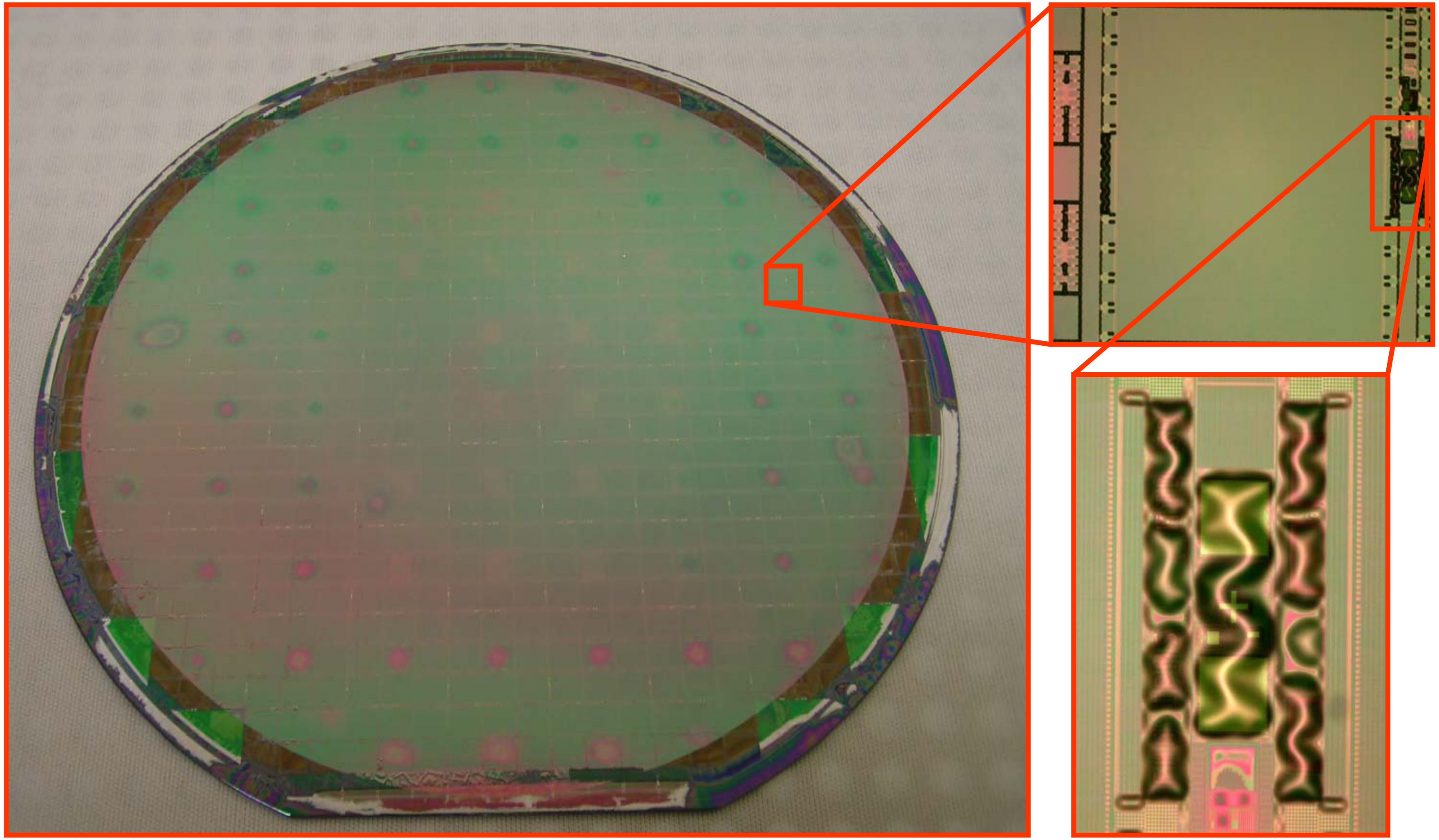
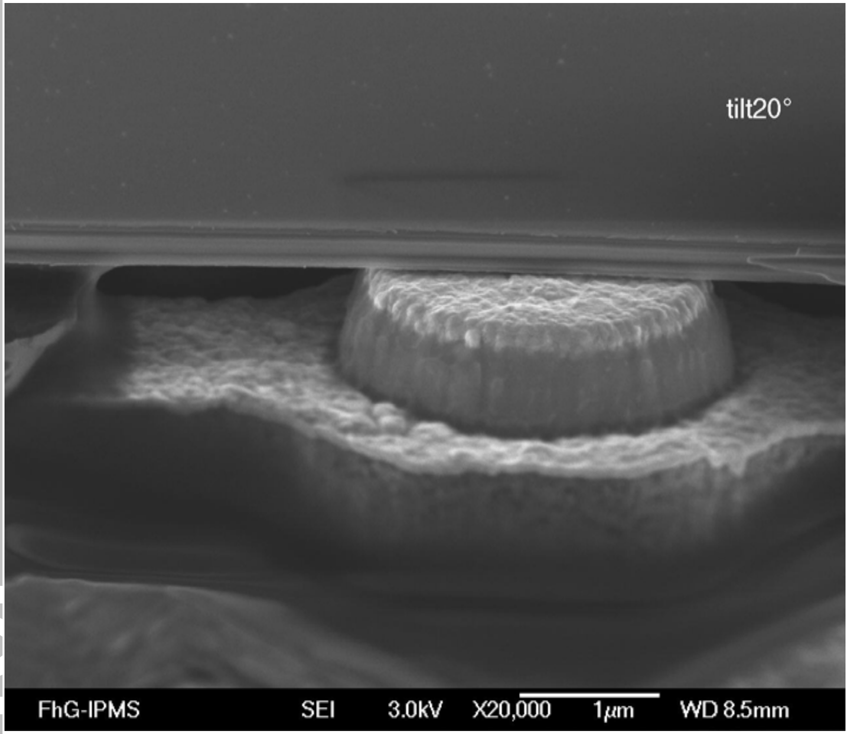
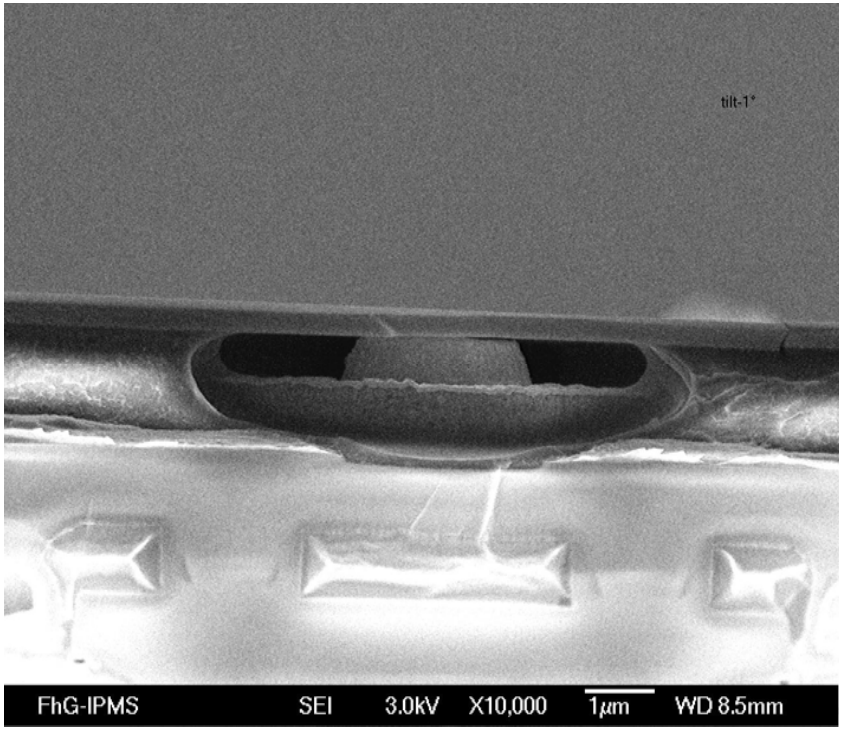
Layer transfer



- 260nm thick silicon layer transferred to a 6“ substrate (with oxide)

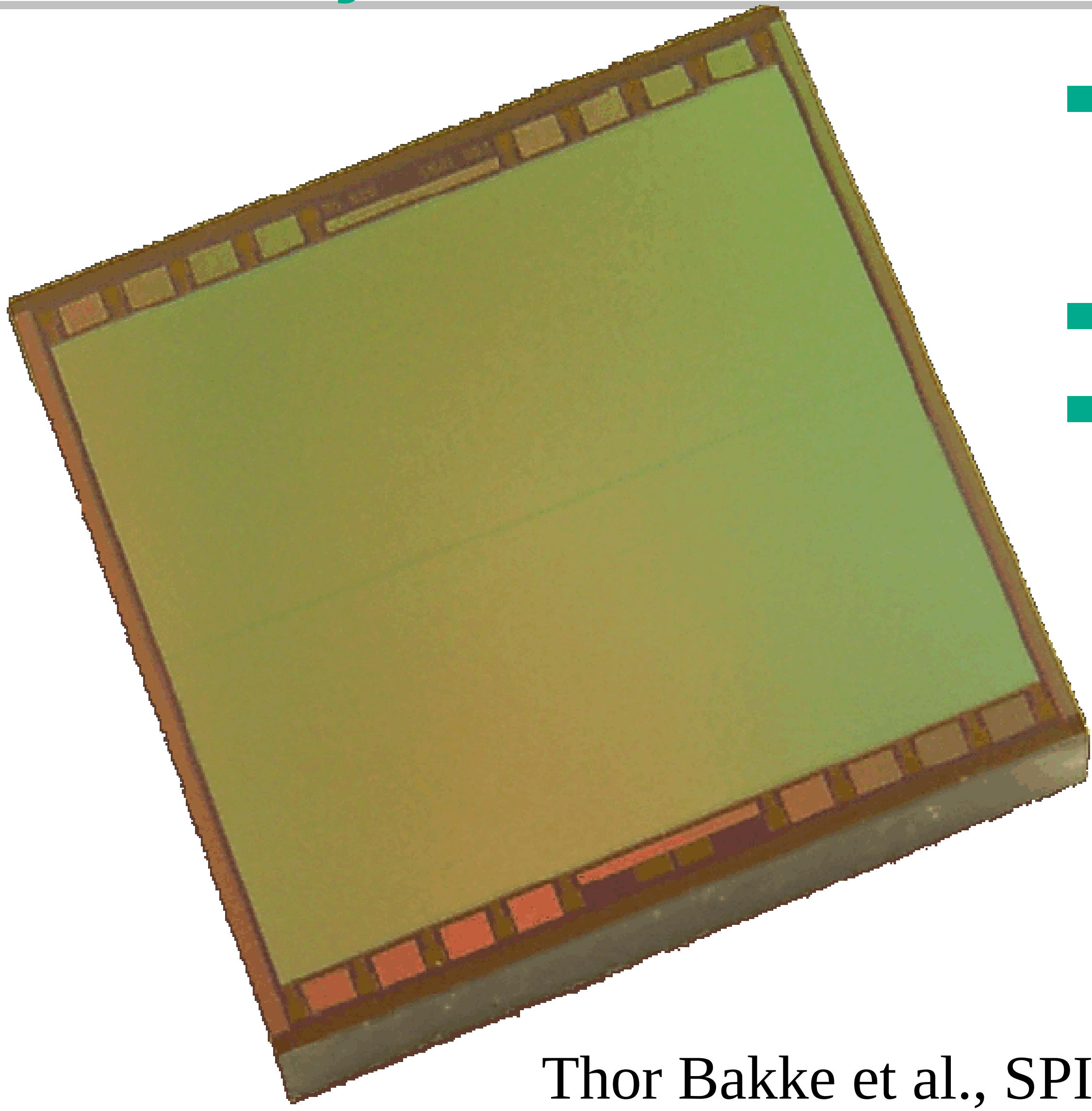
Bonded silicon layer, mirror posts





- A minimum gap between bonded silicon layer and the mirror posts achieved
- Ensures a highly accurate distance between mirrors and actuation electrodes

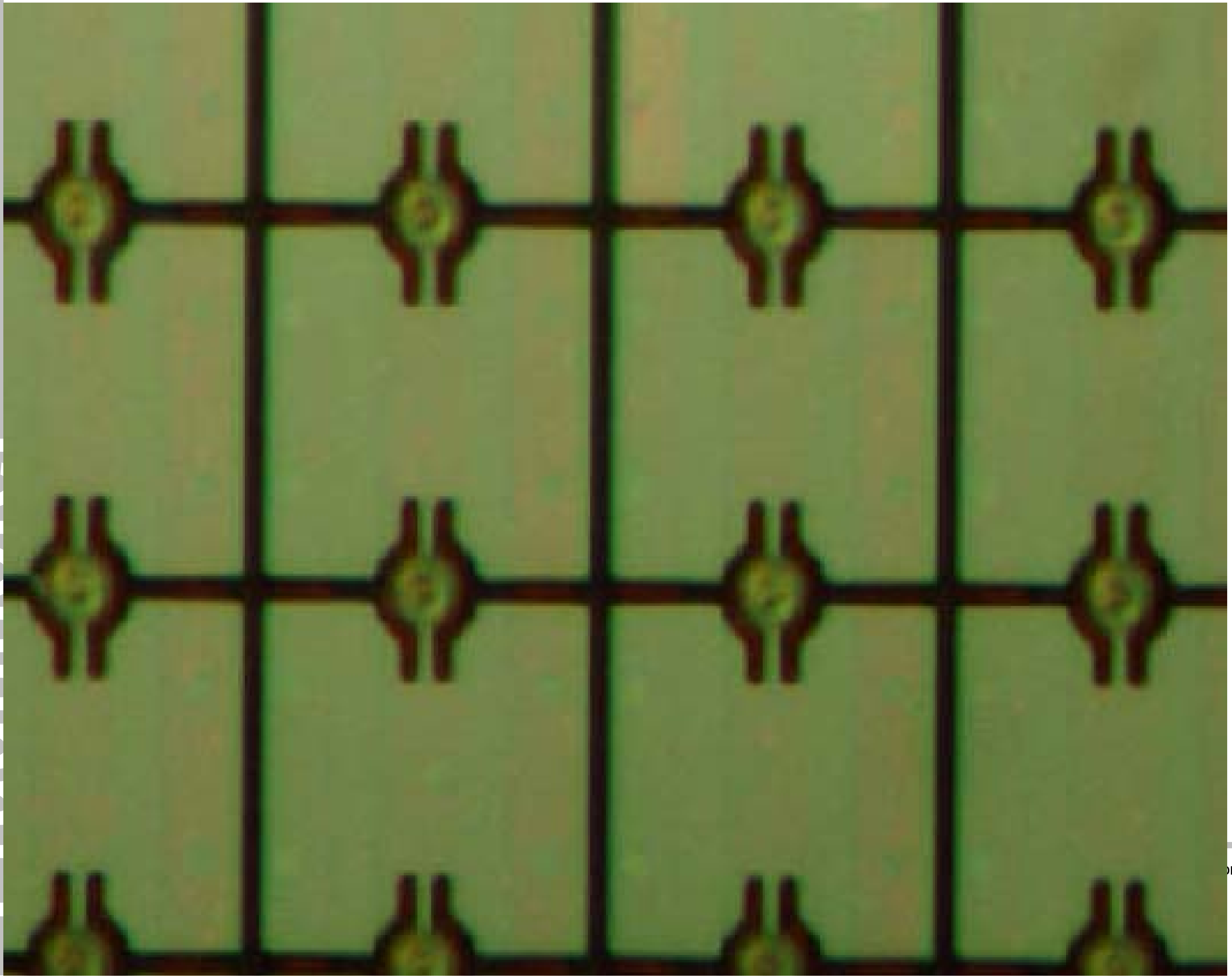
67k array of silicon micromirrors



- Passive mirror arrays successfully fabricated
- 5 x 5 mm^2 chip size
- 240 x 281 mirrors

Thor Bakke et al., SPIE Photonics West 2006

Silicon micromirror array (Microscope)



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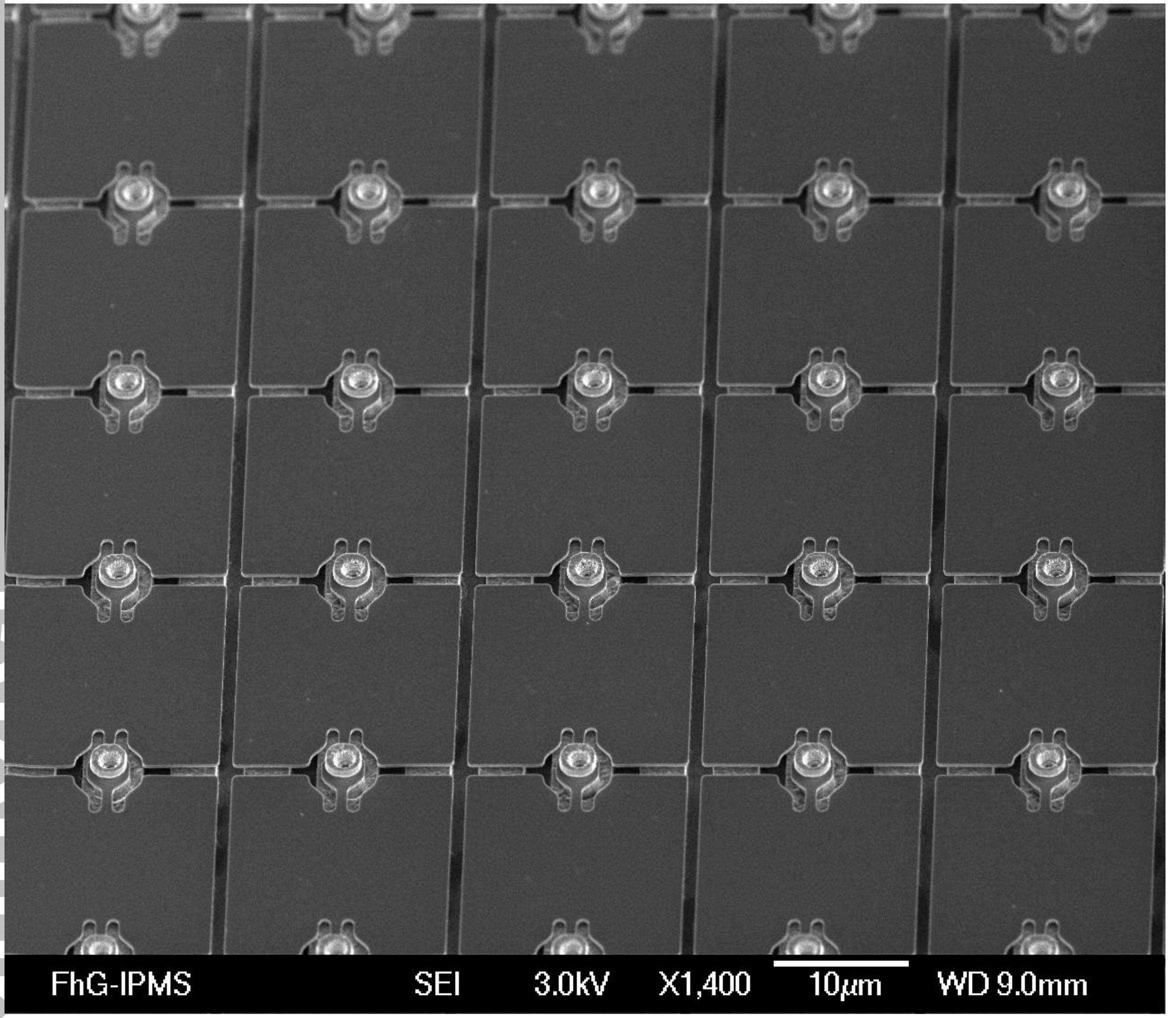
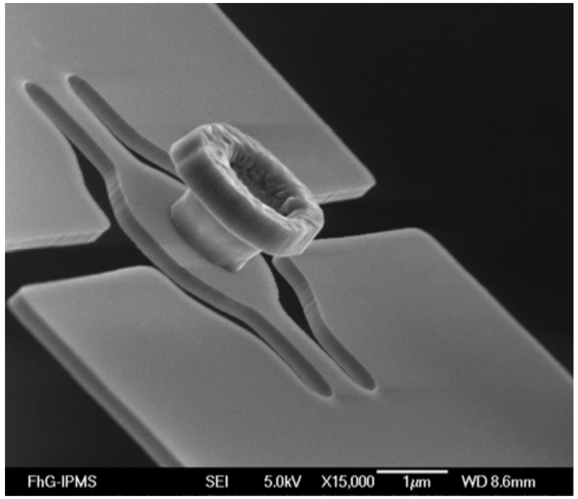
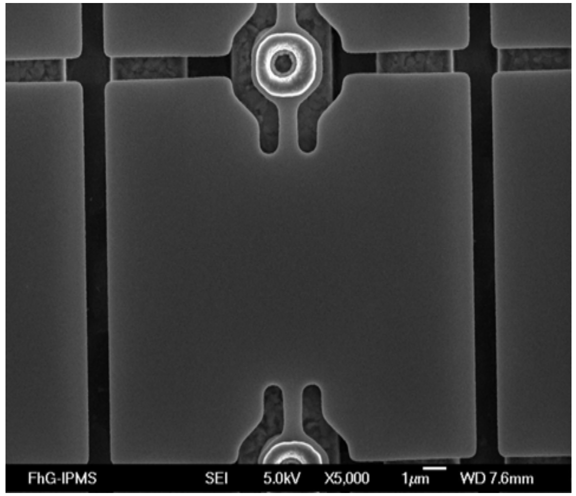
Silicon micromirror array (SEM)

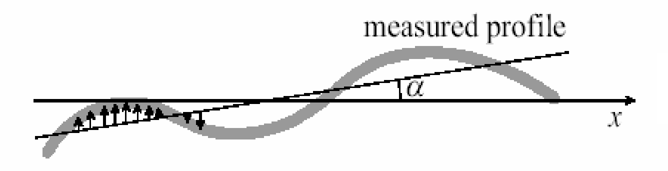




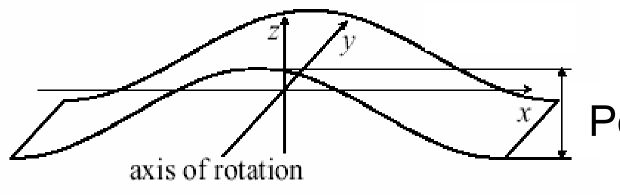


Mirror Planarity

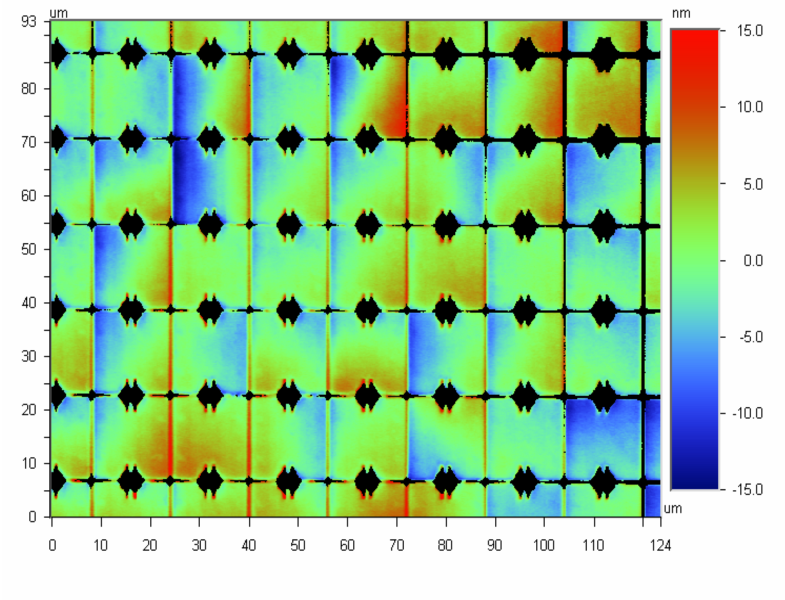
Parameter	Avg. (nm)	Std. dev. (nm)
RMS planarity	0.8	0.1
Peak-to-valley	0.6	0.4



RMS

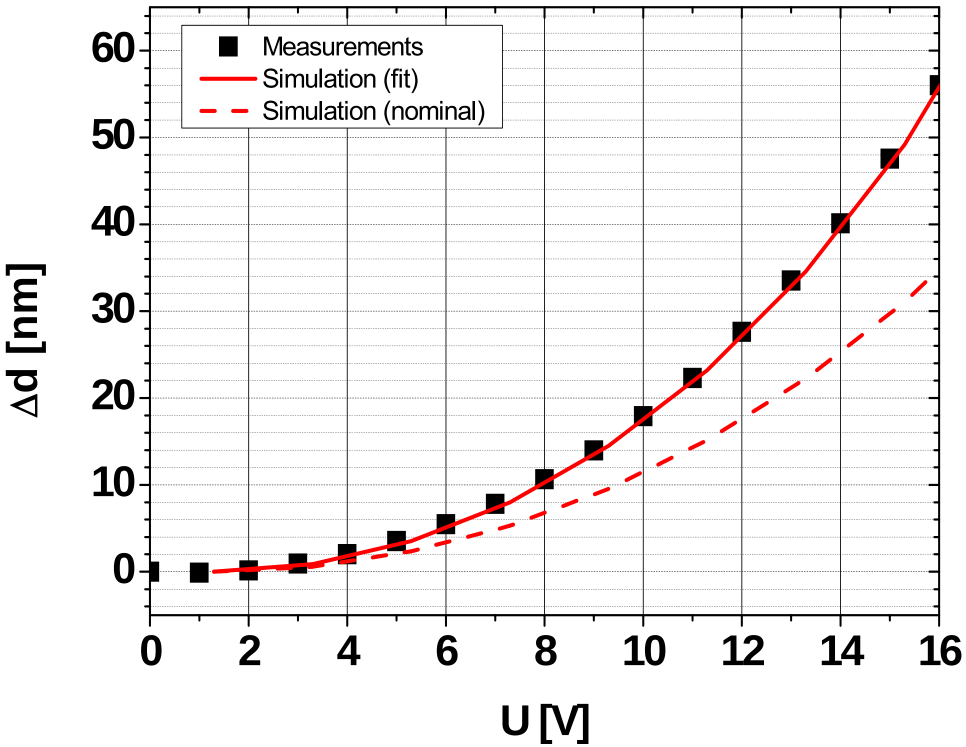


Peak-to-valley

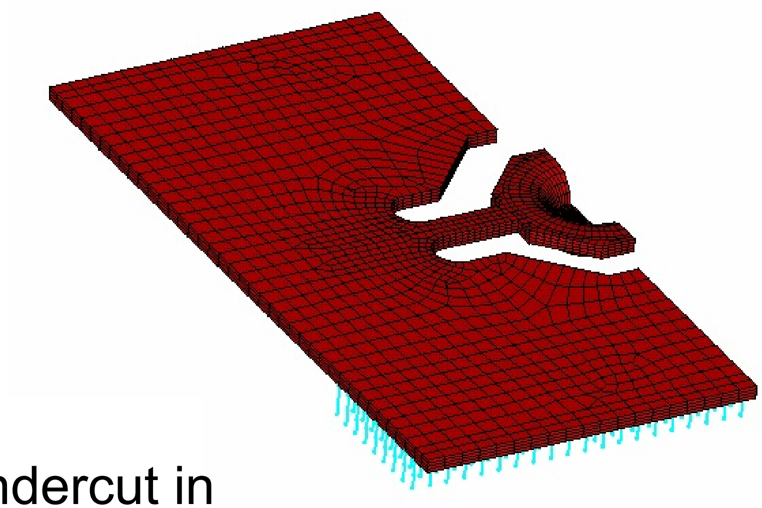


- Mirror array characterized using white light interferometry (phase shift mode, blue light)

Mirror deflection characteristic



- Dimensions
  - Hinge width: 0.8µm (0.6µm)
  - Hinge length: 2.0µm (2.2µm)
  - Thickness: 260nm (260nm)
  - Slit width: 0.8µm (0.8µm)



- FEM simulations indicate a 100nm undercut in the mirror etch, correlates well with SEM observations

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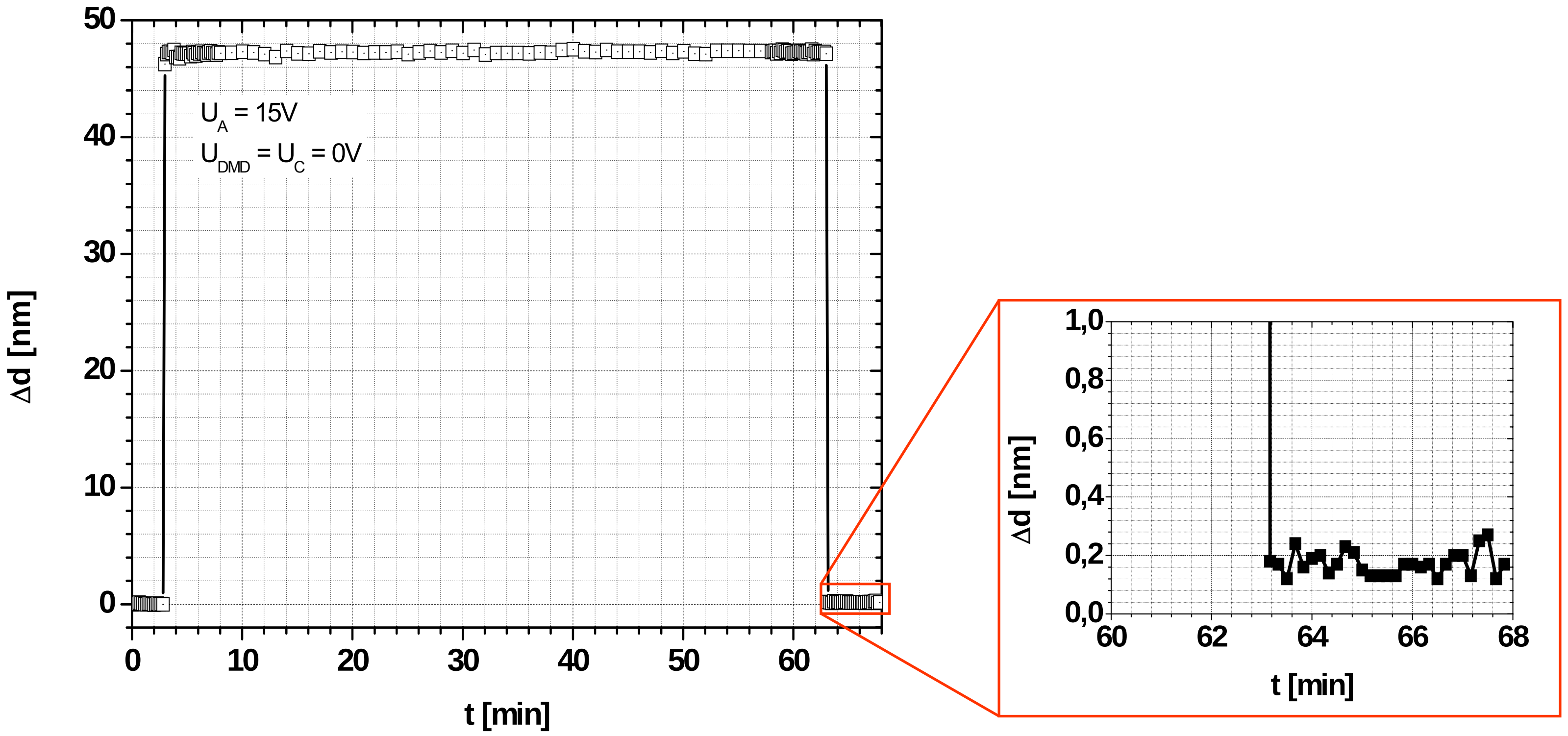
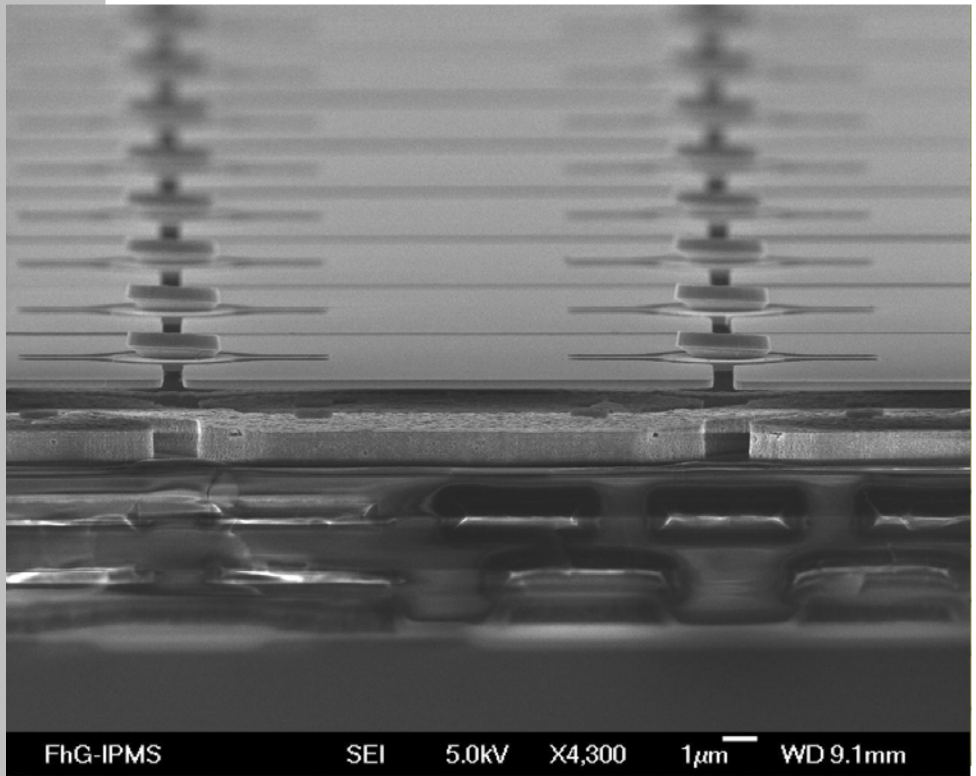
Static deflection



- Drift free operation was confirmed by static deflection for 60 min.
- Mirror deflection completely reversable (return to flat state)

Structured megapixel micromirror arrays on CMOS control electronics



Part of a 1MPixel array of silicon micromirrors on CMOS

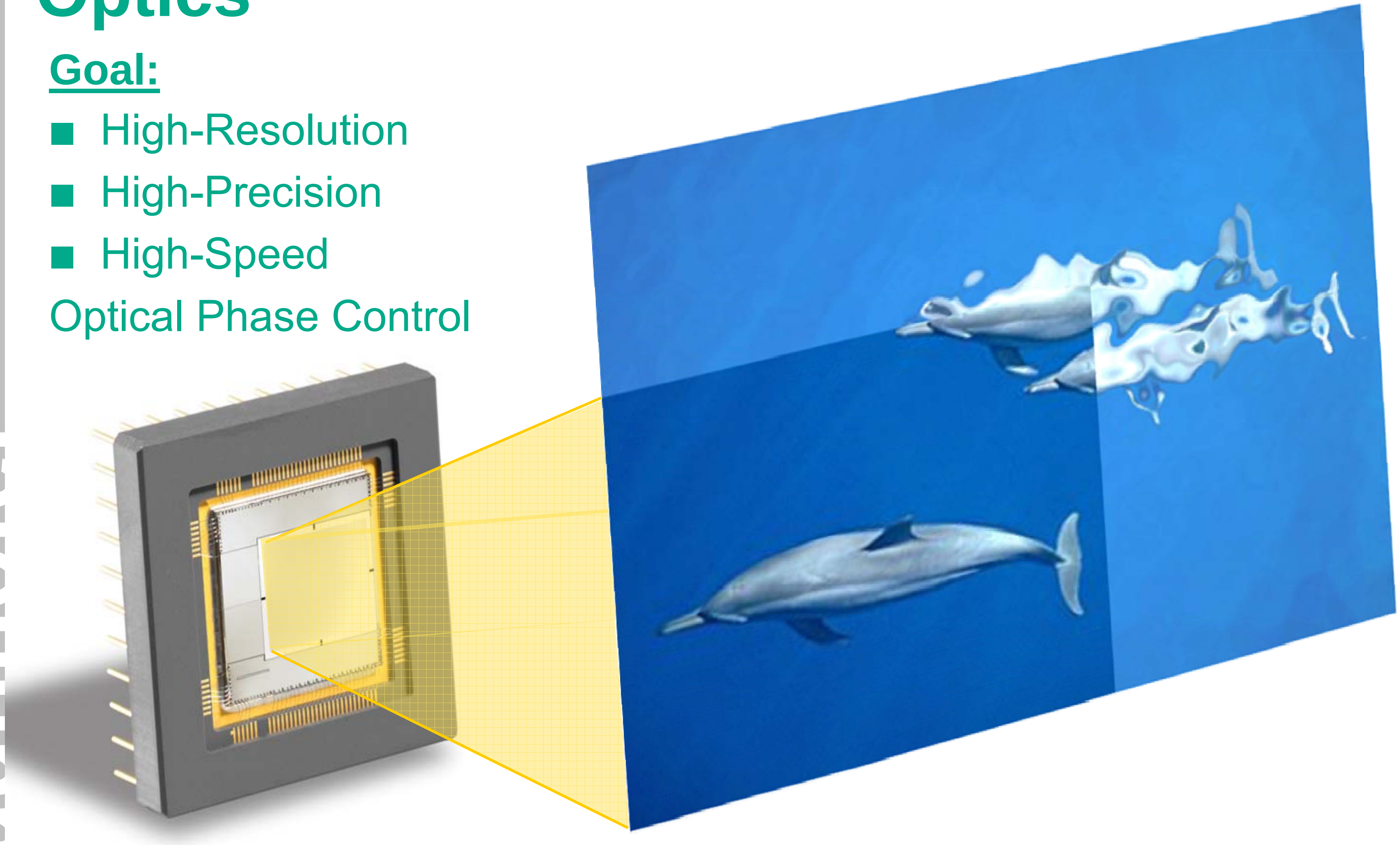
- 1MPixel arrays of monocrystalline silicon micromirrors were structured on CMOS
- The bonded monocrystalline silicon layer survived all subsequent process steps
- A fully CMOS compatible bonding process for optical MEMS has been demonstrated

Spatial Light Modulators for Adaptive Optics

Goal:

- High-Resolution
- High-Precision
- High-Speed

Optical Phase Control



Andreas Gehner et al., Photonics West 2006

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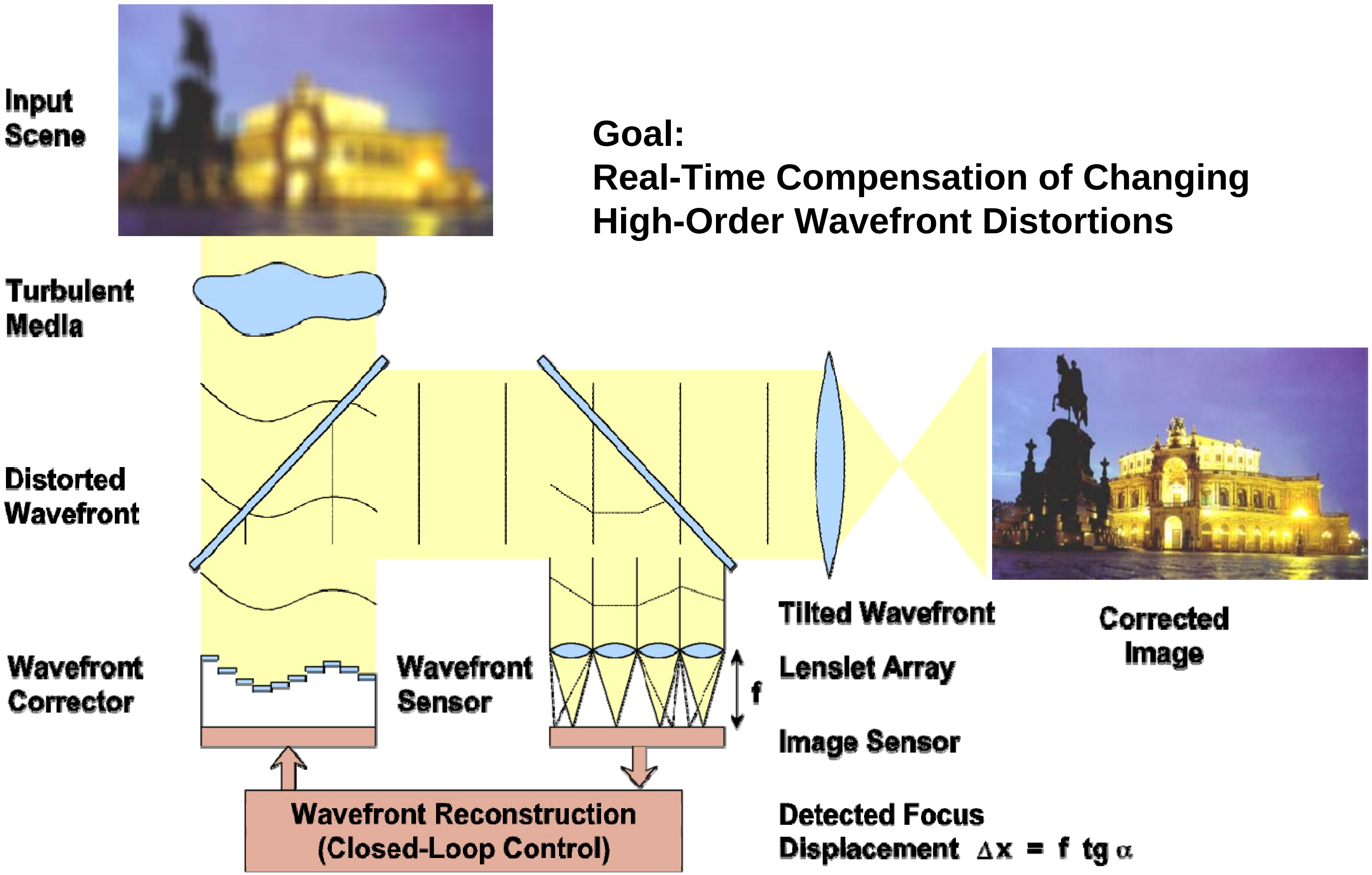
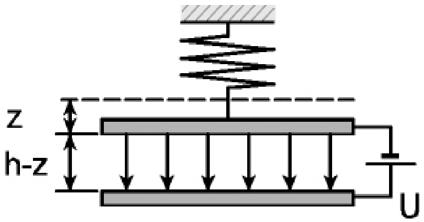
SLM for Adaptive Optics - Example



Goal:
Real-Time Compensation of Changing High-Order Wavefront Distortions

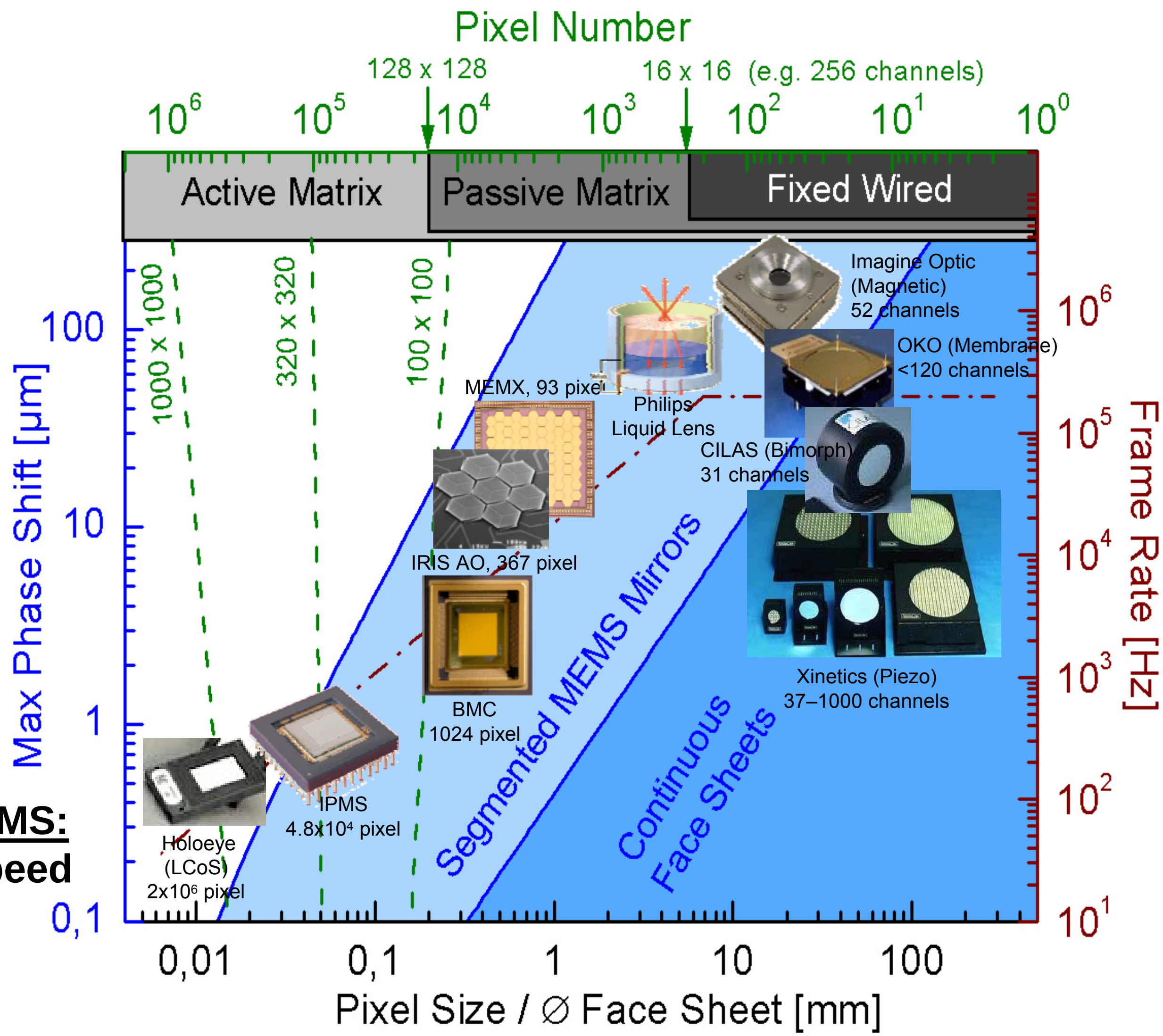
SLM Parameter Space



$$F_M = -k \cdot z$$

$$F_E = \frac{\varepsilon A}{2(h-z)^2} U^2$$

$$z_P = h/3$$



Certain trade-off for MEMS:
Resolution – Stroke – Speed

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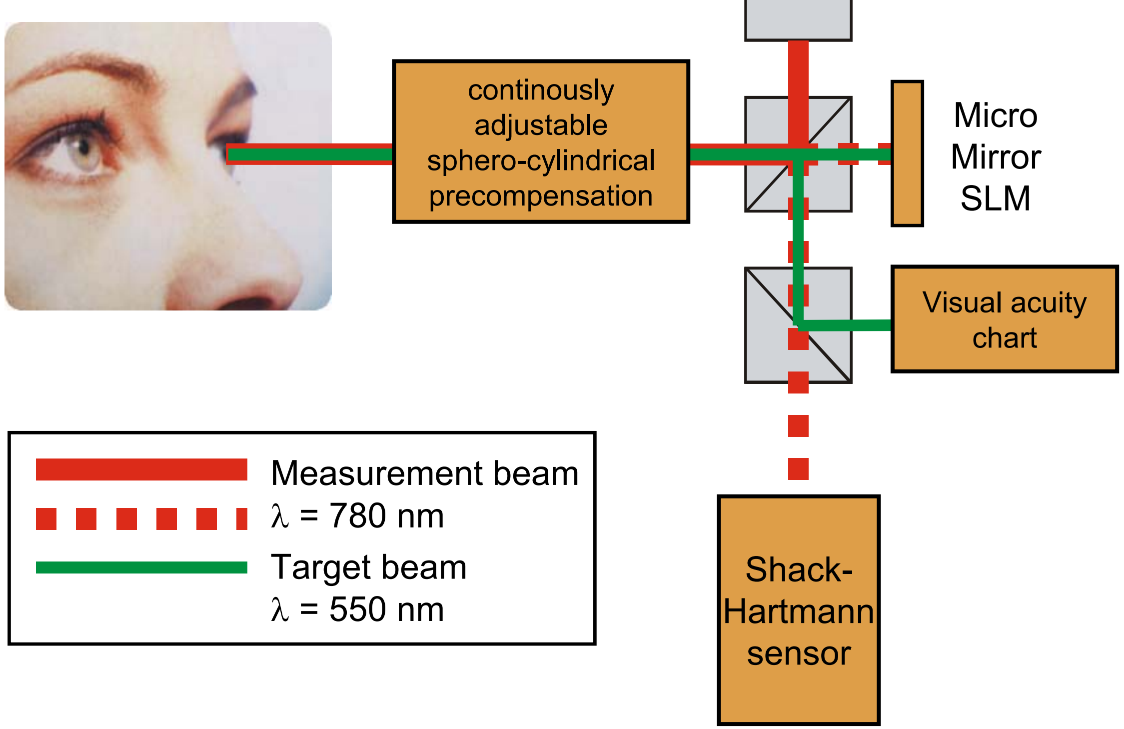
WaveScan® Preview Option

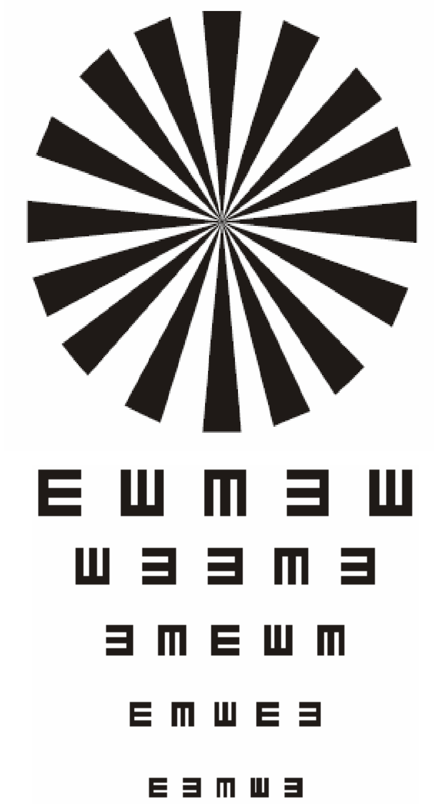
Objectives

- Verification of aberration measurement
- Demonstration of the optical correction
- Individual assessment of the subjective gain in vision improvement

Implemented acuity charts

- Rows of Snellen E's (62,5 - 200% VA)
- Siemens Star for subjective tests & accommodation control





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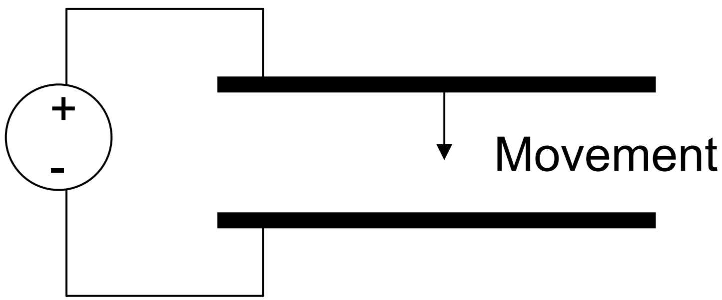
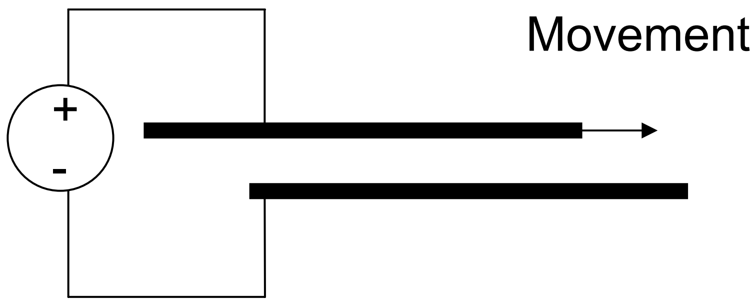
20/10 PERFECT VISION™

Andreas Gehner

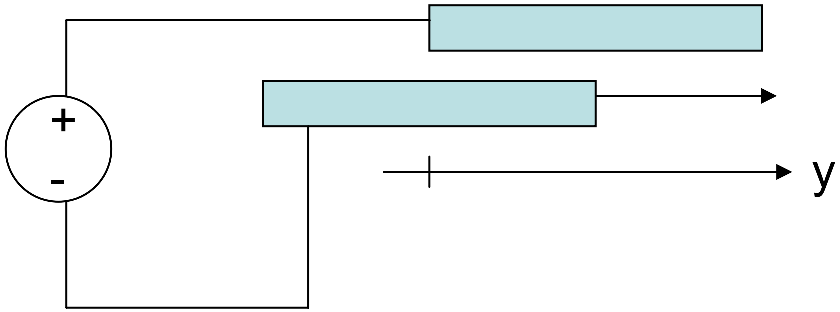
Typical electrostatic actuators used in MEMS

- Parallel-plate capacitor actuator
- Comb-drive actuator





The Comb-Drive Actuator

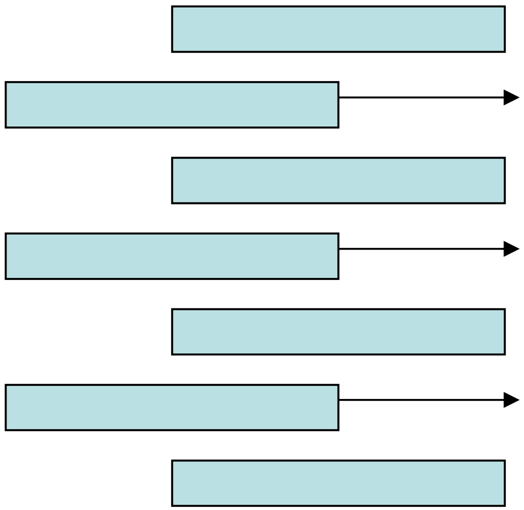


$$C = \frac{\varepsilon A}{g} = \frac{\varepsilon h y}{g}$$

ε – permittivity of vacuum
h – height of plate
y – overlap of plates
g – gap between plates

One comb drive tooth:

$$F = -\frac{dW_T}{dy} = \frac{V^2}{2}\frac{dC}{dy} = \frac{\varepsilon h V^2}{2g}$$

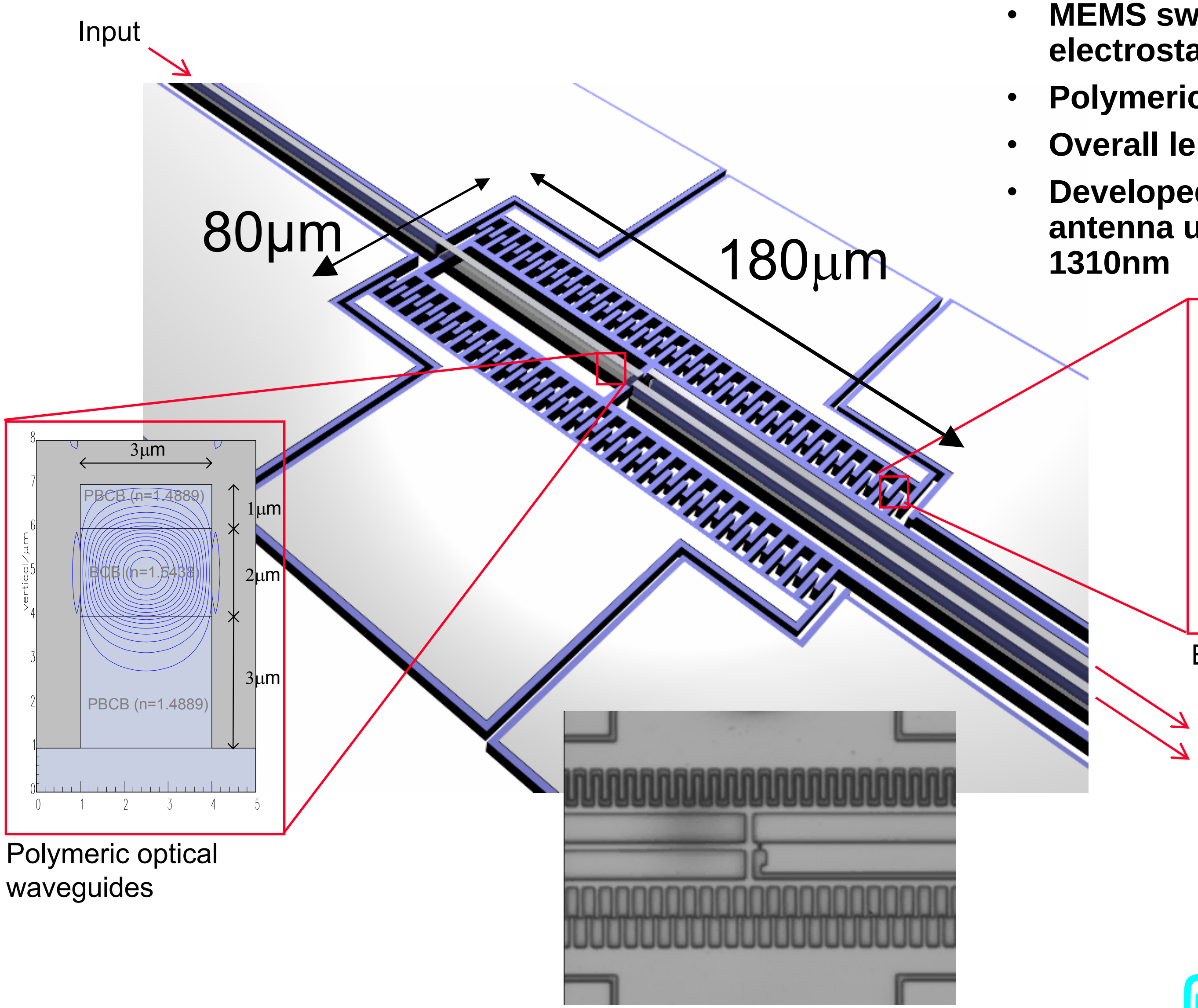


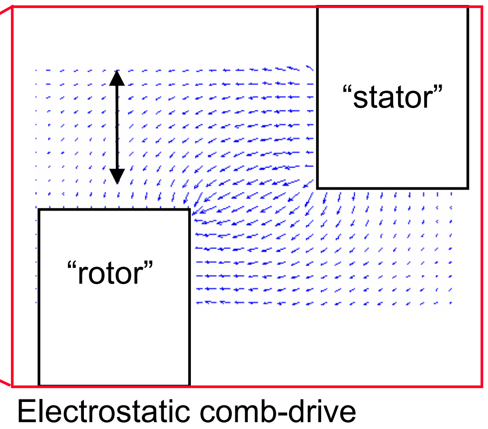
n teeth (both sides of teeth contribute):

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

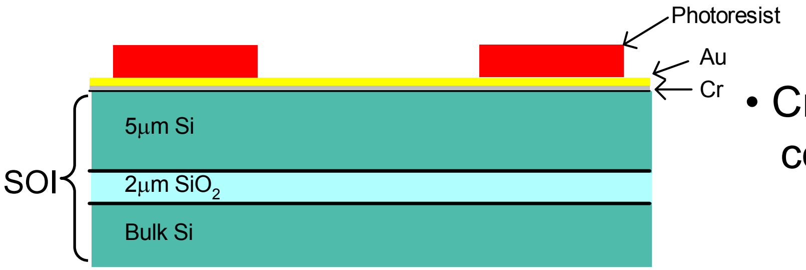
1x2 SOI MOEMS Optical Waveguide Switch

- **MEMS switch structure with electrostatic comb-drives**
- **Polymeric optical waveguides**
- **Overall length 900-1600µm**
- **Developed for spaceborn array antenna using true time delay at 1310nm**



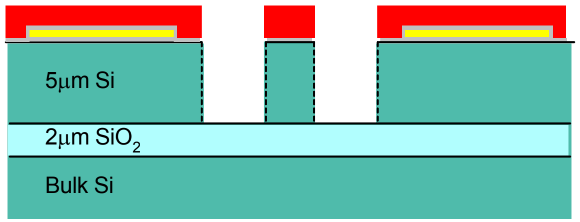


Silicon-On-Insulator (SOI) Micromachining



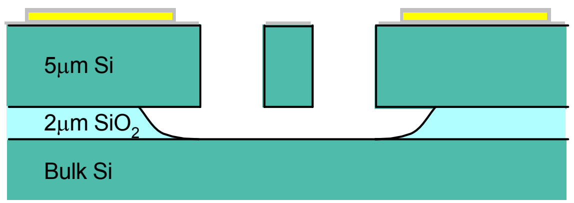
- Cr/Au ohmic contacts

- Cr adhesion layer for polymeric waveguides



- Photoresist etch mask for mechanical structure
- Open up window in Cr
- DRIE

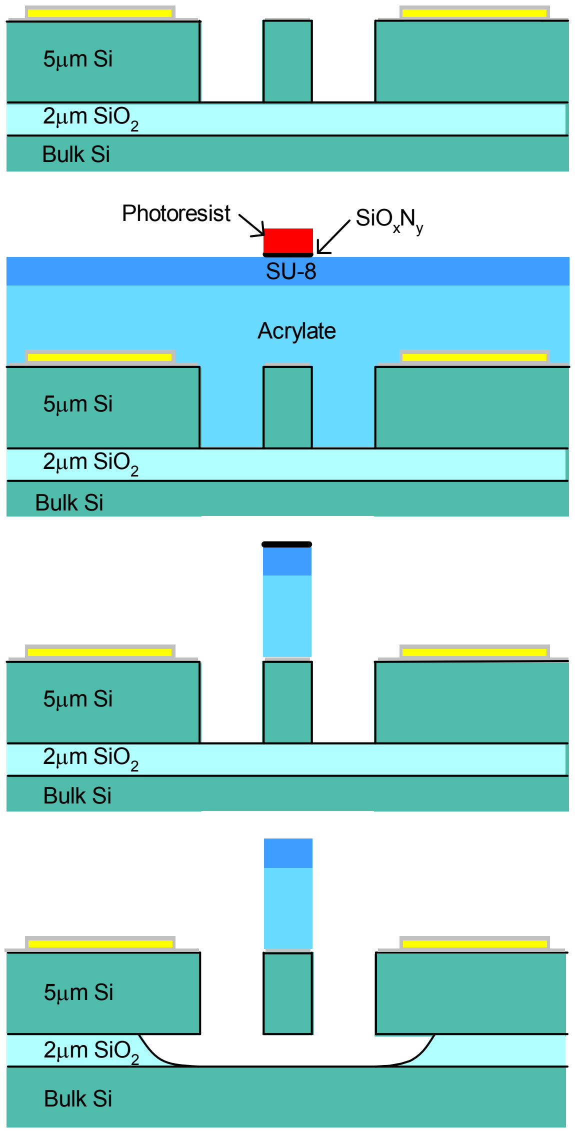
(Polymeric waveguide post-processing)



- Release in Buffered Oxide Etch (BOE)
- Sublimation drying

- **SOI wafer (5μm Si, 2μm thermal SiO_2, Silicon)**
- **0.01ohm*cm resistivity**
- **Wafers are commercially available**
- **SOI is single crystalline and low stress**
- **DRIE etching for high aspect ratio etching**
- **SiO_2 provides an excellent etch-stop**

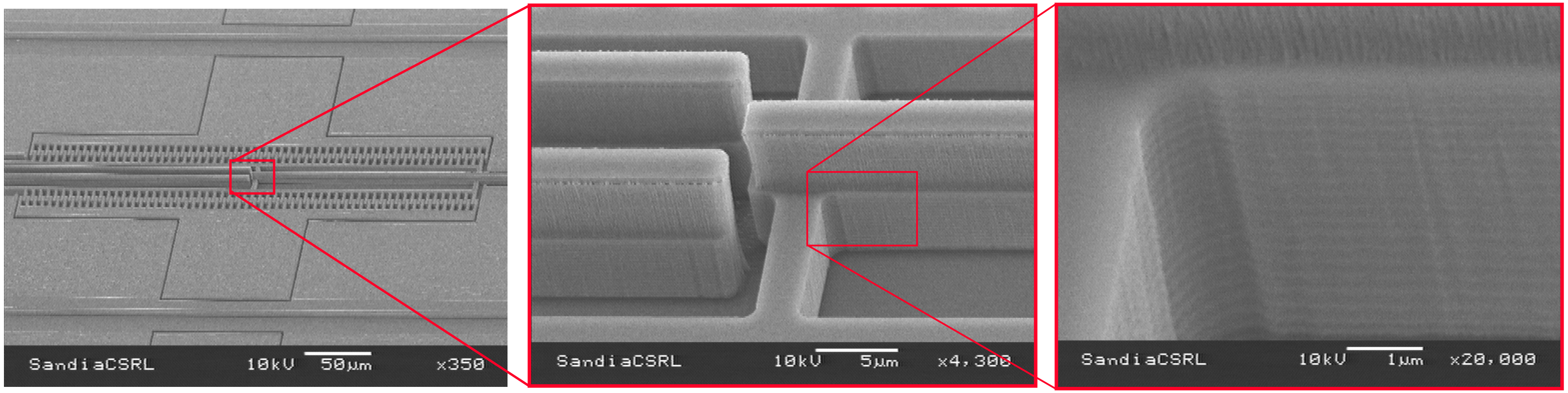
Polymeric Waveguide Post-Processing

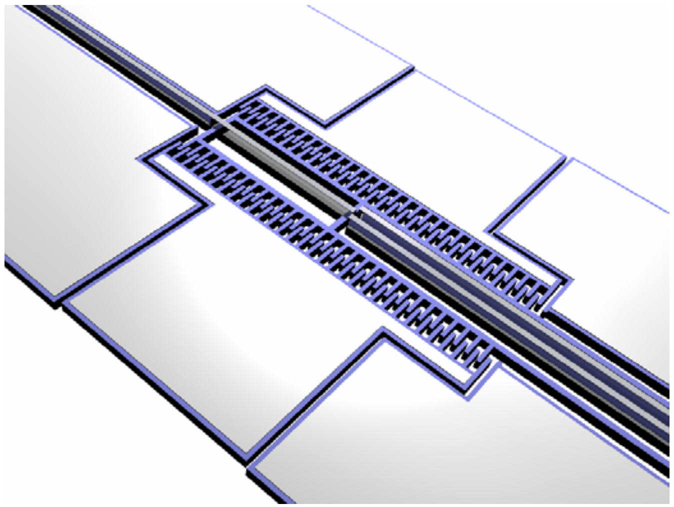


- Structure after BOSCH etch
- Spin coat planarizing polymeric thin-films
- Deposit and pattern SiON mask
- Etch polymer stack + 100% overetch to clear gaps
- Release in BOE
- Sublimation drying

- **Polymeric waveguide post-processing is done prior to release of mechanical structure**
- **Acrylate is used to planarize and also constitutes the lower cladding of the waveguide**
- **A long overetch is used to clear out the acrylate in the gaps of the mechanical structure**
- **Chrome provides adhesion during release and drying process**
- **Release can be carried out directly without protection of the waveguide structure**

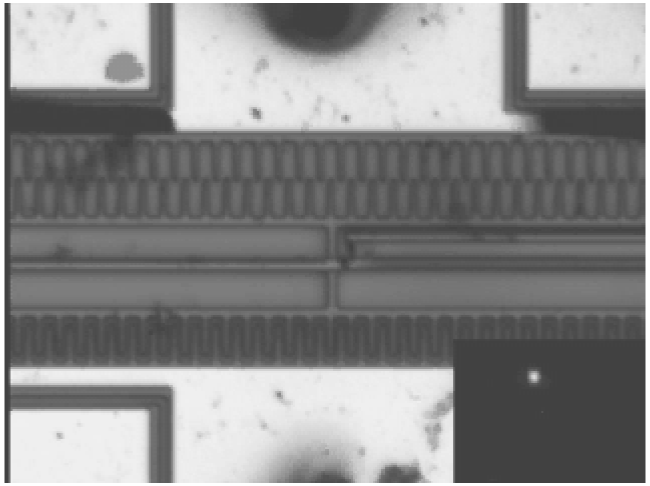
SOI MOEMS Switch with Post Processed Polymeric Optical Waveguides



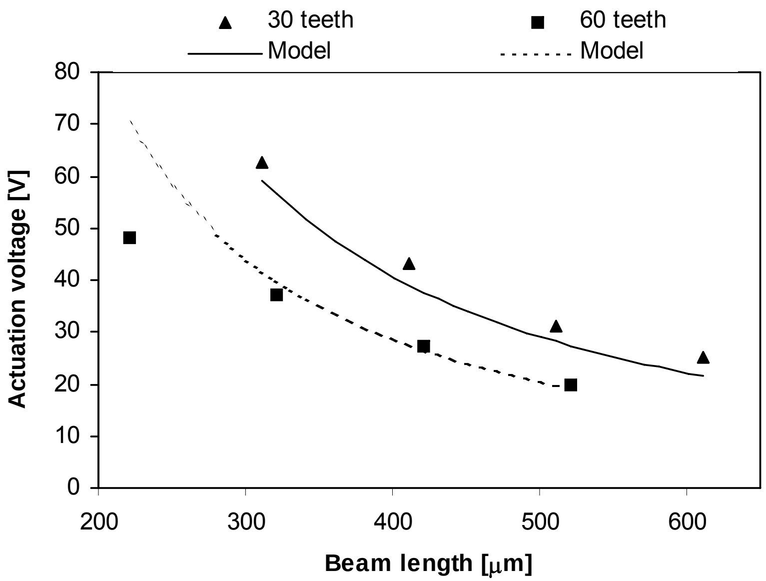


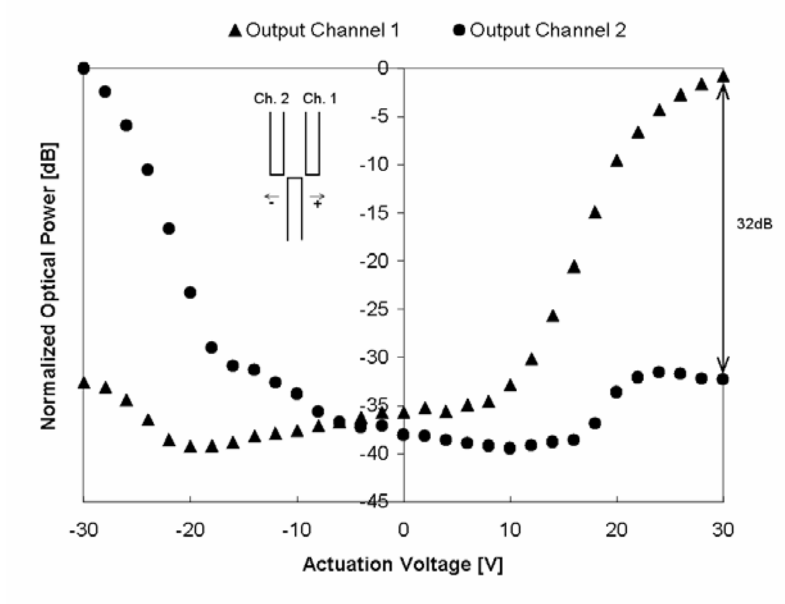
- **Polymeric waveguides post-processed onto mechanical structure with high degree of feature resolution**
- **Overetch of polymeric stack cleans up mechanical structure to allow release**

Switch Characteristics



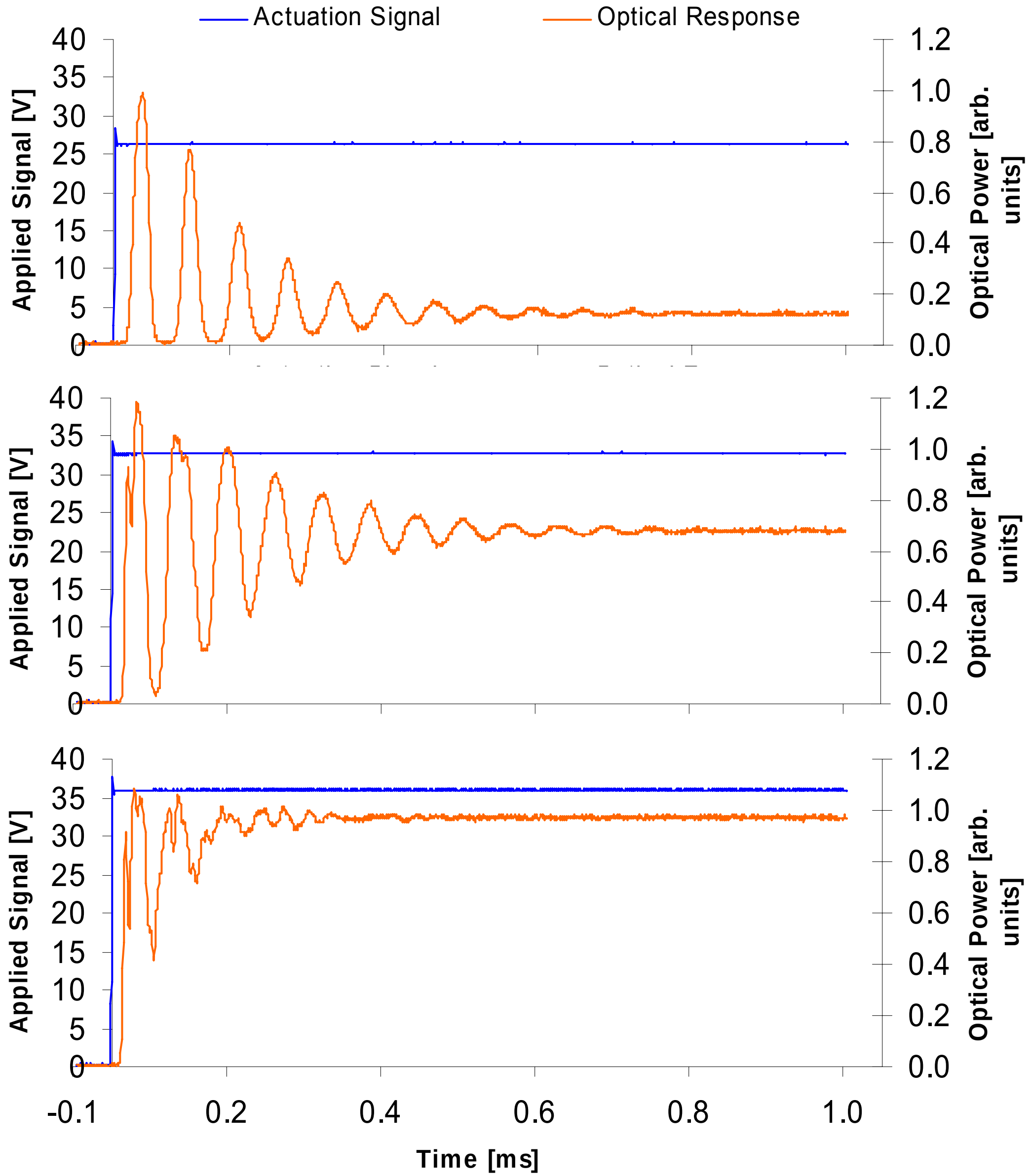
- **Fully released 1x2 optical switch with SU-8 / Acrylate waveguides demonstrated**
- **Actuation voltage 20 - 60V, depending on beam length**
- **Crosstalk measured to be <–32dB**
- **Excess switch loss of 3.4dB measured, due to:**
  - Waveguide loss (1.7dB/cm)
  - Reflection from air gap
  - Non-perfect waveguide end facets (light scattering)
  - Non-perfect waveguide alignment





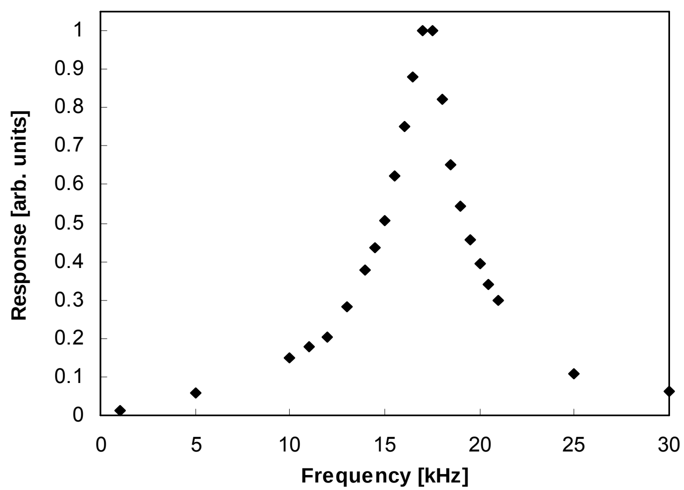
IEE Electronics Letters, vol. 38, no. 4, February 2002

Dynamical Response

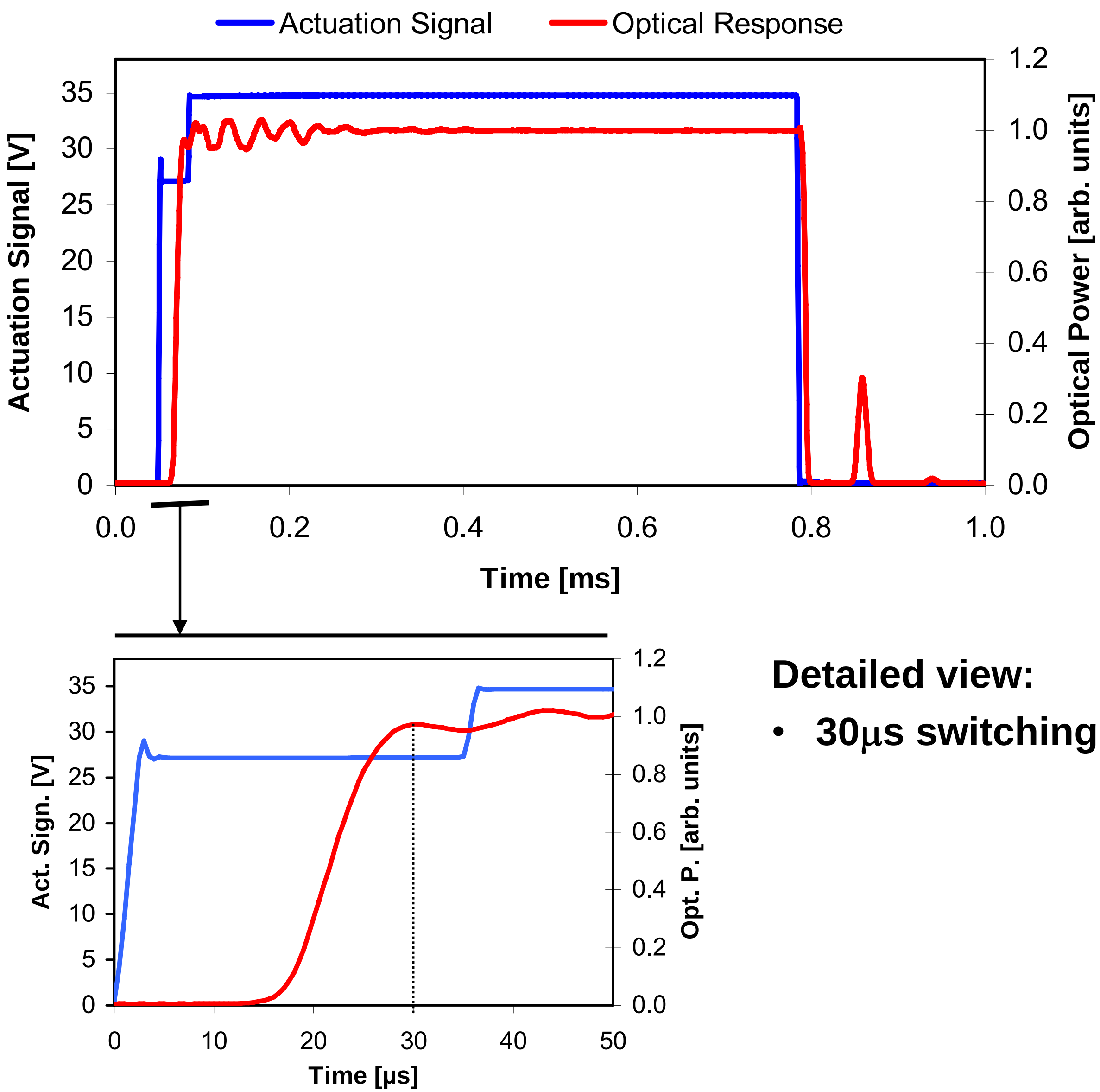


- **Temporal response of switch with 500µm long input beam and 60 comb drive teeth measured**
- **Ringing at resonance frequency of 16-17kHz for sub threshold operation**
- **Harmonics introduced when beam hits bumper**
- **Settling time is about 300µs**

Frequency response:



Tuned Temporal Response



- **Tuned, two-step actuation signal applied to reduce ringing**
- **First, a 35μs long 27V pulse, then 35V steady state**
- **The demonstrated switch overshoots slightly (settles at lower than optimum optical output power)**

Detailed view:

- **30μs switching time**

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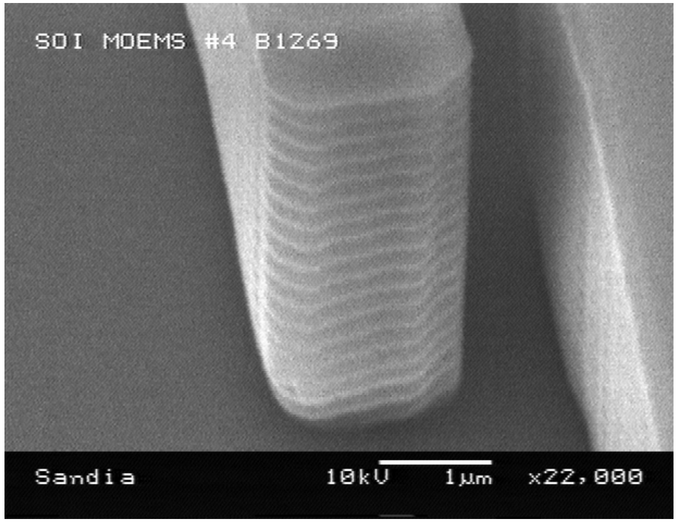
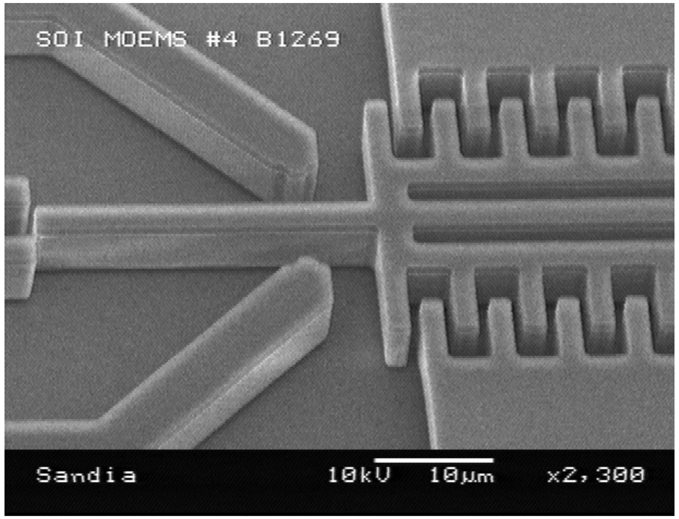
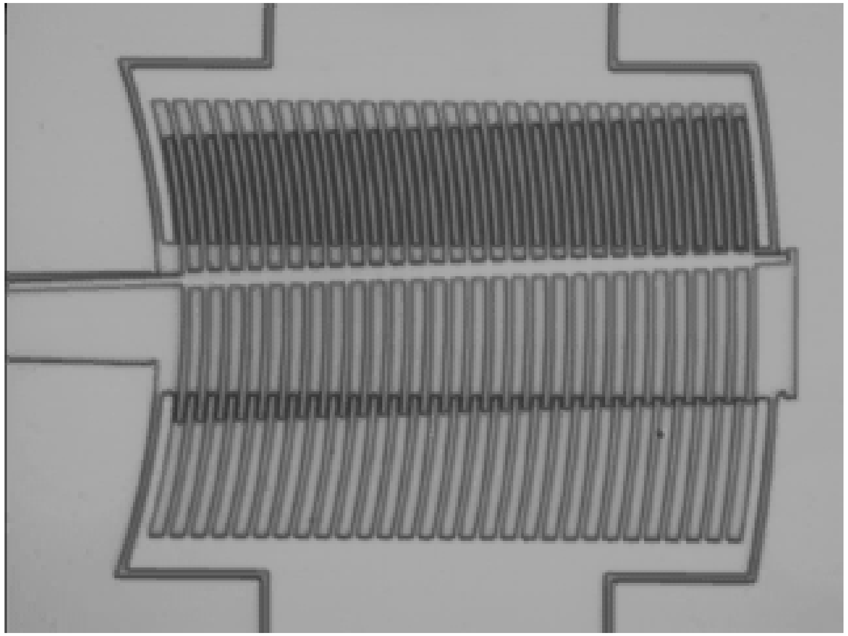
Deep Reactive Ion Etching of Silicon-on-Insulator





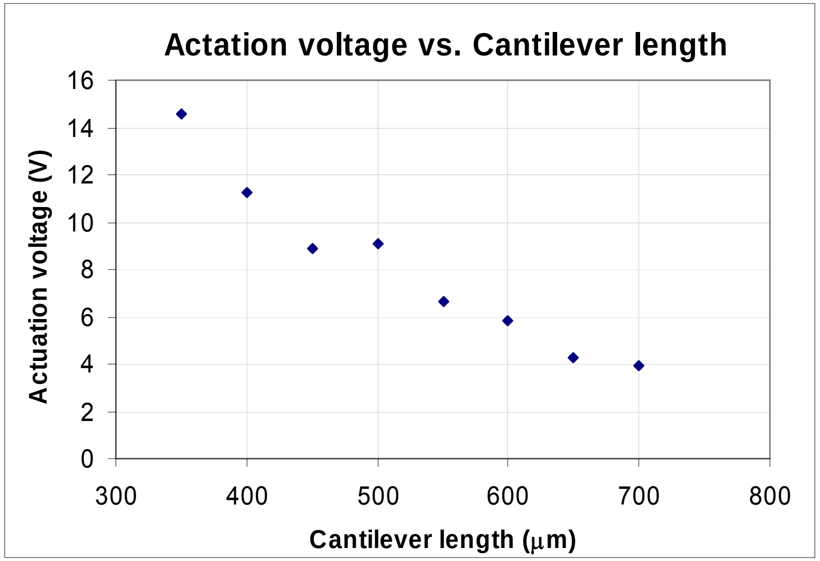
- **High Aspect Ratio Dry Etching of Silicon using the Deep Reactive Ion Etch (DRIE) process**
- **Process developed for smoother sidewalls and improved feature resolution**
- **Actuator comb drives consist of 2μm wide, 5μm tall teeth with 1μm gaps**
- **Single layer of photoresist used as mask material**
- **Process is highly reliable with ~100% yield**

Cantilever Beam Mechanical Design



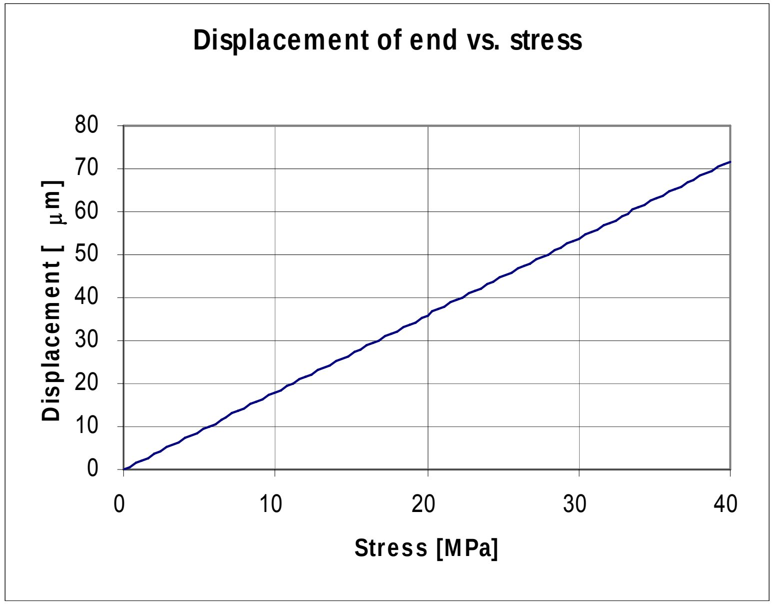
Cantilever beam design with 20μm deflection of tip

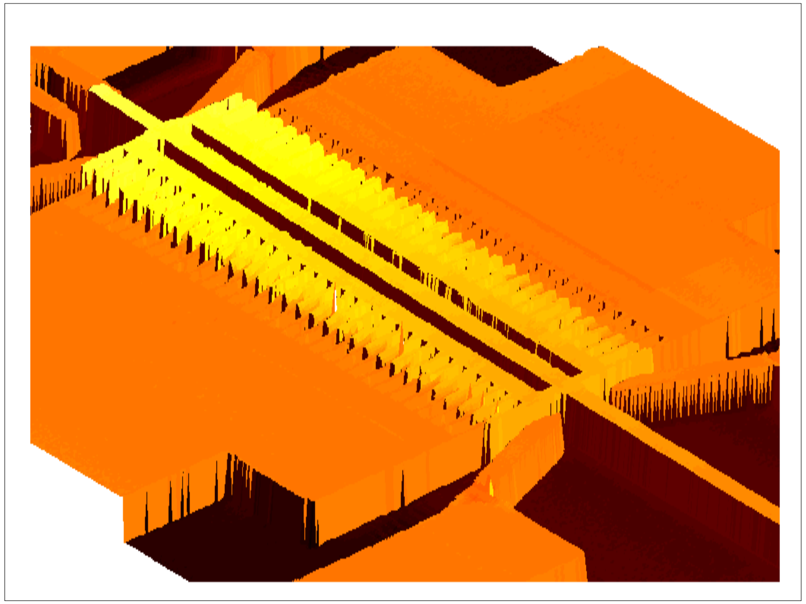
- **A single side clamped cantilever structure provides low actuation voltage (<10V) and large deflection range (>20μm)**
- **Cantilever design unsuitable for the non-symmetric stress introduced by polymeric waveguides**



4μm deflection of beam tip

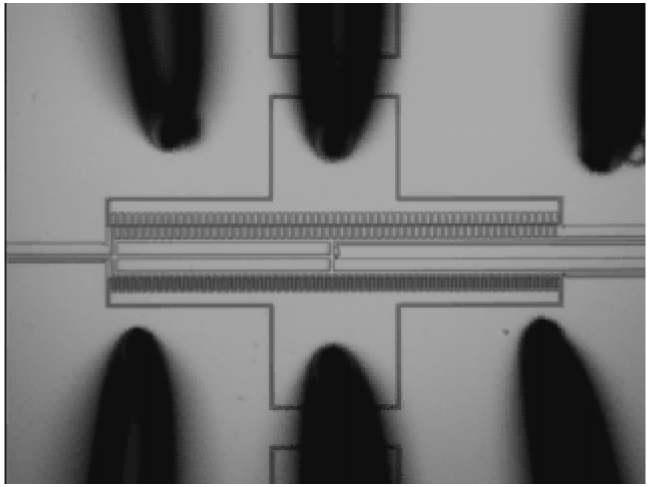
Stress Induced Vertical Deflection

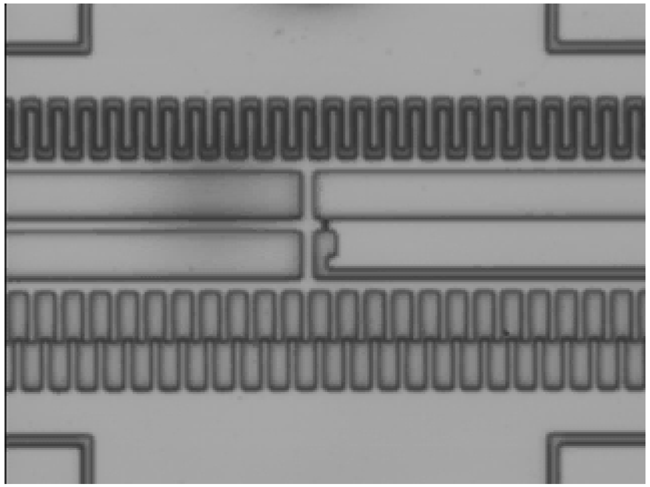




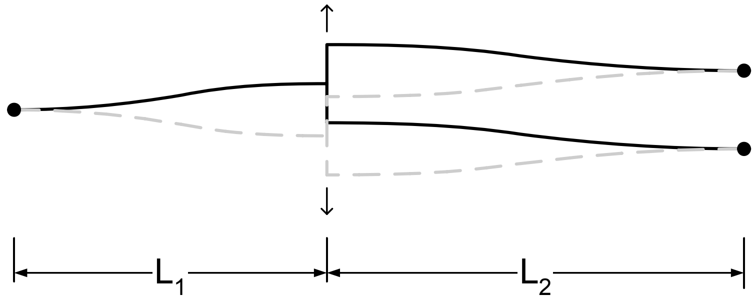
- **Stress induced by polymers is typically 30-40MPa tensile**
- **This is enough to displace the waveguide tip to completely miss the output waveguide**
- **A stress resistant structure is required**

Doubly Clamped, Suspended Beam Design





- **Suspended beam structure to accommodate stress induced by polymeric waveguides**

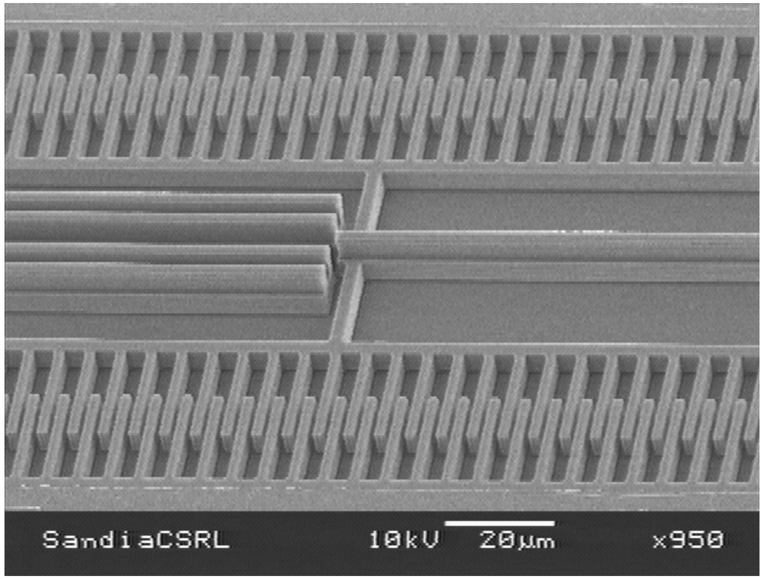


- **Beam lengths designed to give pure piston action of electrostatic comb drive:**

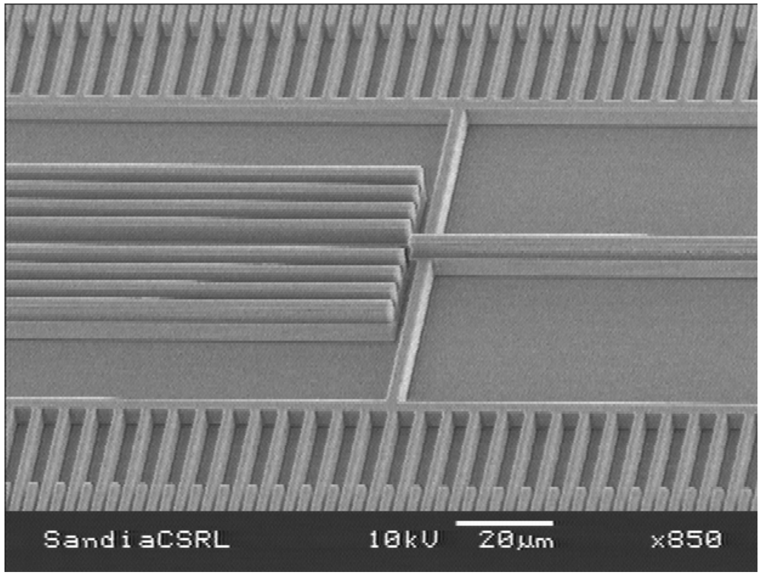
$$L_1 = 2^{-1/3} L_2$$

- **Beam structure 5μm high to provide vertical rigidity and 3μm wide to allow lateral deflection**
- **Comb drive tooth width is 2μm and comb drive gap is 1μm**
- **Total number of comb drive teeth is 30-60**
- **Total switch length is 900-1600μm**

Scalability of Design



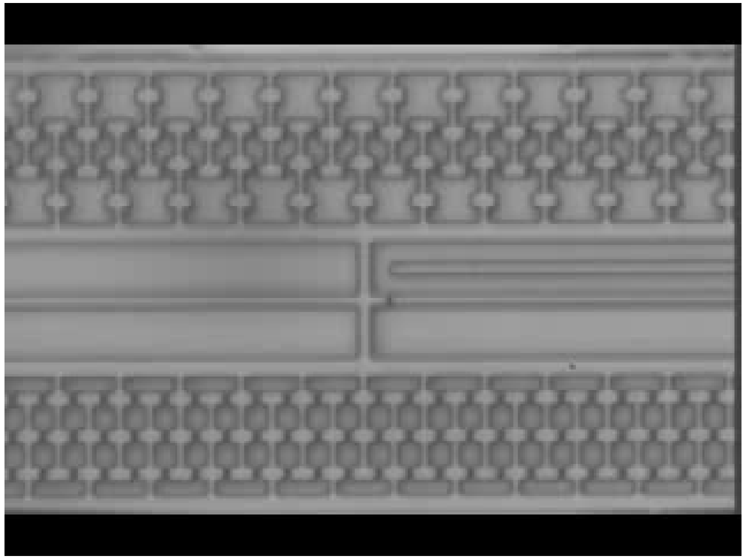
1x4

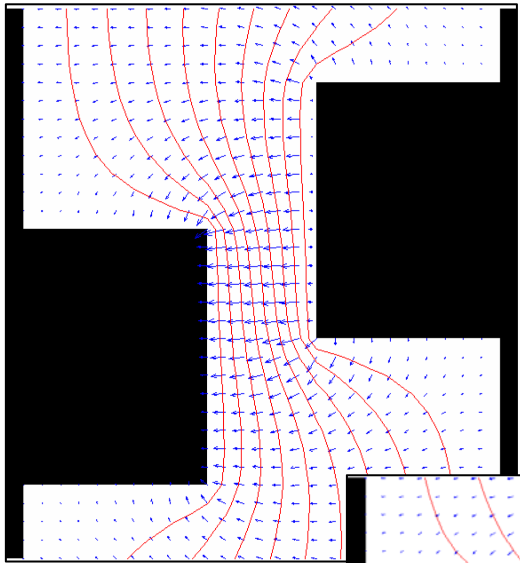


1x8

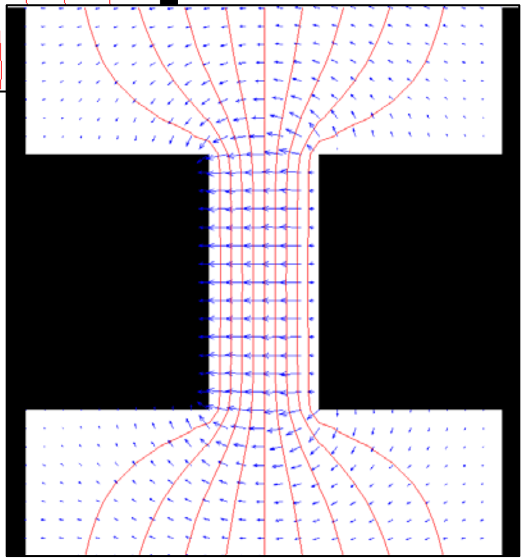
- 1x4 and 1x8 switches have been fabricated
- Actuation with 20-40µm long comb drive teeth demonstrated
- More flexibility should be built into the bearings to allow large deflection with low voltage operation
- Multiple elements can be cascaded

Electronic Registration Comb Drives





Non-symmetric field



Symmetric field, stable position

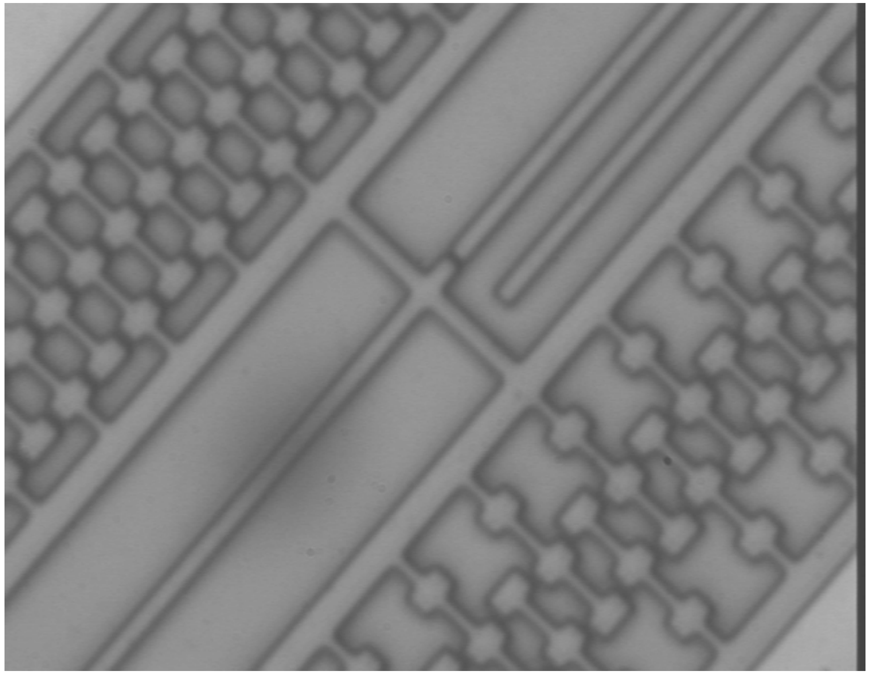
Mechanical registration (bumpers):

- **Involves parts that touch**
- **Accuracy is process dependent**
- **Reliability issue**

Electronic Registration:

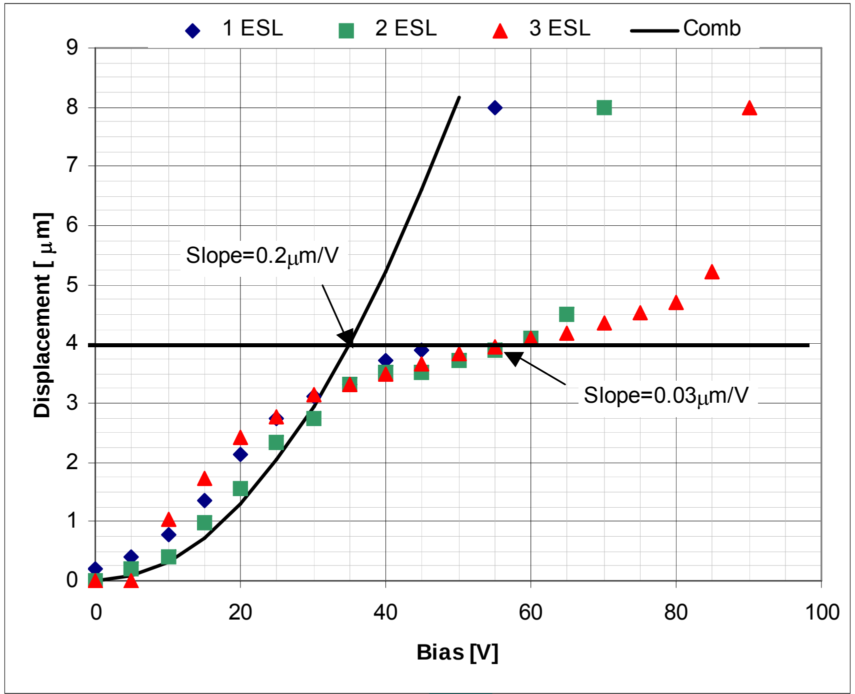
- **Electrostatic "latching" (ESL)**
- **Field symmetry ensures high accuracy**
- **No process dependence due to symmetry**

Displacement vs. Actuation Voltage

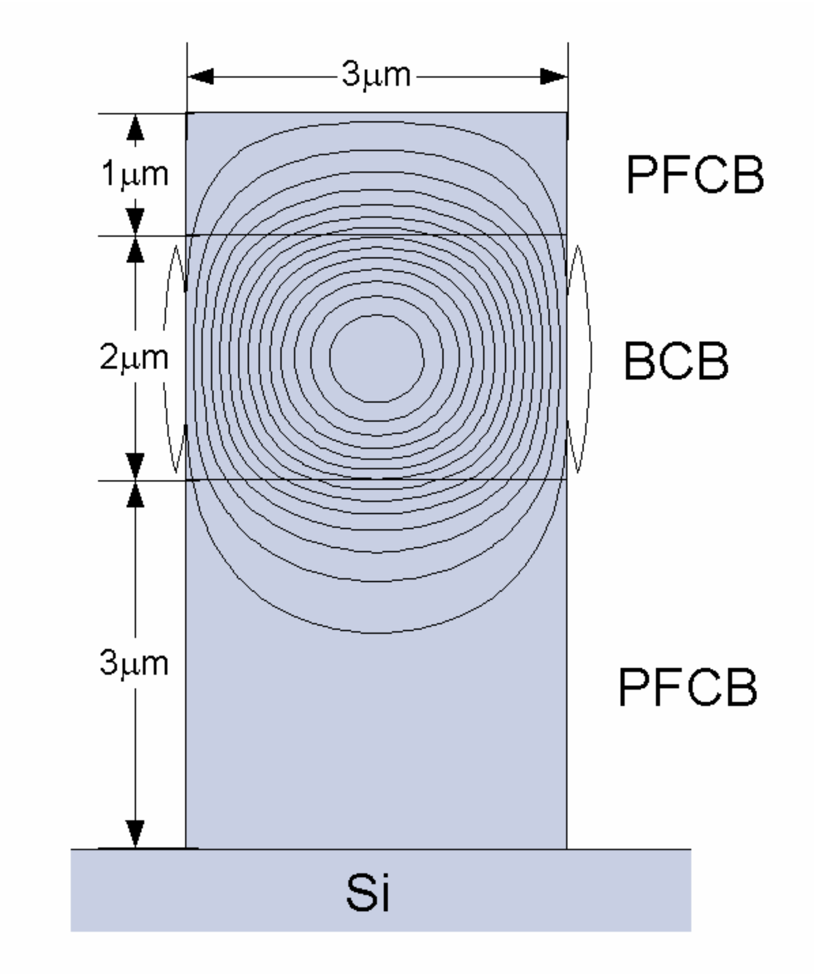


- Snap-in at excessive voltages
- Extended possibilities:
    - Push-pull actuators with lower actuation voltage
    - MEMS structures with various holding force
    - Multiple positions for 1xN switches

- Registration achieved with no touching parts
- Less actuation voltage sensitivity than ordinary comb drive



Optimum Waveguide Design

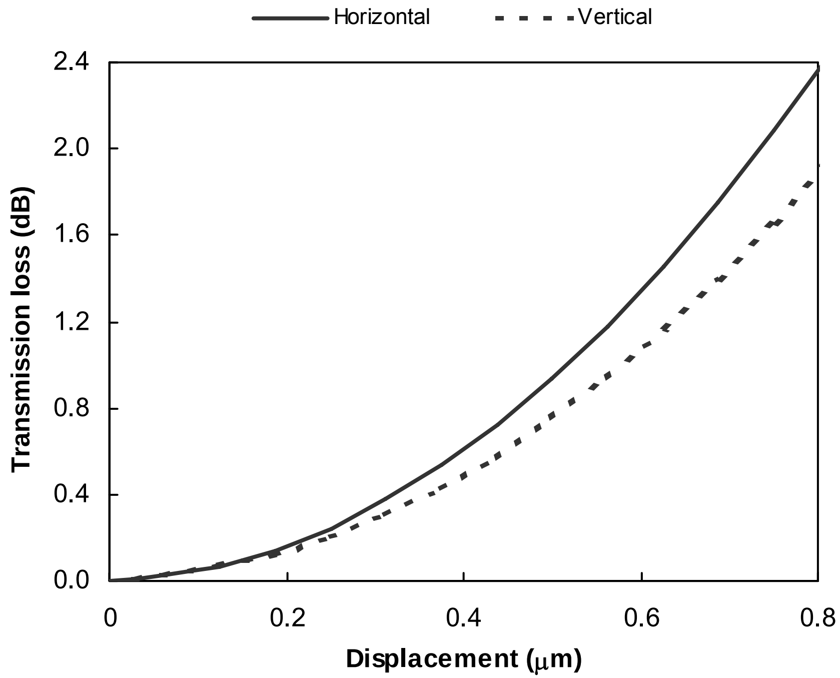


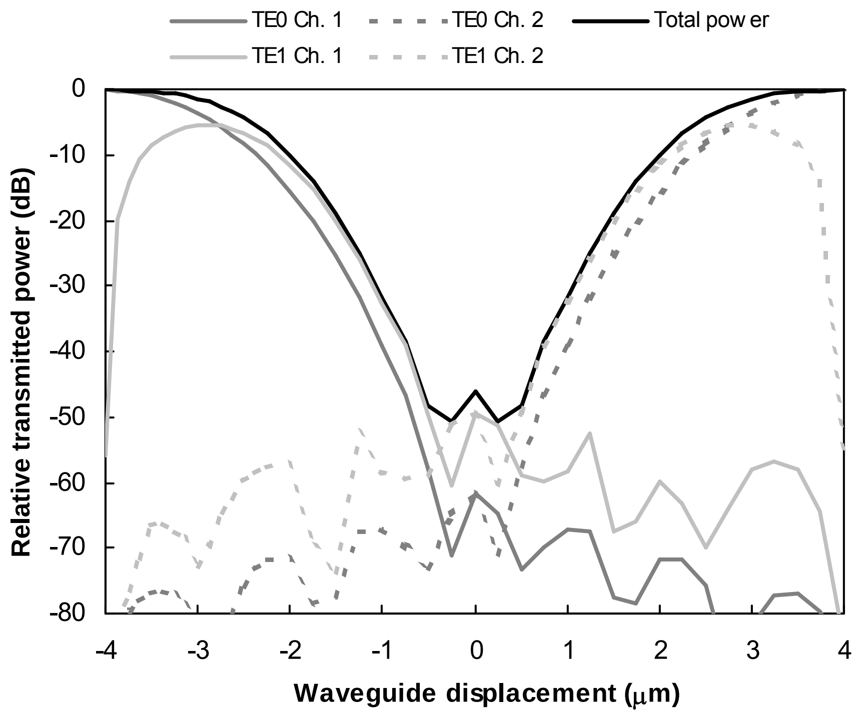
- **1µm upper cladding**
- **2µm core**
- **3µm under cladding**

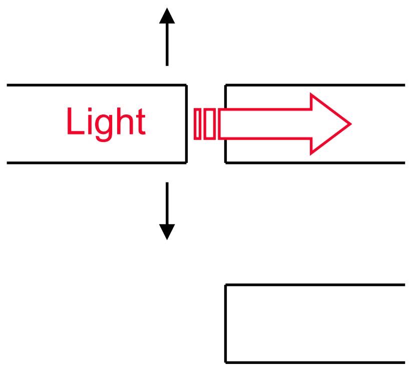
Theoretical mode attenuation:

Mode	**TE00**	**TE10**	**TE01**
Attenuation (dB/cm)	**0.03**	**1.4**	**8.9**

Switch Loss due to Waveguide Misalignment

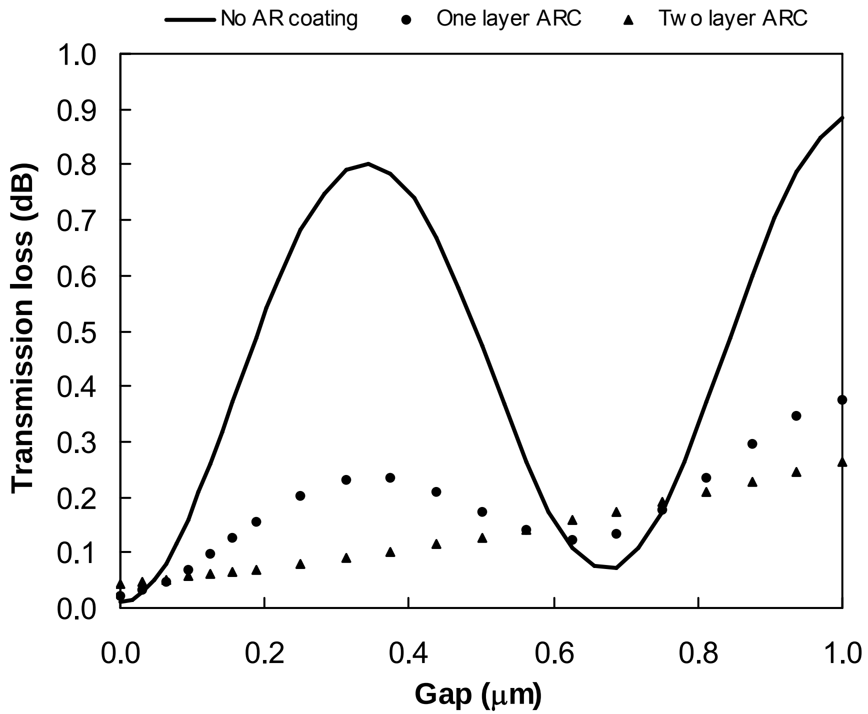


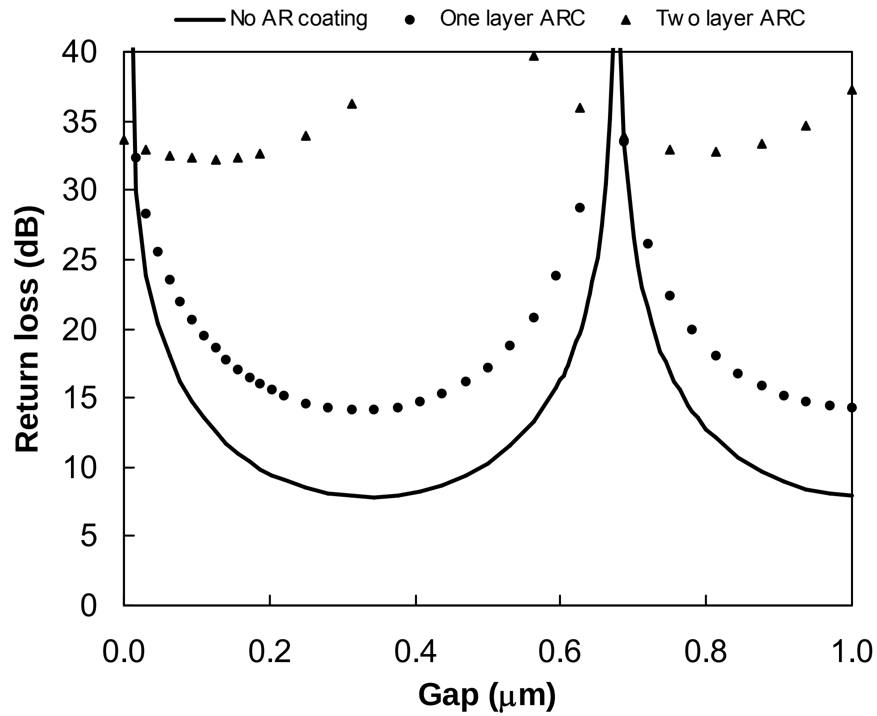


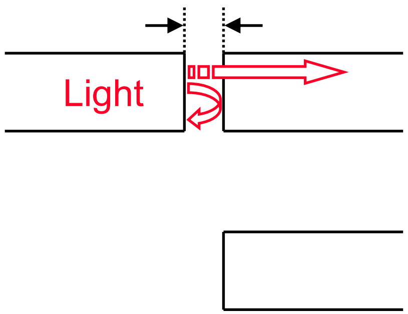


- **Waveguide registration critical in order to avoid coupling loss**
- **Positioning better than ±0.15μm for loss <0.1dB**

Switch Loss due to Air Gap Reflection

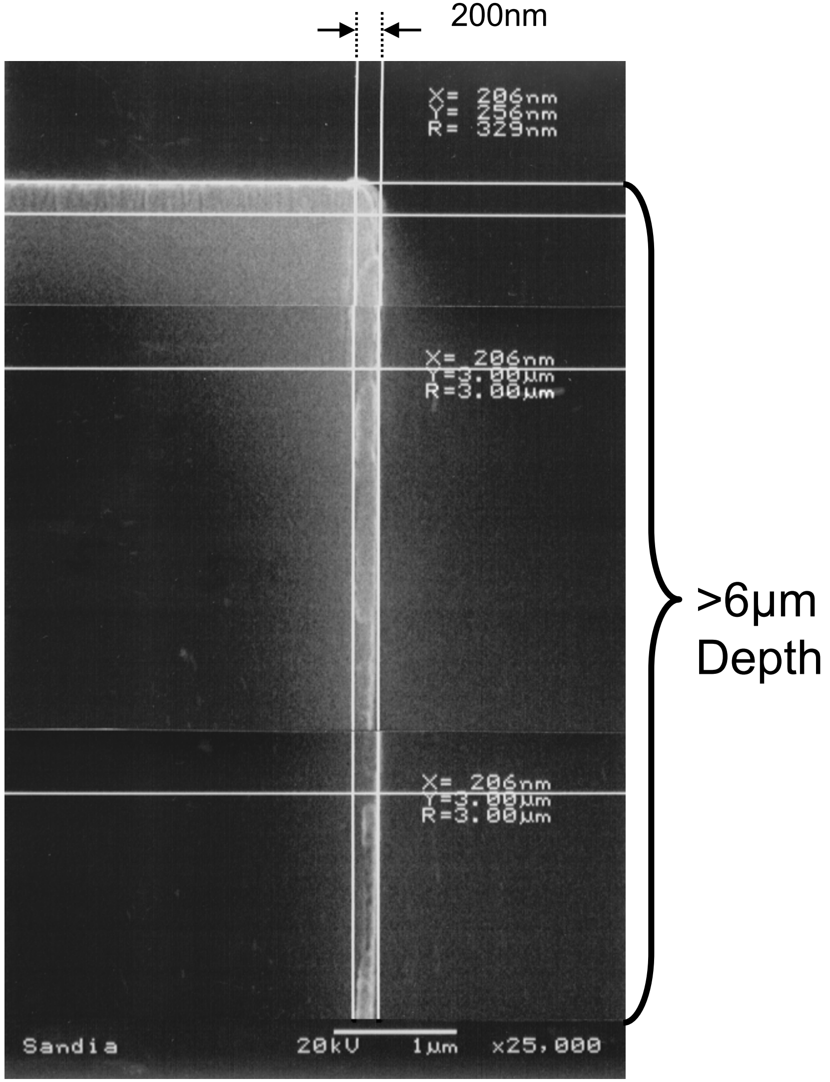




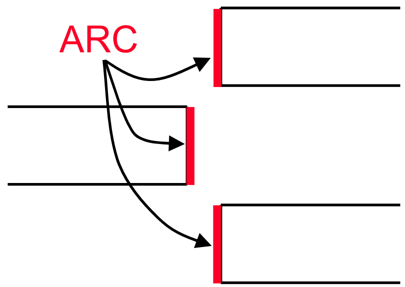


- **Air gap gives rise to standing waves (Fabry-Perot cavity)**
- **Transmitted and reflected power a function of air gap length, optimum for 0.67μm**
- **Must be controlled to ±0.1μm for transmission loss <0.1dB and return loss >15dB**
- **Anti reflective coatings (ARC) on end facets improve performance**

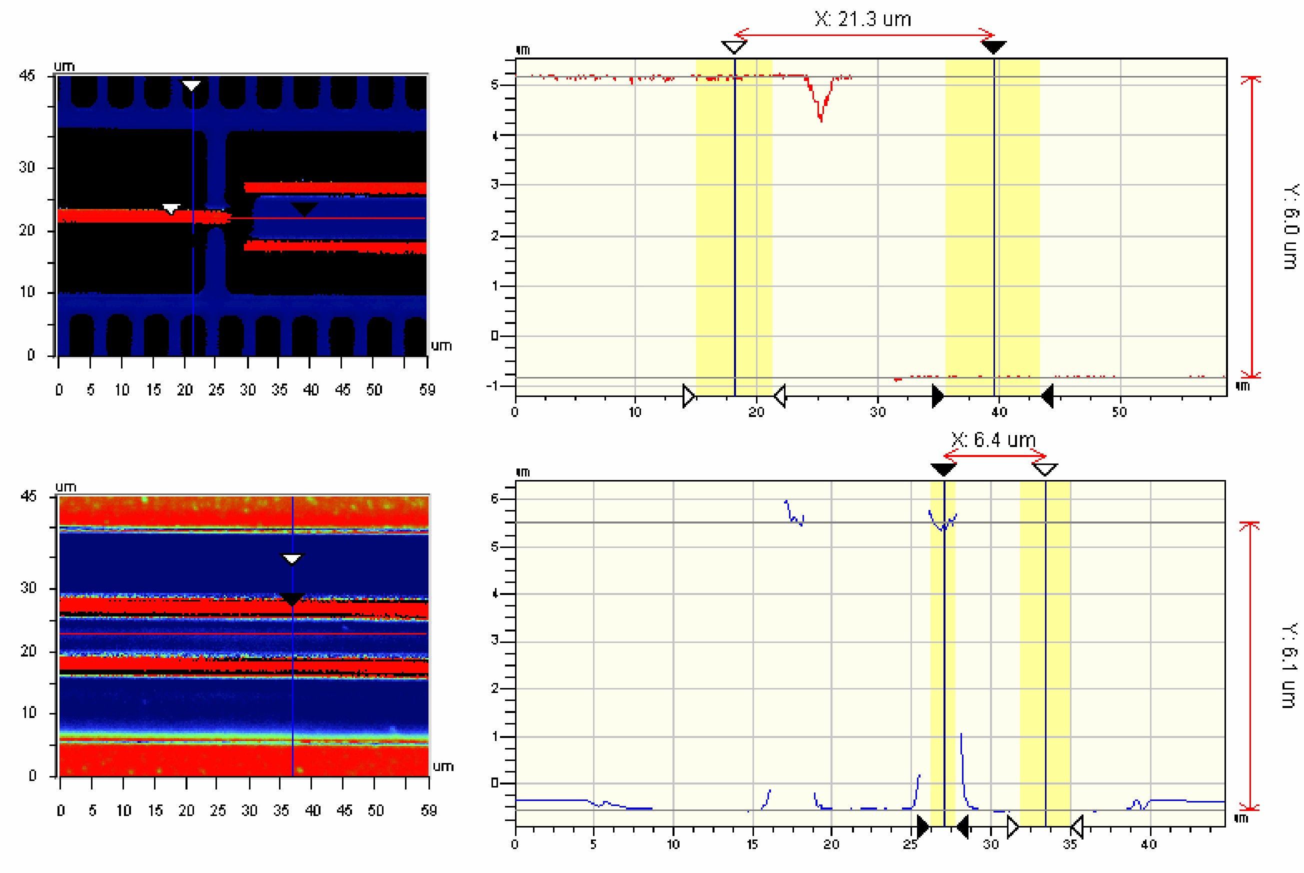
Anti Reflective Coating (ARC) Deposition



- **High density plasma deposition of SiO_xN_y for AR coating (ECR-PECVD)**
- **Tunable refractive index (1.44–1.82)**
- **Good uniformity of sidewall coverage down to 6µm**
- **Allows formation of multilayer ARC**

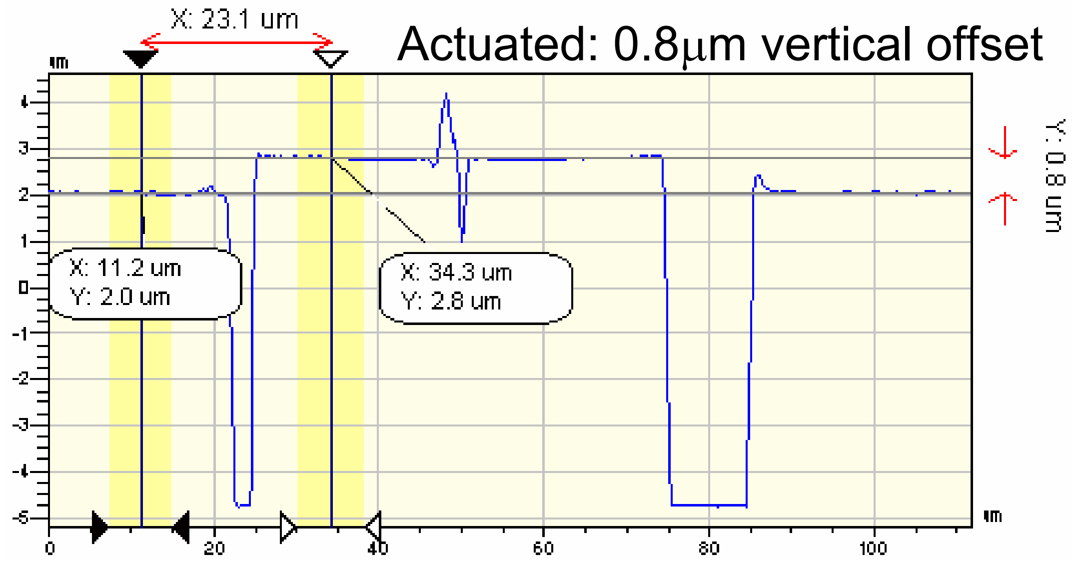


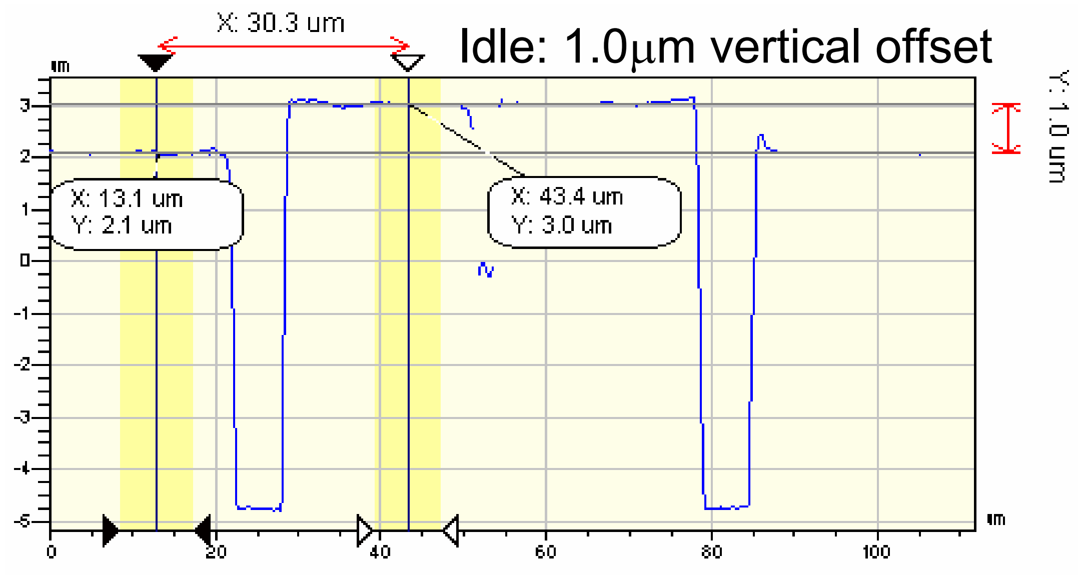
SU-8 / Acrylate Planarization

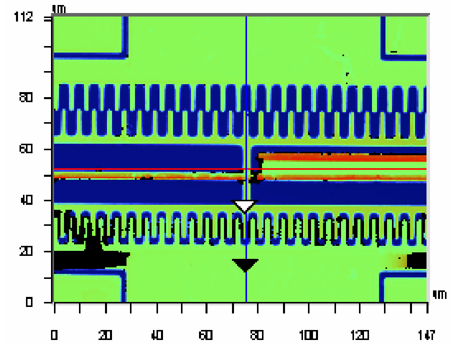


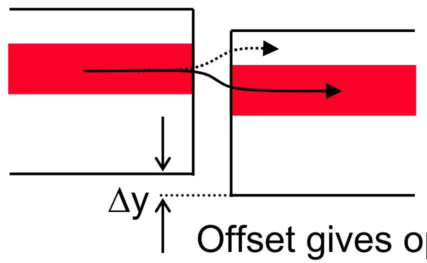
- **Excellent planarity by spin coating acrylate polymer on MEMS structure**
- **Virtually no waveguide thickness variation between areas with large gaps and no gaps**

Vertical Offset of Switch Waveguide

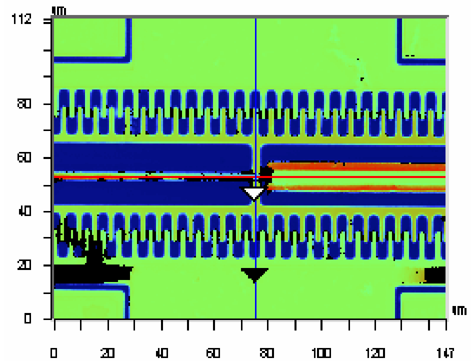








Offset gives optical loss of 1.6dB



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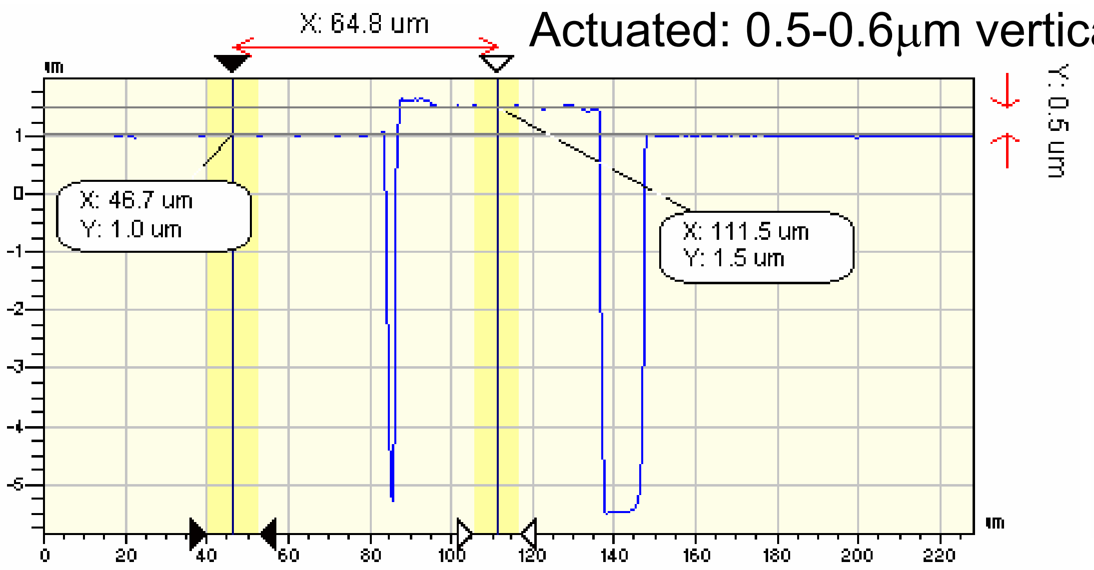
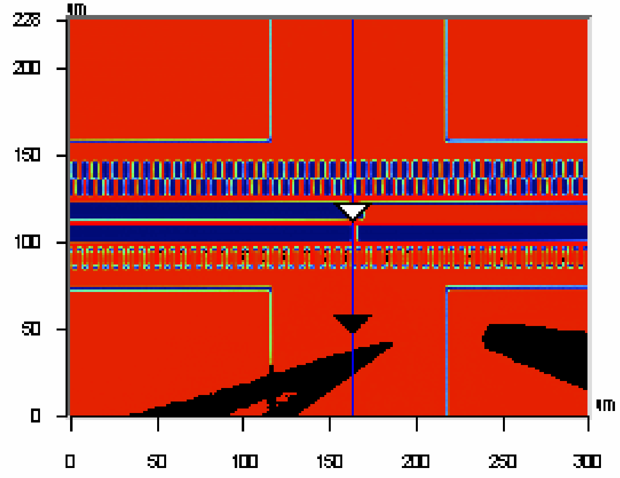
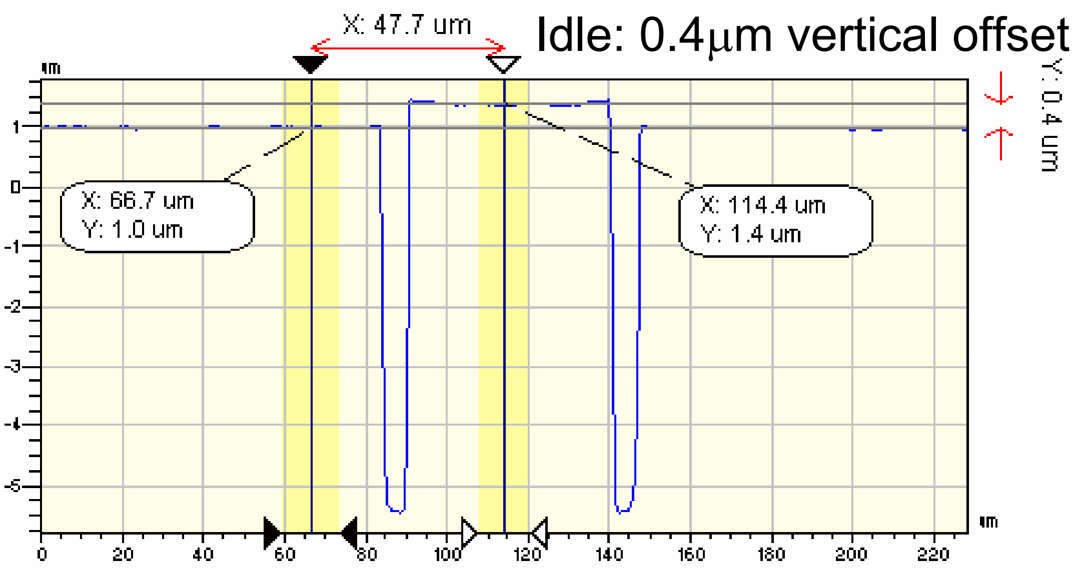
Vertical Offset of Switch Structure without Waveguides

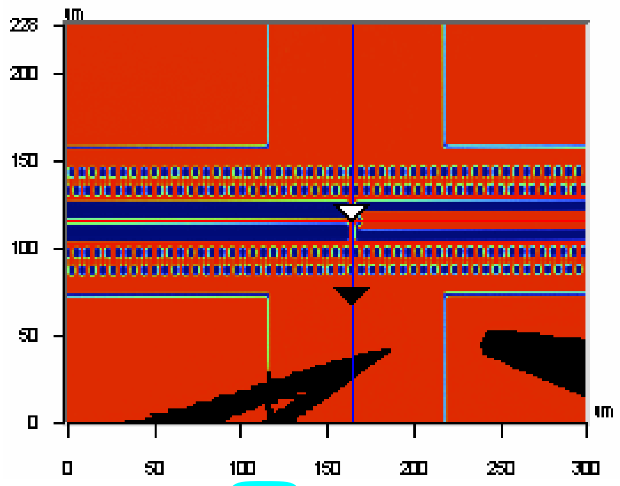
Actuated: 0.5-0.6μm vertical offset



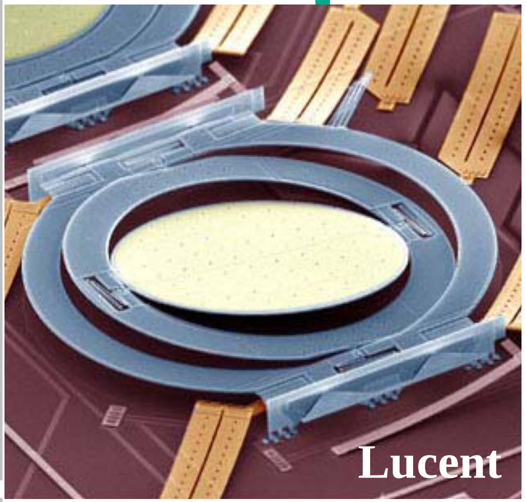


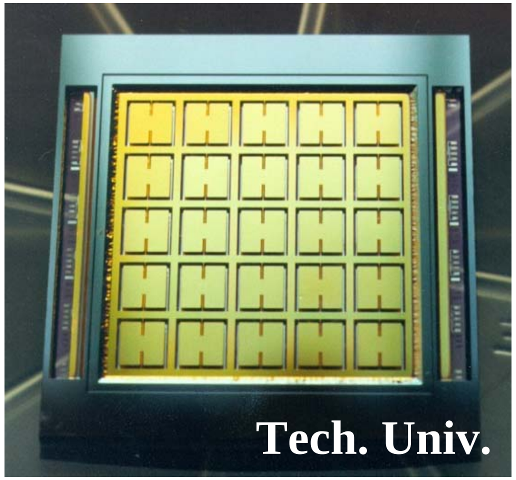
Idle: 0.4μm vertical offset

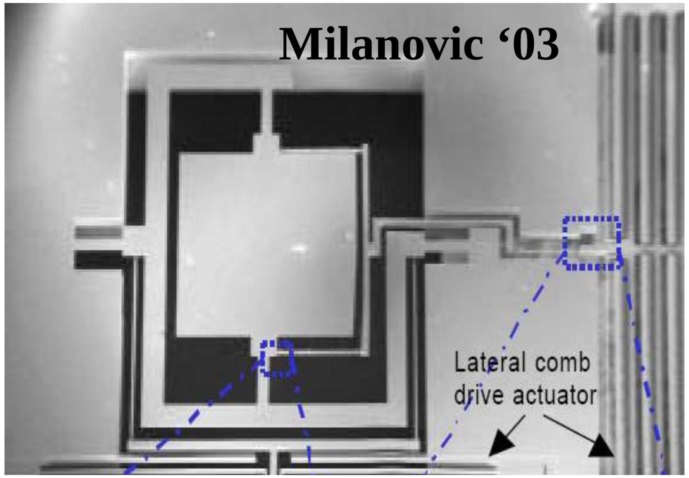


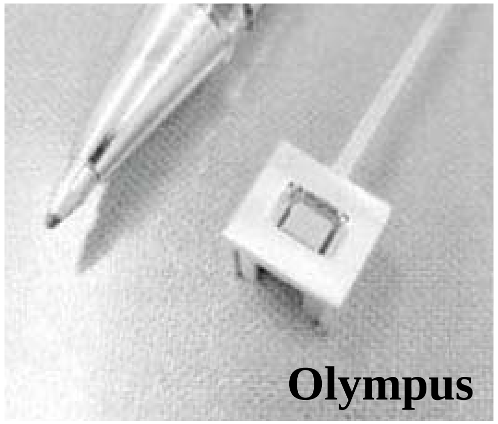


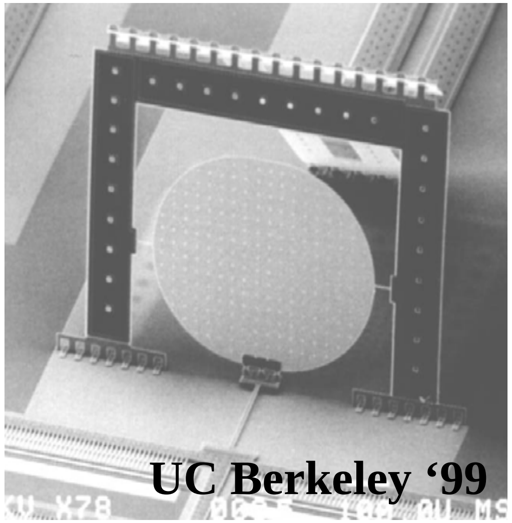
Examples of MEMS scanners

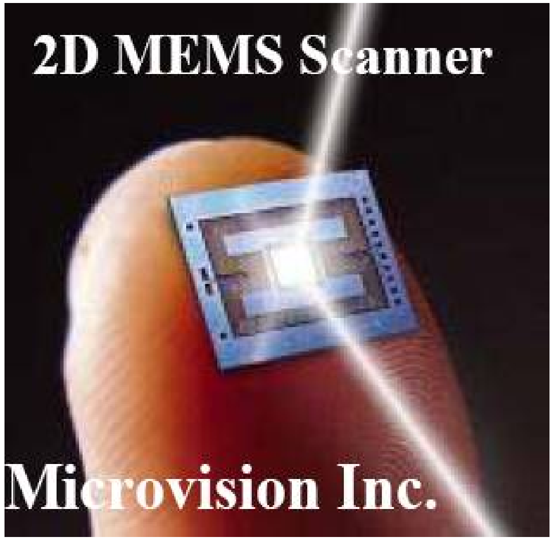












Fraunhofer Institut Photonische Mikrosysteme

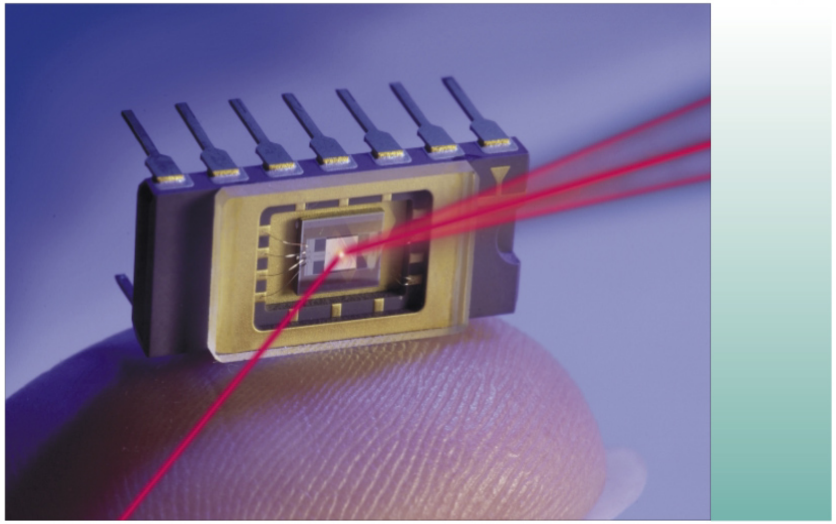
Harald.Schenk@ipms.fraunhofer.de

The Fraunhofer IPMS

Micro Scanning Mirror

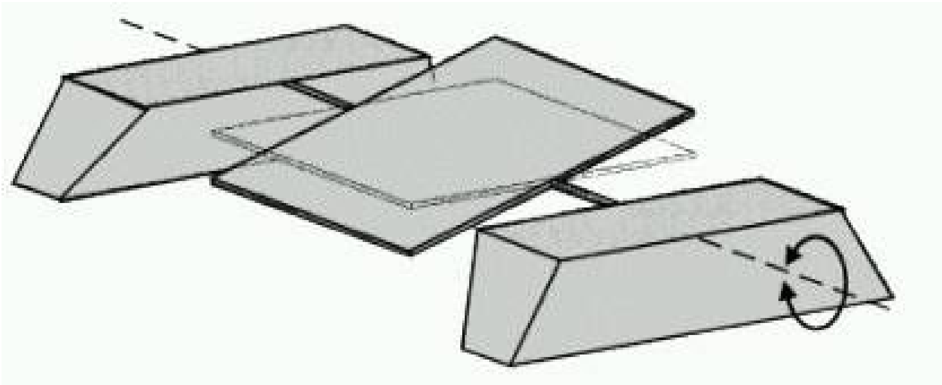
is a single mirror device
for periodic laser beam deflection

MicroSystem Technology



What is so particular about it?

- **properties**
  - very compact
  - large deflection , 2D, fast
  - low voltage / low power
- **mature technology**
  - in manufacture
  - volume testing
  - long product life



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IPMS Fraunhofer Institut Photonische Mikrosysteme

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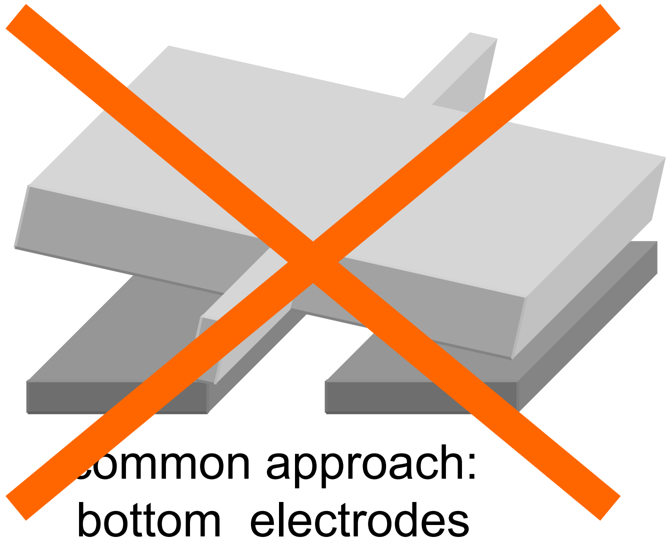
Electrostatic drive: out-of-plane comb drives

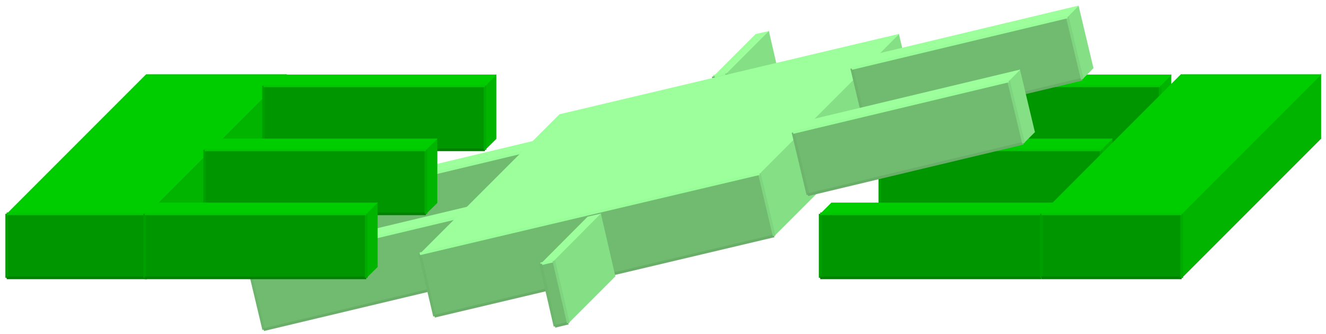
What is so particular about it?

Properties:

- large deflection angle (typ. ±15°)
- low voltage (typ. below 20V)
- resonant operation (200Hz .. 35kHz)
- 1D and 2D (2D by gimbal)
- low power consumption



Common approach:
bottom electrodes
- limited deflection
- several 100V



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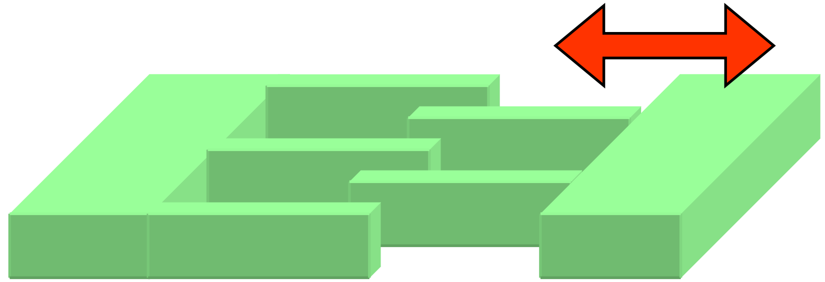
Out-of-plane comb drives

Conventional in 1997

- **Longitudinal in-plane displacement**
  - large stroke
  - as drive combs



- **Lateral in-plane displacement**
  - large capacitance variation
  - for position sensing

New principle in 1997 (patent)

- **Out-of-plane comb drives**
  - large capacitance variation
  - unlimited deflection

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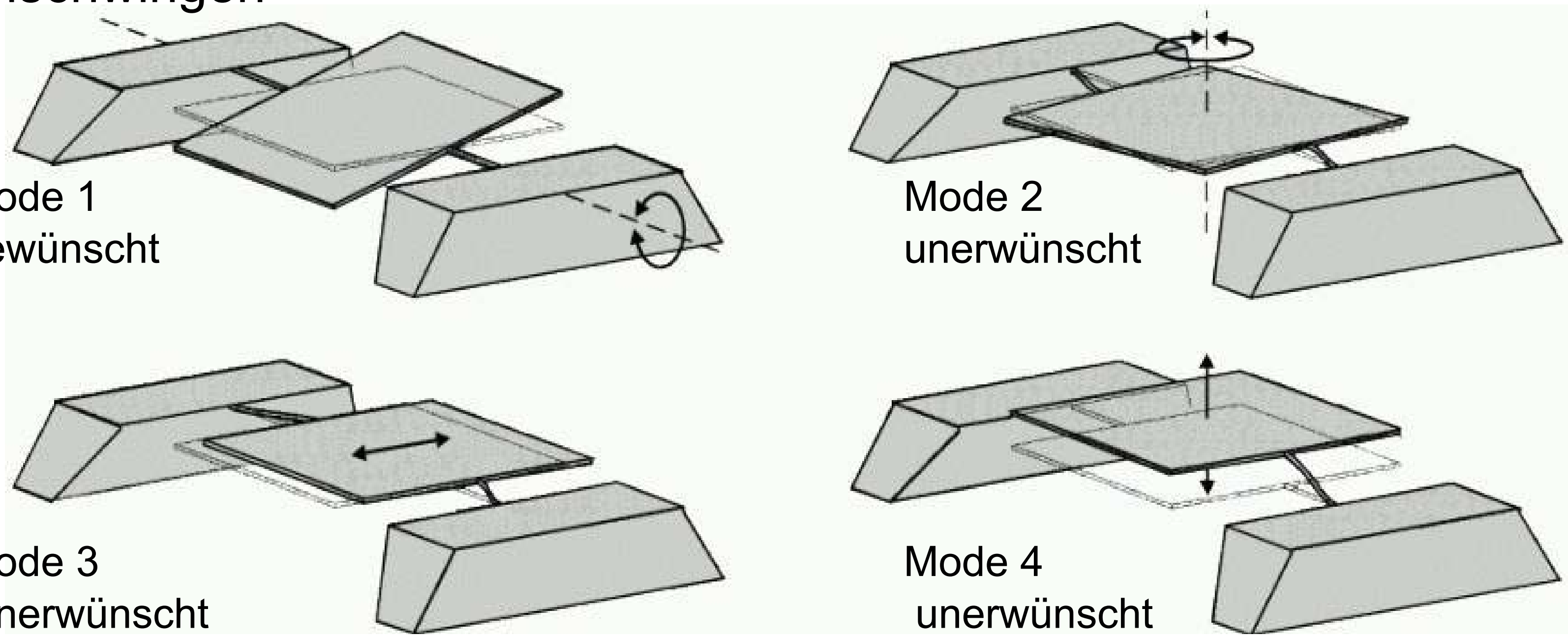
Mögliche Schwingungen

Durch Simulation wird im Voraus kontrolliert, dass unerwünschte Schwingungsmoden höhere Resonanzfrequenzen haben und nicht anschwingen



Mode	Oscillation	ANSYS	Analytical
1	**torsion around spring axis**	**684 Hz**	**672 Hz**
2	**translation in mirror plane**	**1672 Hz**	**1680 Hz**
3	**torsion in mirror plane**	**2757 Hz**	**2505 Hz**
4	**translation perp. to mirror plane**	**5139 Hz**	**5600 Hz**

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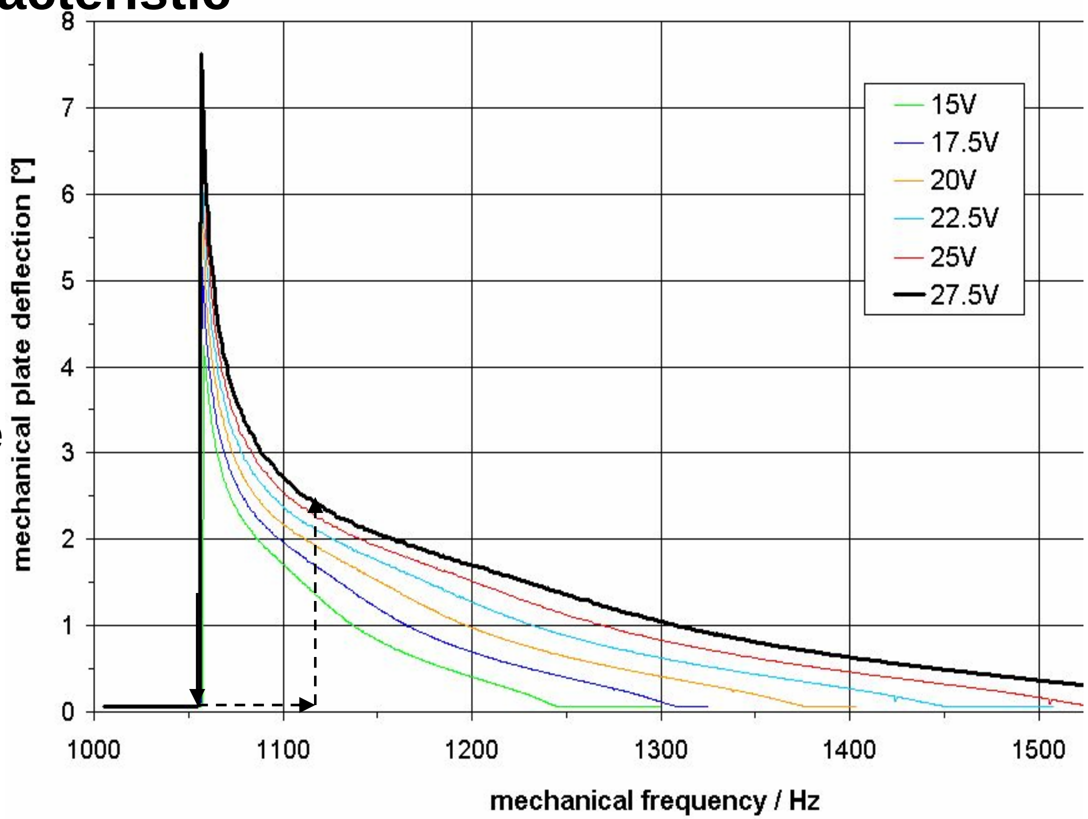
Fixed frequency operation

Amplitude-frequency-characteristic
(inharmonic drive)

- **high amplitude peak** near natural frequency
- **no oscillation below**
- reduced amplitude above
- no stable working point at maximum amplitude



Exploiting max amplitude:

- **Closed-loop operation**

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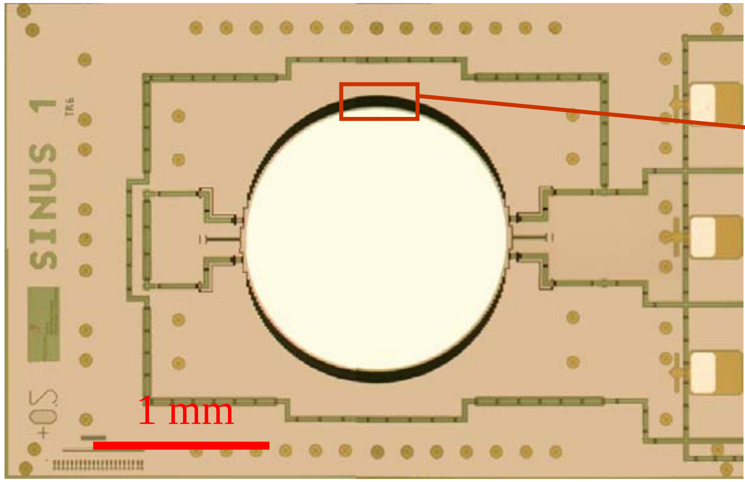
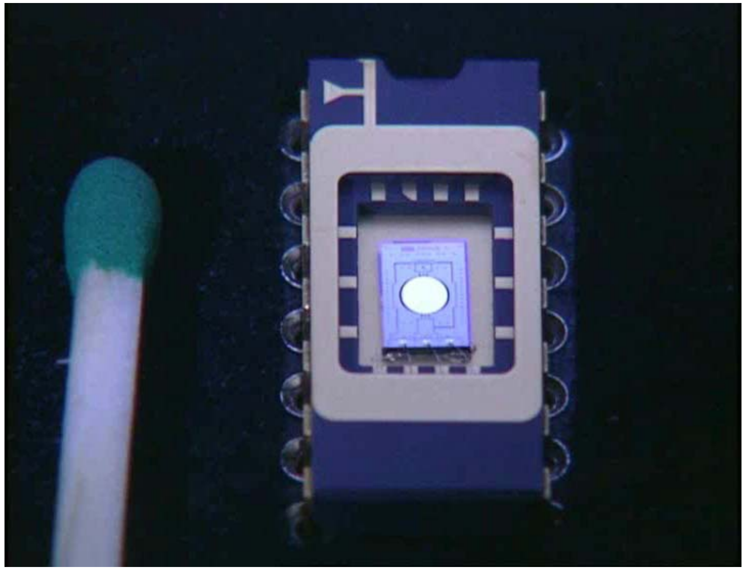
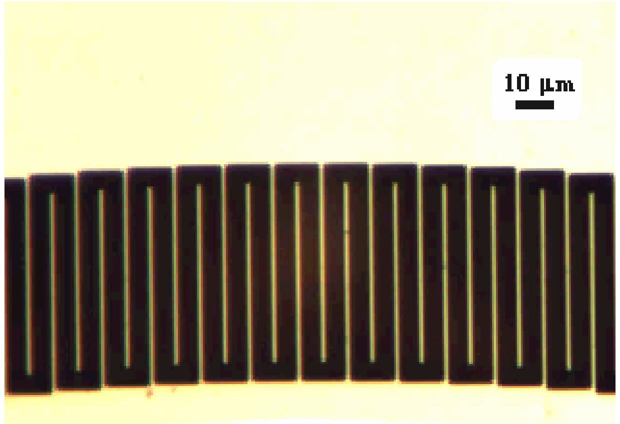
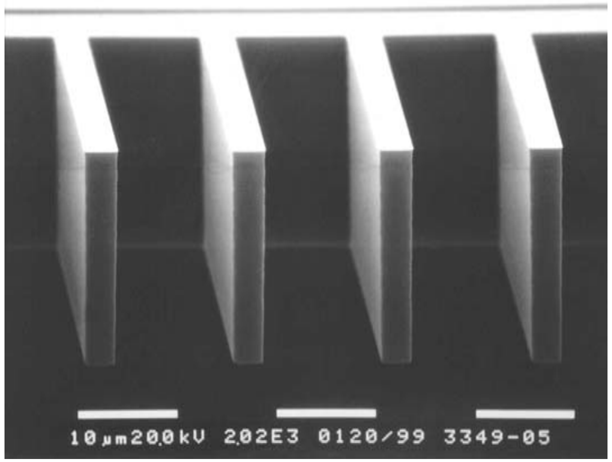
Circular 1D Micro Scanning Mirror









example of parameters	**1D**
scan frequency	300 Hz
scanned range	60 °
mirror plate	circular, 1.5 mm
chip size	2.9 x 4.3 mm²

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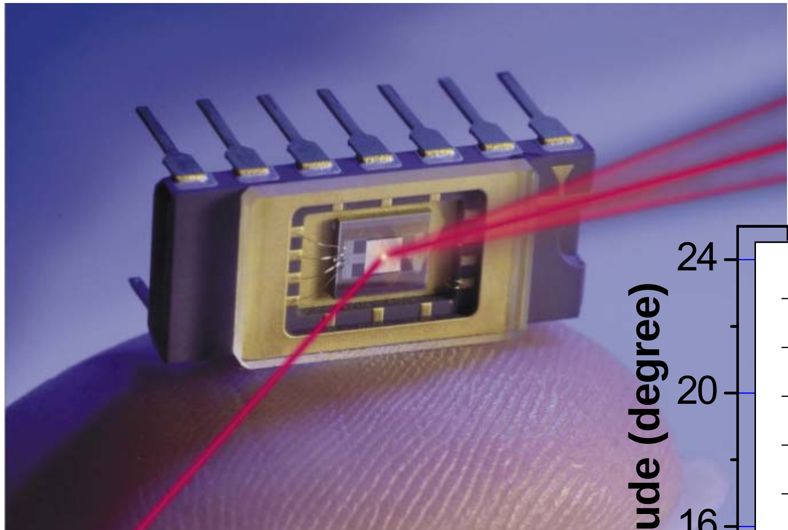
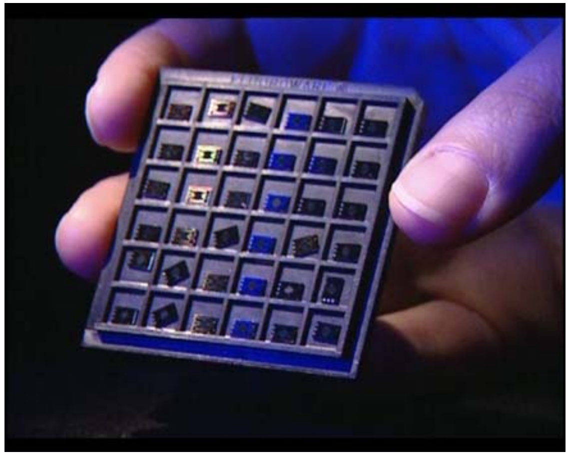
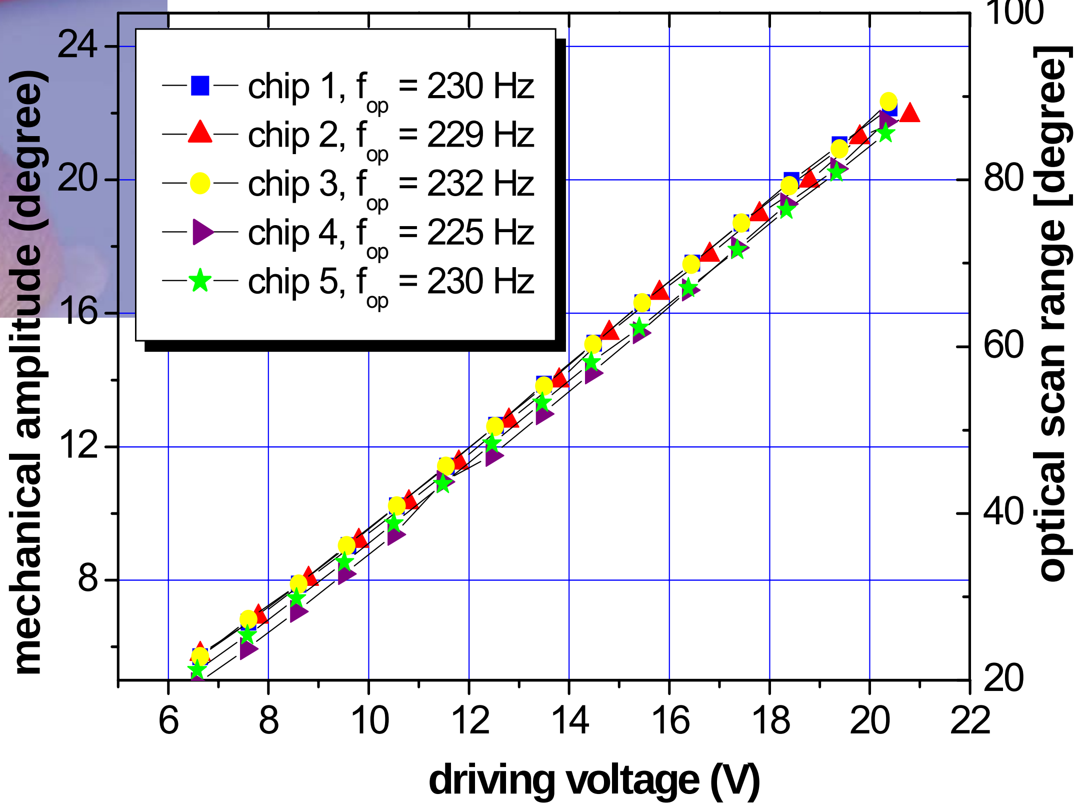
1D Micro Scanning Mirror







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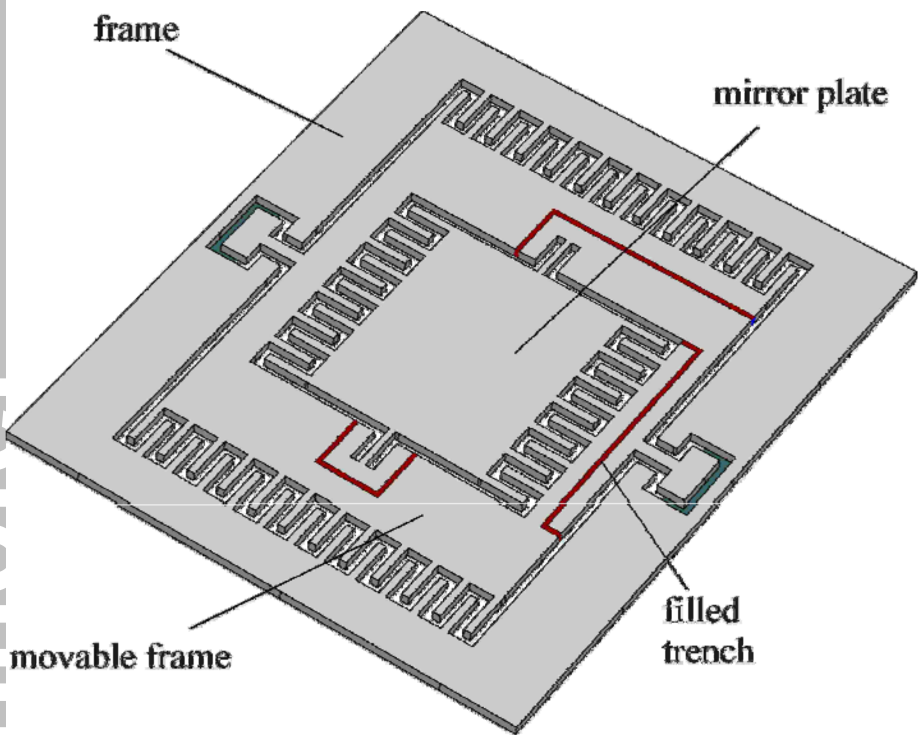
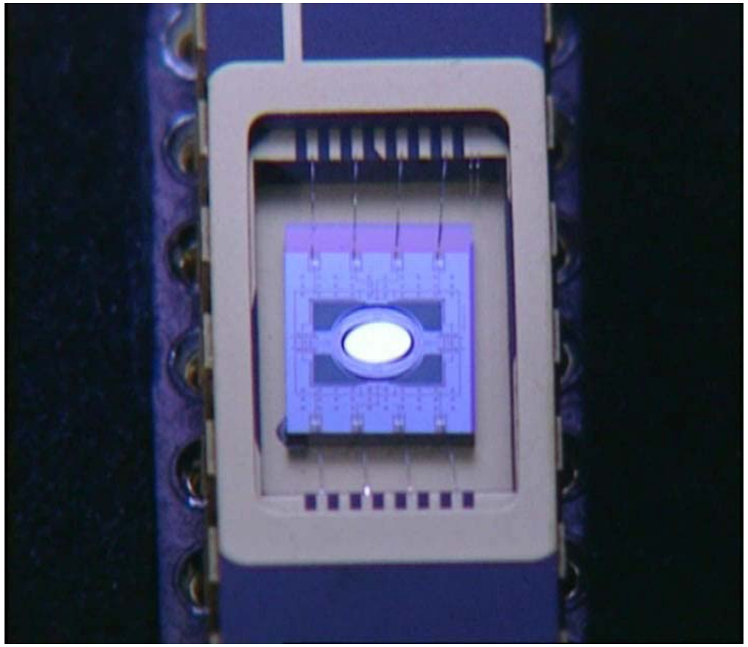
2D-Micro-Scanner



Gimbal
- **Deflectable mirror plate**
- **in a larger deflectable plate**
- **with perpendicular axes**

Advantages
- **independent frequencies**
- **no sagging**



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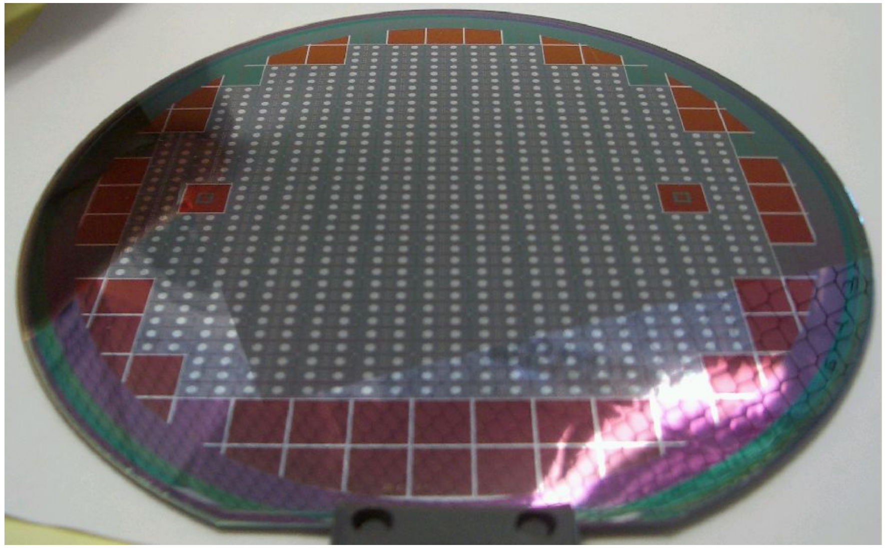
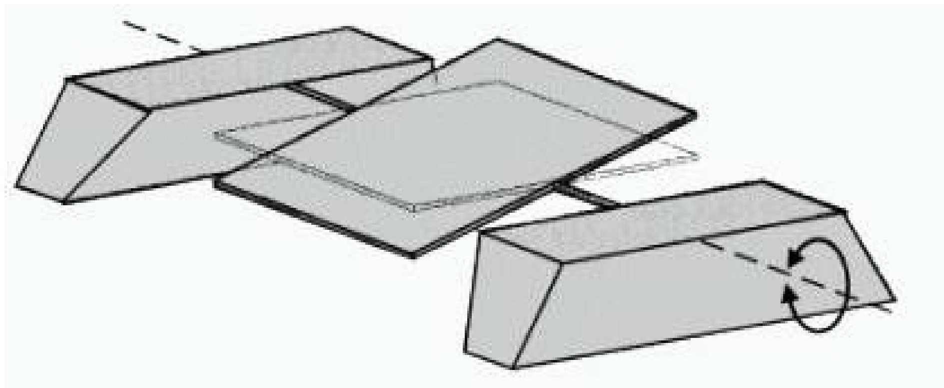
The Fraunhofer IPMS

Micro Scanning Mirror

How is it made?

- Monolithic integration
  - wafer process
- all elements in single crystalline silicon
  - torsional hinges
  - mirror plate
  - stiff frame





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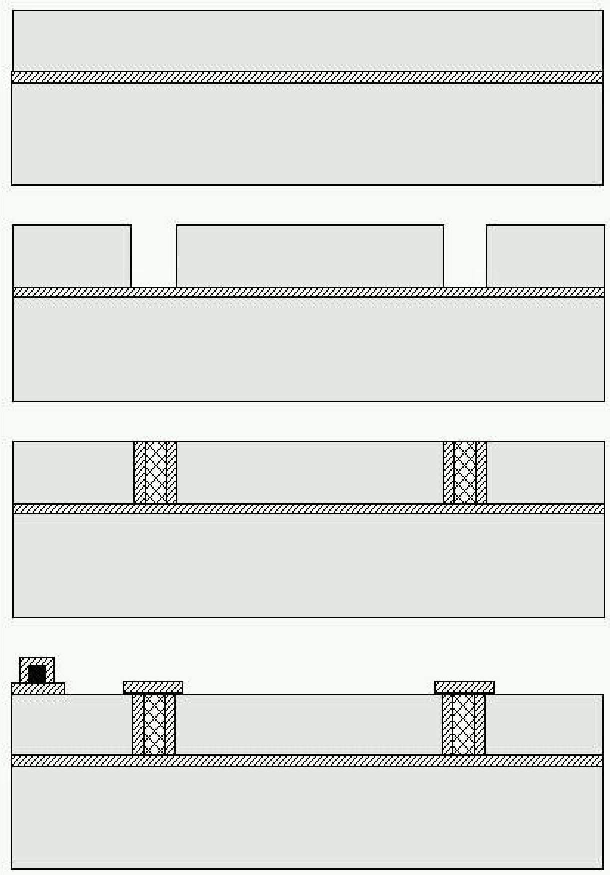
How is it made?

Process flow (feature: filled isolation trenches)



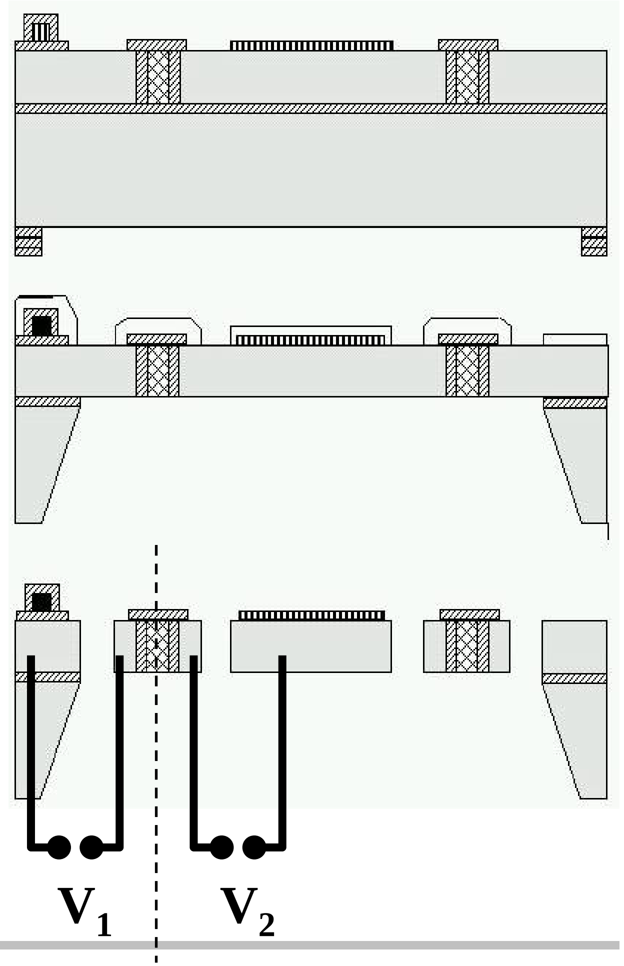
SOI
30µm crystalline Si
<0.025 Ωcm

DRIE
dry anisotropic

oxidization
thermal

re-fill **poly-Si**

capping
CVD



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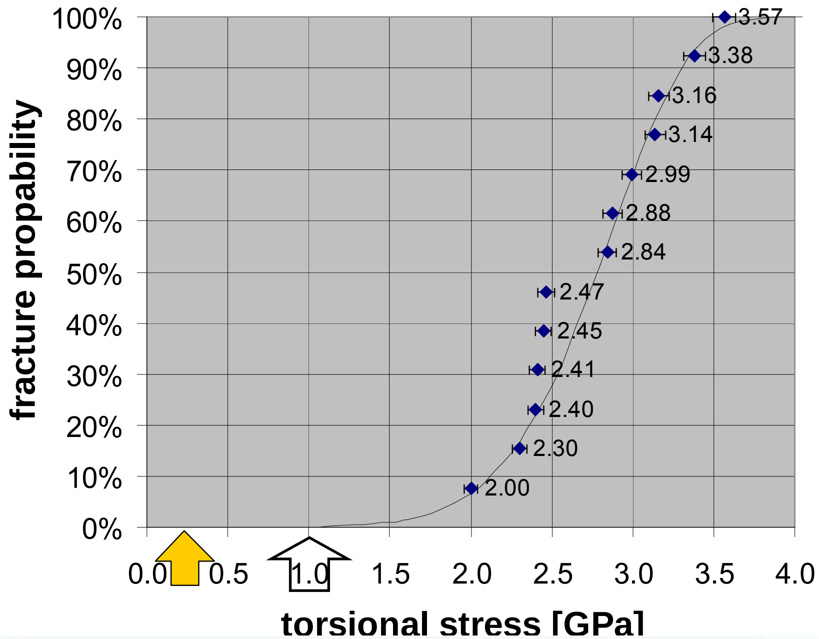
Where are the limits?

Torsional stress in springs

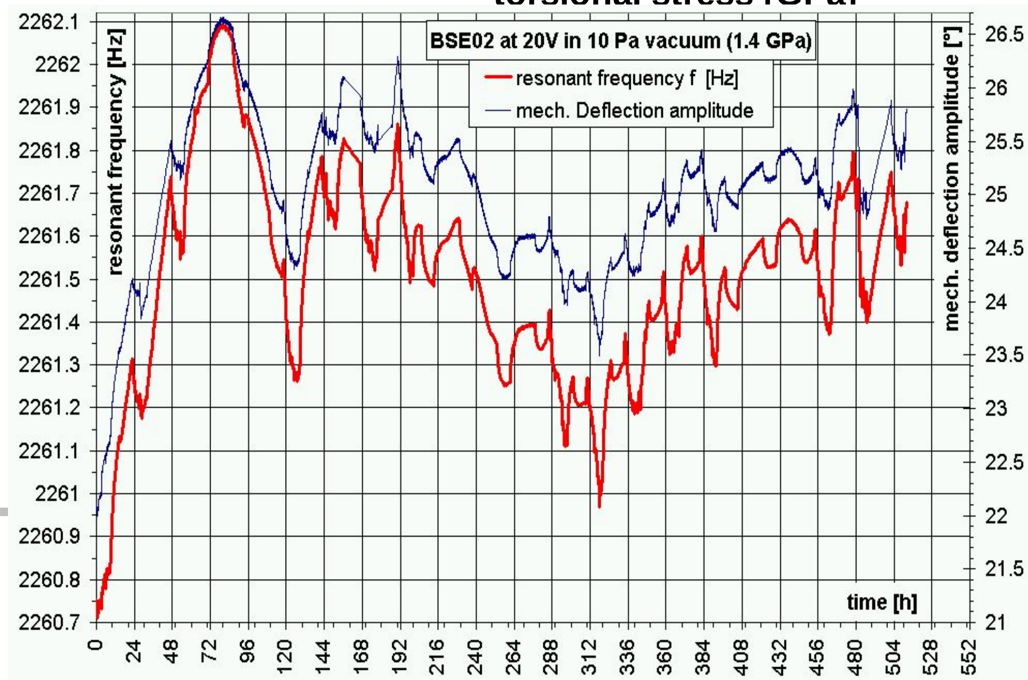
High loads

- Fracture at 2 GPa .. 3.6 GPa
- Safe operation below 1.0 GPa



Fatigue in long-run

- 1.4 GPa for 500h
- No frequency drift
  2261.4Hz ± 0.7Hz
  (±0.03%)
- No amplitude drift
  24.3° ±2.3° (±4.6%)
- No sign of fatigue



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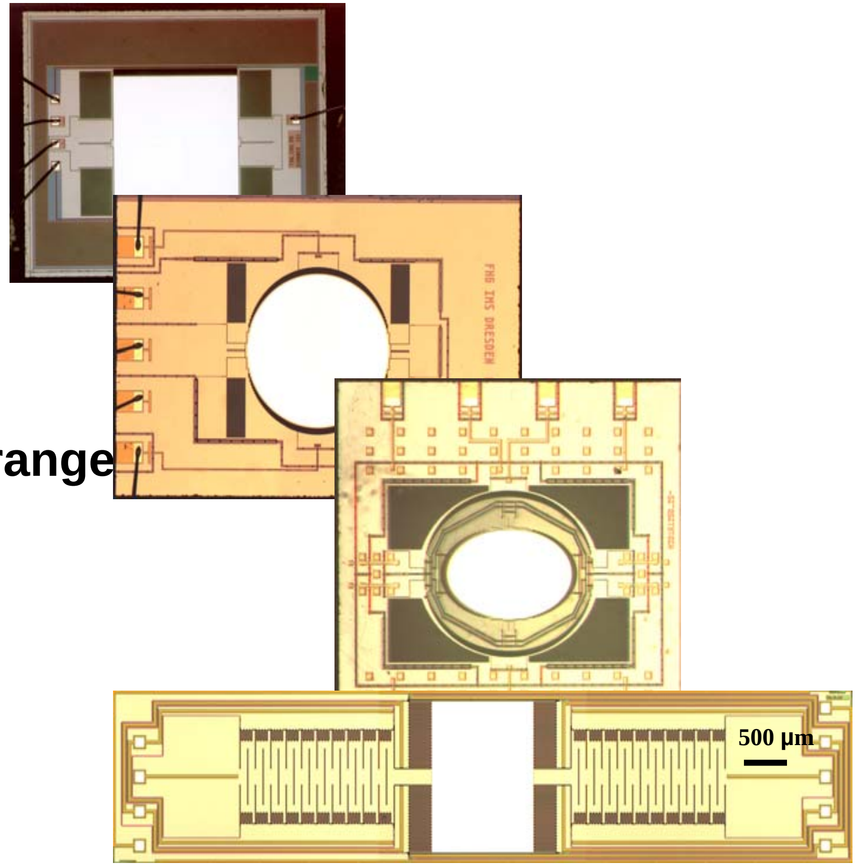
Design space in current standard technology

- Frequencies
  - **0.2 kHz … 35 kHz**
- Mirror diameter
  - **0.5 mm … 3.0 mm**
- Deflection angle
  - **Up to +/- 34° (136° optical scan range**
- Mirror flatness
  - **Better than** $\lambda/10$
- 1D and 2D, rotational
- Translational



Note: Not all of the parameters can be combined

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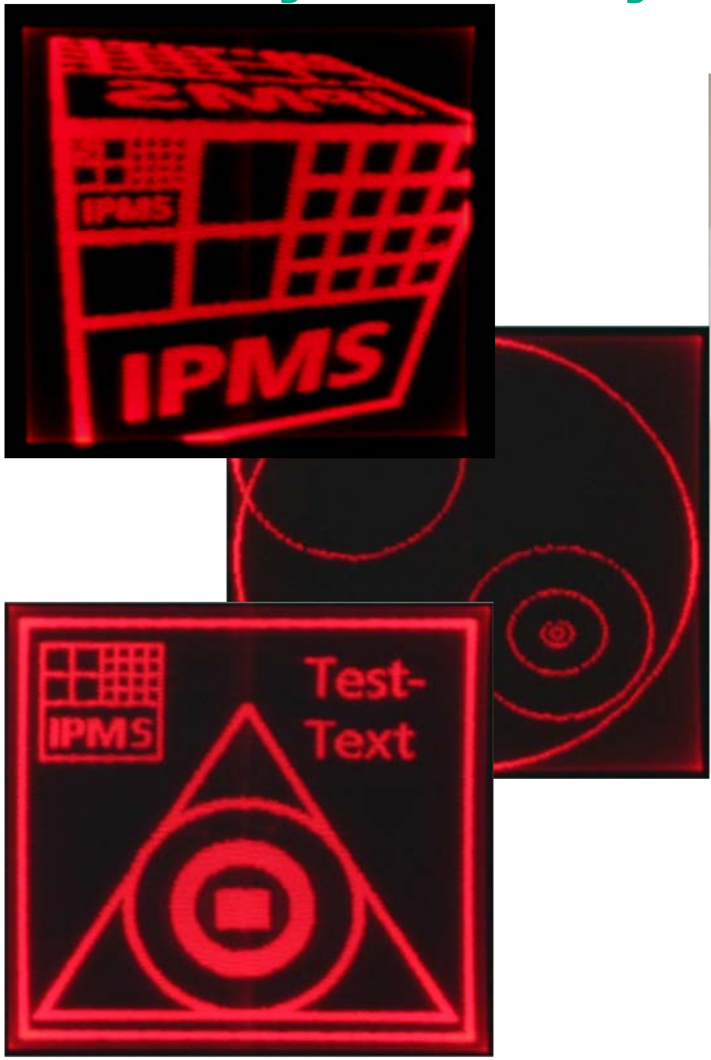
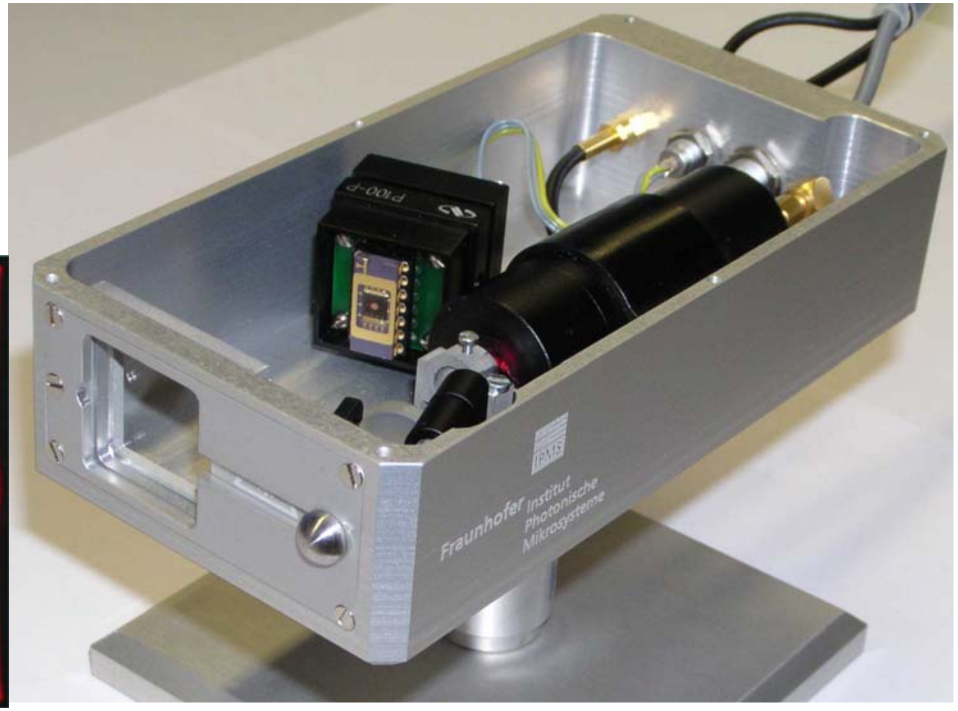
Lissajous-Projection





Frequency ratio: 1 : 6.7
256 x 256 addressed pixels
Repetition rate: 40 Hz

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