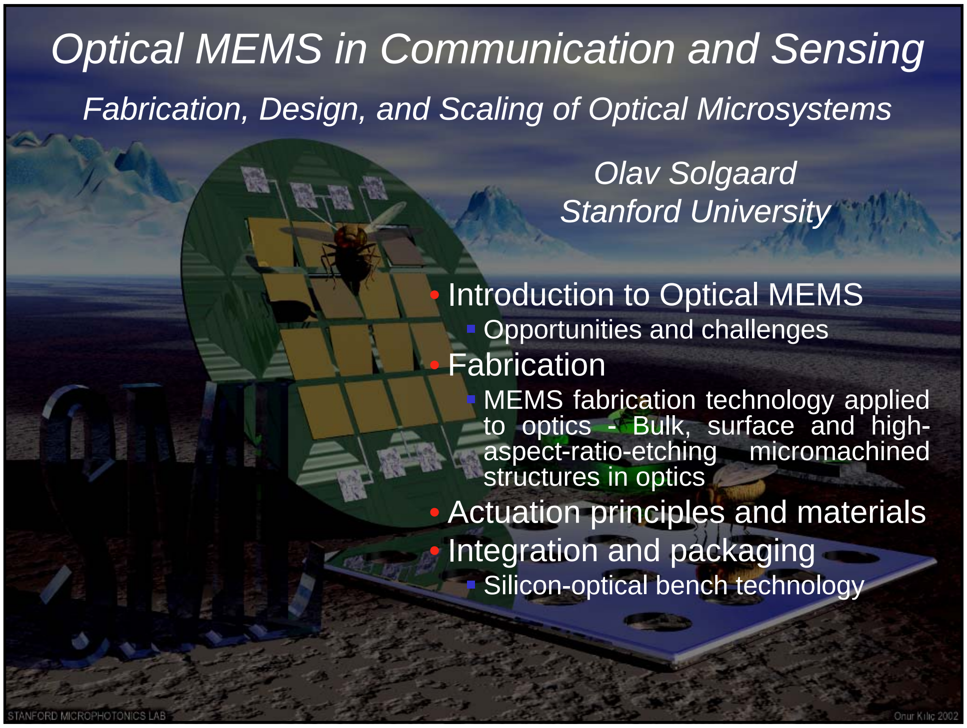


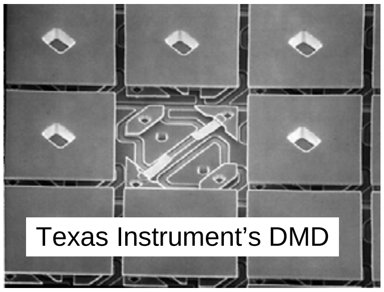
Optical MEMS in Communication and Sensing

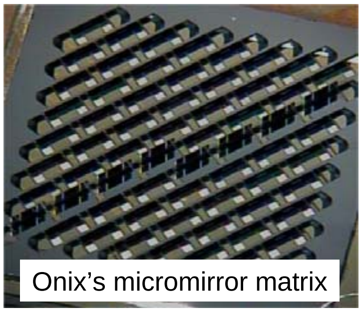
Fabrication, Design, and Scaling of Optical Microsystems

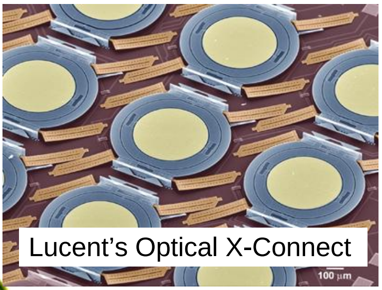
Olav Solgaard
Stanford University

- Introduction to Optical MEMS
  - Opportunities and challenges
- Fabrication
  - MEMS fabrication technology applied to optics - Bulk, surface and high-aspect-ratio-etching micromachined structures in optics
- Actuation principles and materials
- Integration and packaging
  - Silicon-optical bench technology

Micromirror Arrays


Texas Instrument's DMD


Onix's micromirror matrix

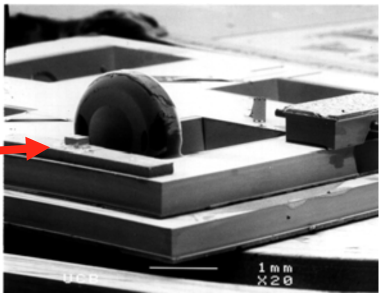


Lucent's Optical X-Connect

- Large arrays => Large apertures
- The optical quality of the individual microoptical elements is not critical
- Uniformity is very important
- Integration, not optical quality, is the biggest challenge
- IC technology is preferred!

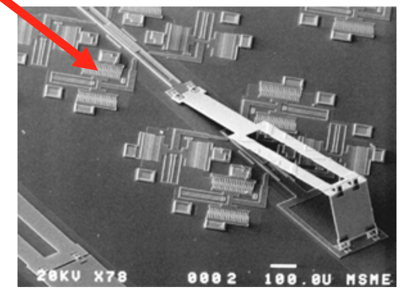
Integration

System on a chip

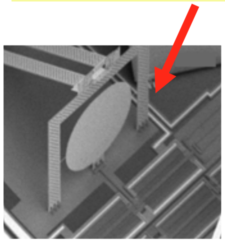


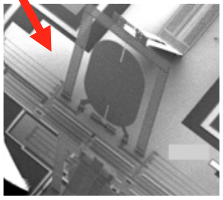
Laser-to-fiber coupling

Micropositioners for mirrors and gratings



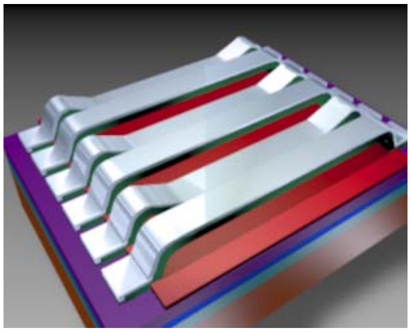
High-resolution raster scanner





Unique Functionality

- Diffractive/Adaptive micro optics
- Sub-wavelength structures and Photonic Crystals
- Applications:
  - 1-D and 2-D spatial light modulators (Projection displays - Silicon Light Machines)
  - Displacement sensors (AFM arrays - C. Quate)
  - IR sensors
  - Sensor integration, free-space communication
  - Diffractive lenses and holograms (Fresnel zone plates - M. Wu, UCLA)
  - Spectroscopy

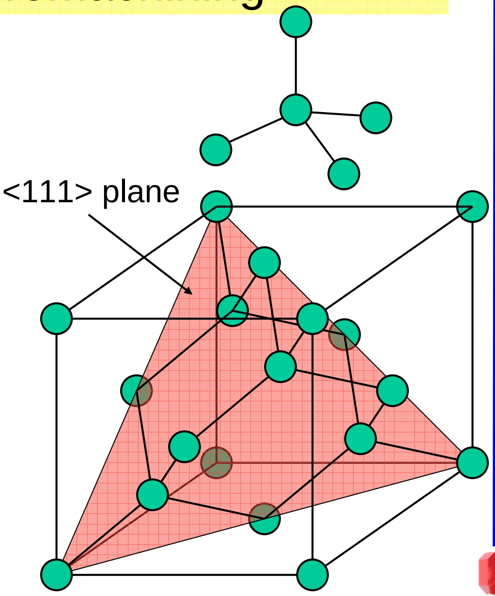


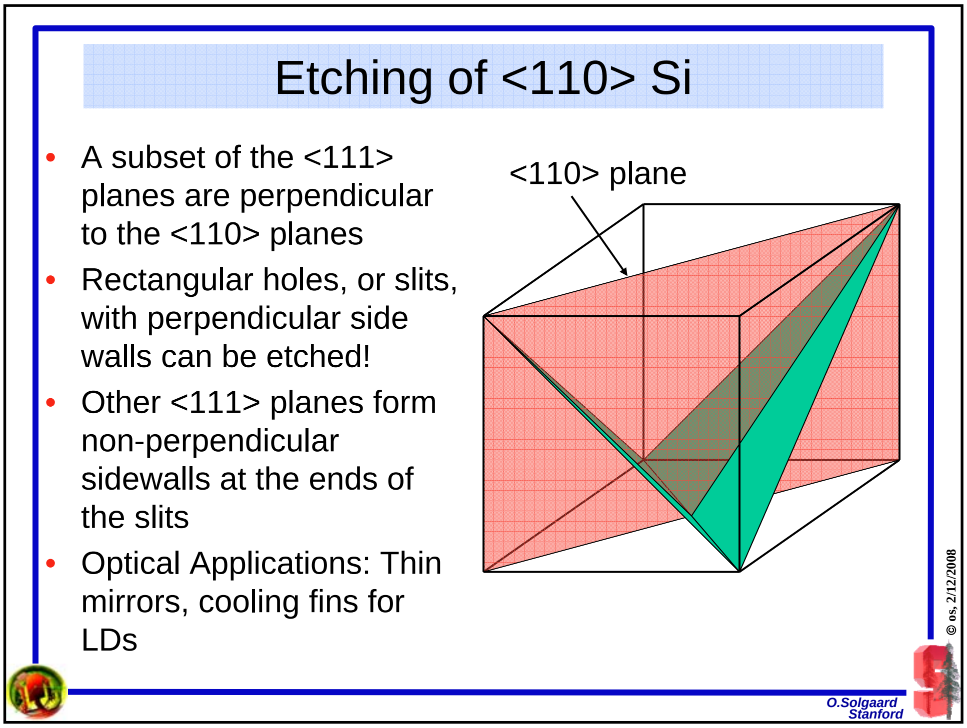
Why Optical MEMS?

- Parallel processing, arrays
  - Compatible with IC-fabrication technology
- Systems on a chip
  - Integration of optics, electronics, and mechanics
- New functionality
  - Diffractive/adaptive optics, Photonic bandgap, Subwavelength structures
- Applications
  - Spatial light modulators, communication, transducers, Raster-scanning displays, fiber switches, data storage, barcode readers, femtosecond laser-pulse shaping, optical coherence tomography, adaptive optics, external cavity lasers, printing, vector scan, surveillance, optical interconnects, FTIR ......
- Challenges:
  - Alignment, Resolution, Optical quality, Mechanical stability, high speed, high contrast, high optical power
  - Design for parallel processing and integration
- Micromachining is an enabling technology!

Bulk Micromachining

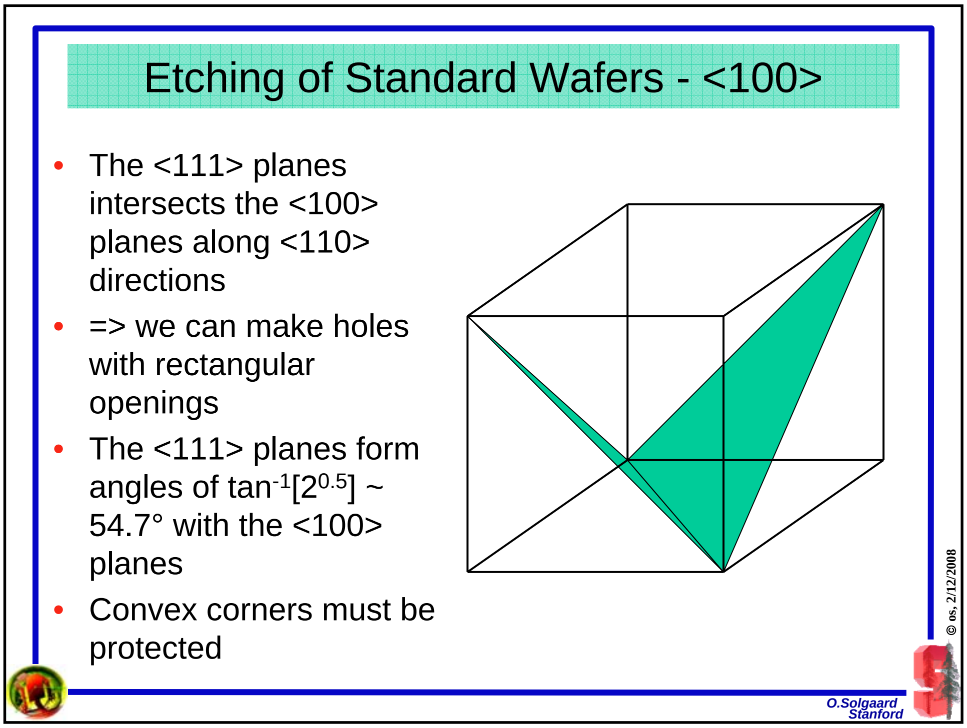
- Si and Ge crystals have diamond structure
- The <111> planes have fewer dangling bonds
- => <111> planes etches slowly in some etchants
- the etch-rate ratio can exceed 1,000
- Common anisotropic etchants: Potassium hydroxide (KOH), Ethylene Diamine (EDP), Tetramethyl Ammonium Hydroxide (TmAH),





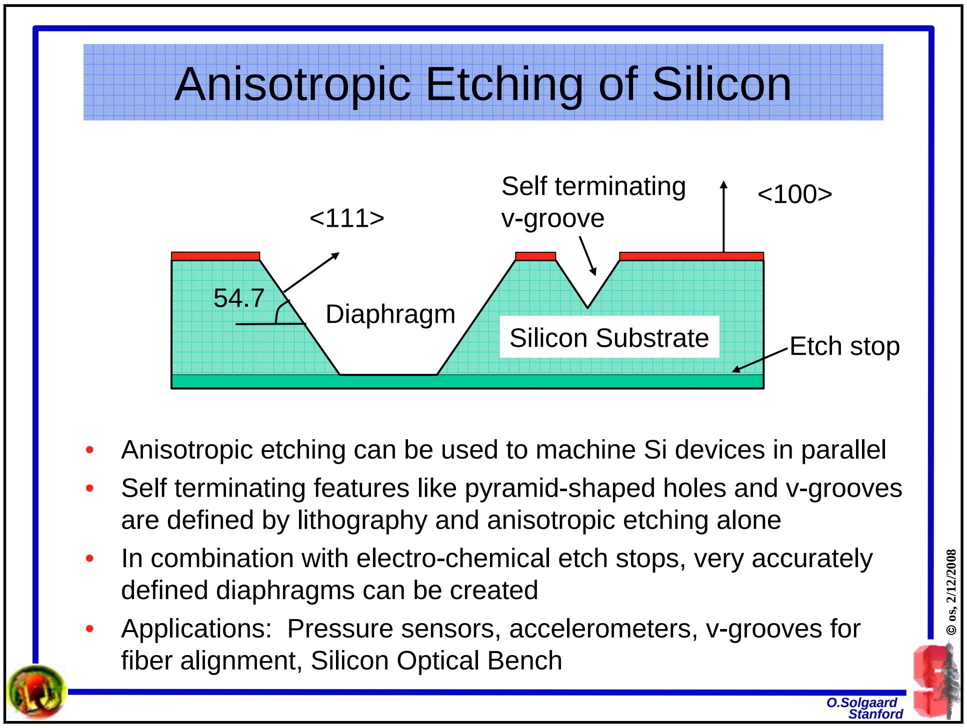
Etching of <110> Si

- A subset of the <111> planes are perpendicular to the <110> planes
- Rectangular holes, or slits, with perpendicular side walls can be etched!
- Other <111> planes form non-perpendicular sidewalls at the ends of the slits
- Optical Applications: Thin mirrors, cooling fins for LDs



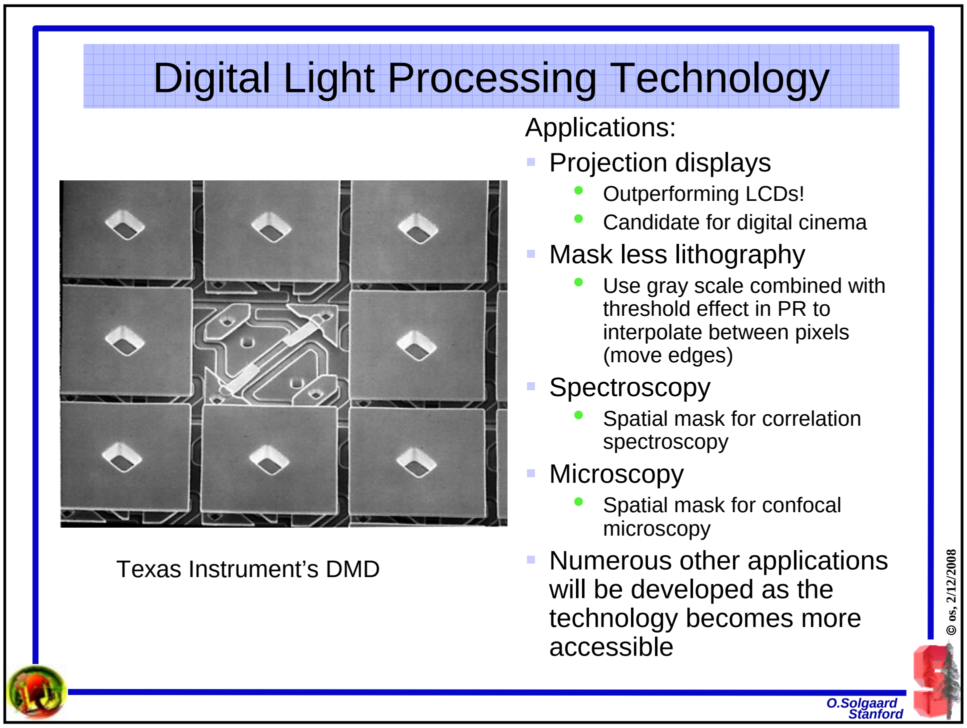
Etching of Standard Wafers - <100>

- The <111> planes intersects the <100> planes along <110> directions
- => we can make holes with rectangular openings
- The <111> planes form angles of $\tan^{-1}[2^{0.5}]$ ~ 54.7° with the <100> planes
- Convex corners must be protected



Anisotropic Etching of Silicon

- Anisotropic etching can be used to machine Si devices in parallel
- Self terminating features like pyramid-shaped holes and v-grooves are defined by lithography and anisotropic etching alone
- In combination with electro-chemical etch stops, very accurately defined diaphragms can be created
- Applications: Pressure sensors, accelerometers, v-grooves for fiber alignment, Silicon Optical Bench

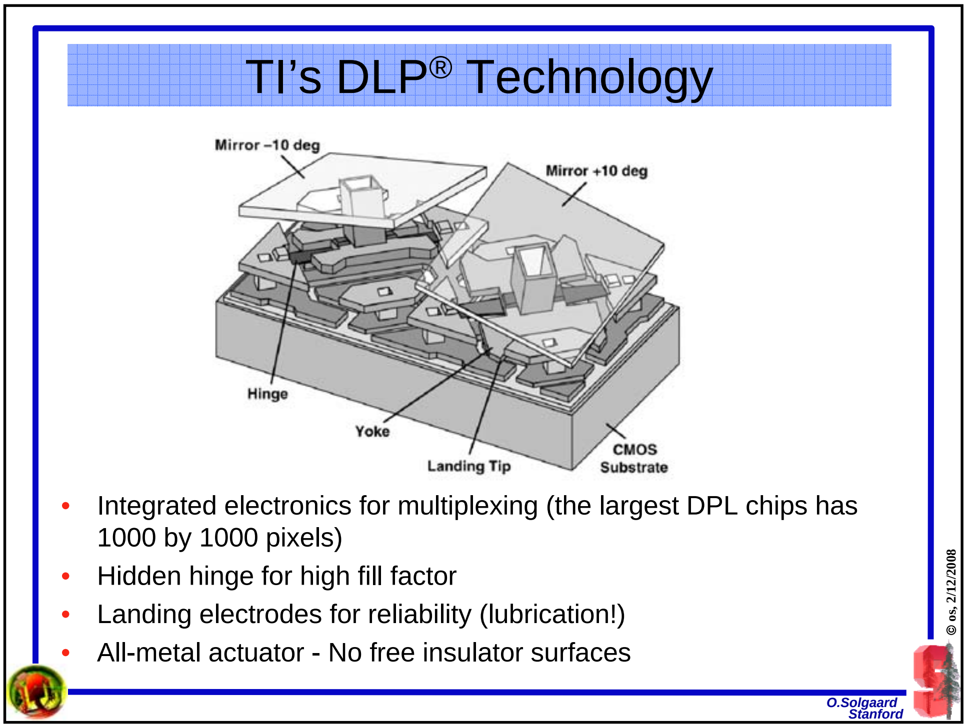


Digital Light Processing Technology

Texas Instrument's DMD

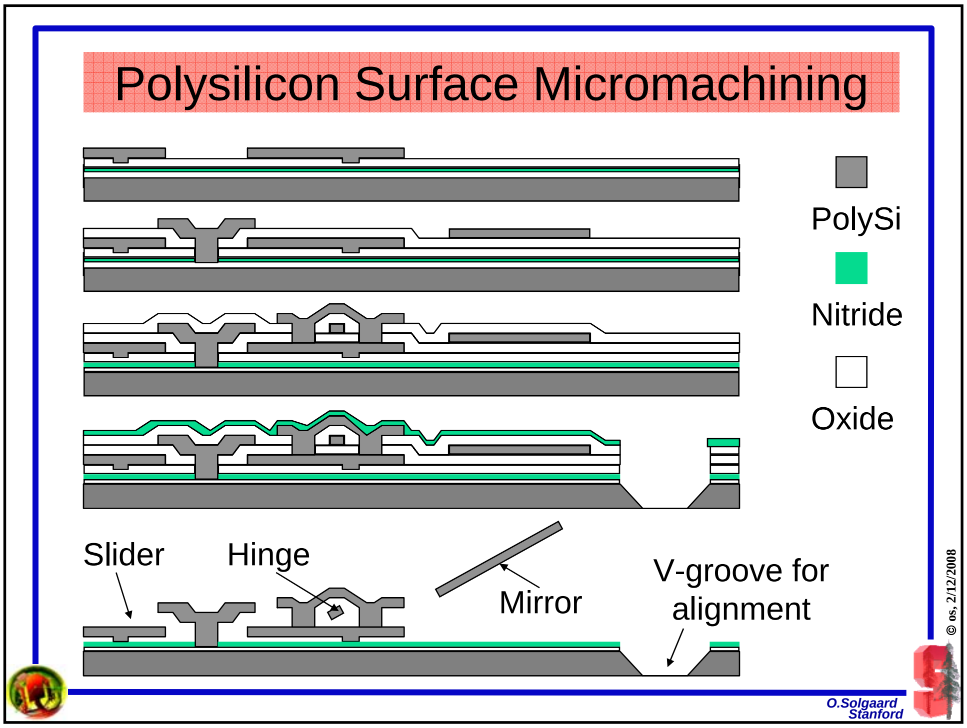
Applications:

- Projection displays
  - Outperforming LCDs!
  - Candidate for digital cinema
- Mask less lithography
  - Use gray scale combined with threshold effect in PR to interpolate between pixels (move edges)
- Spectroscopy
  - Spatial mask for correlation spectroscopy
- Microscopy
  - Spatial mask for confocal microscopy
- Numerous other applications will be developed as the technology becomes more accessible



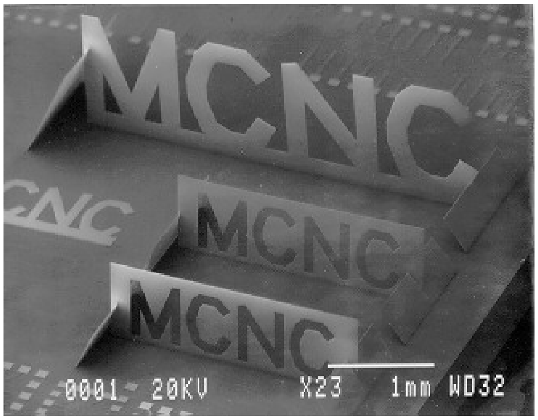
TI's DLP® Technology

- Integrated electronics for multiplexing (the largest DPL chips has 1000 by 1000 pixels)
- Hidden hinge for high fill factor
- Landing electrodes for reliability (lubrication!)
- All-metal actuator - No free insulator surfaces



Polysilicon Surface Micromachining

Commercial Polysilicon Surface micromachinig



MCNC's Multi User MEMS Process (MUMPS) – started 1992

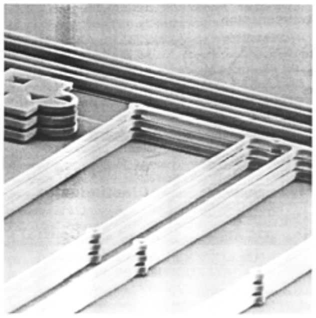
Sandia process: planarization => stackable poly

**5-Level Polysilicon surface Micromachine Technology:
Application to Complex Mechanical Systems**

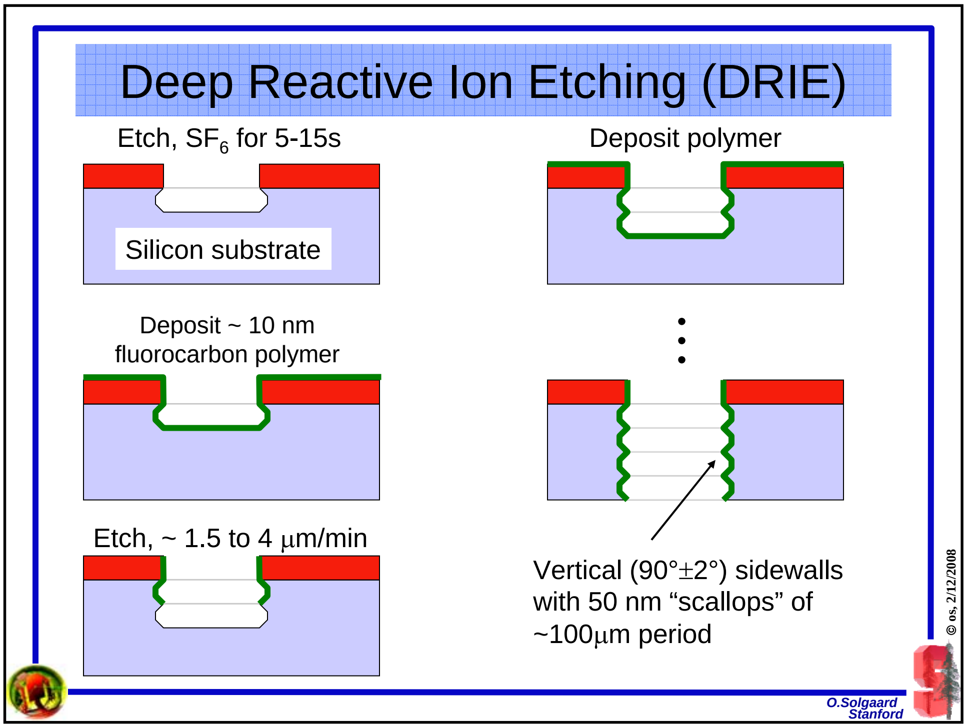
M. Steven Rodgers and Jeffry J. Sniegowski
Intelligent Micromachine Department Sandia National Laboratories
Albuquerque, New Mexico 87185-1080

Solid-State Sensor and
Actuator Workshop
Hilton Head 1998

Picture 4. All four mechanical layers of polysilicon are utilized to increase electrostatic actuator performance. In this region, the first two are laminated together to form a more rigid base layer.



Picture 5. Similar layering of the support springs generates a structure that is approximately 100 times stiffer than first generation devices in the "z" axis.



Deep Reactive Ion Etching (DRIE)

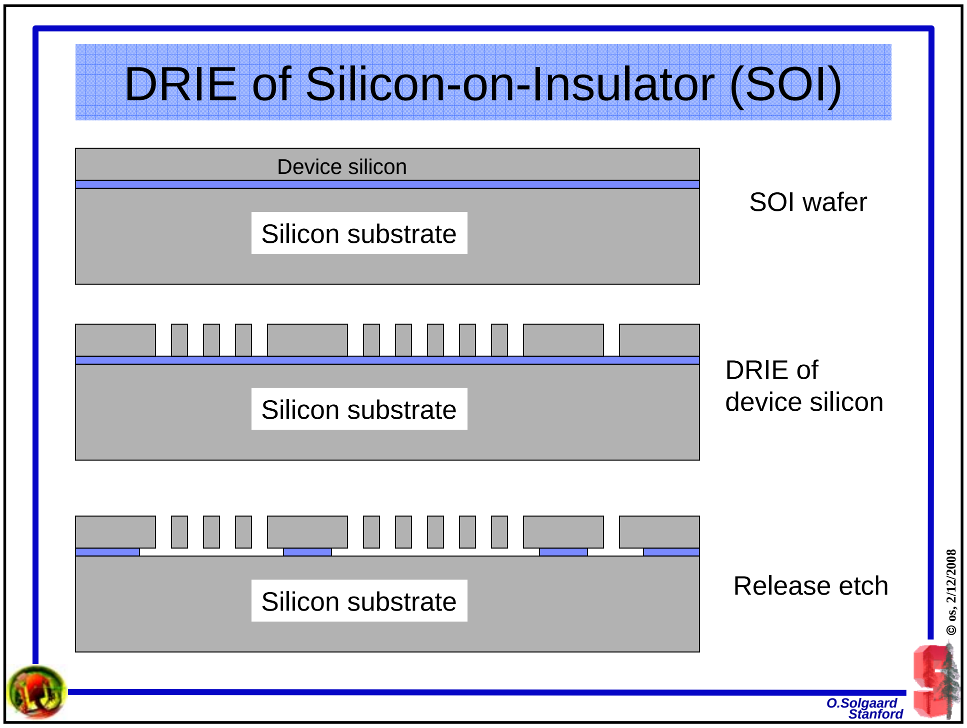
Etch, SF_6 for 5-15s

Deposit ~ 10 nm fluorocarbon polymer

Etch, ~ 1.5 to 4 μm/min

Deposit polymer

Vertical (90°±2°) sidewalls with 50 nm “scallops” of ~100μm period

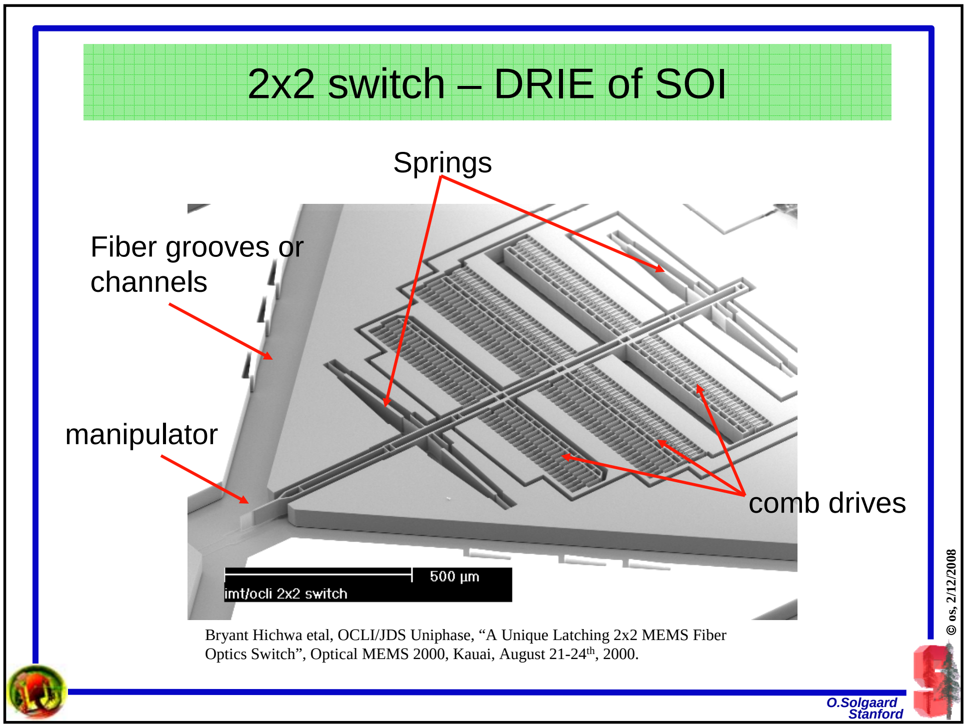


DRIE of Silicon-on-Insulator (SOI)

SOI wafer

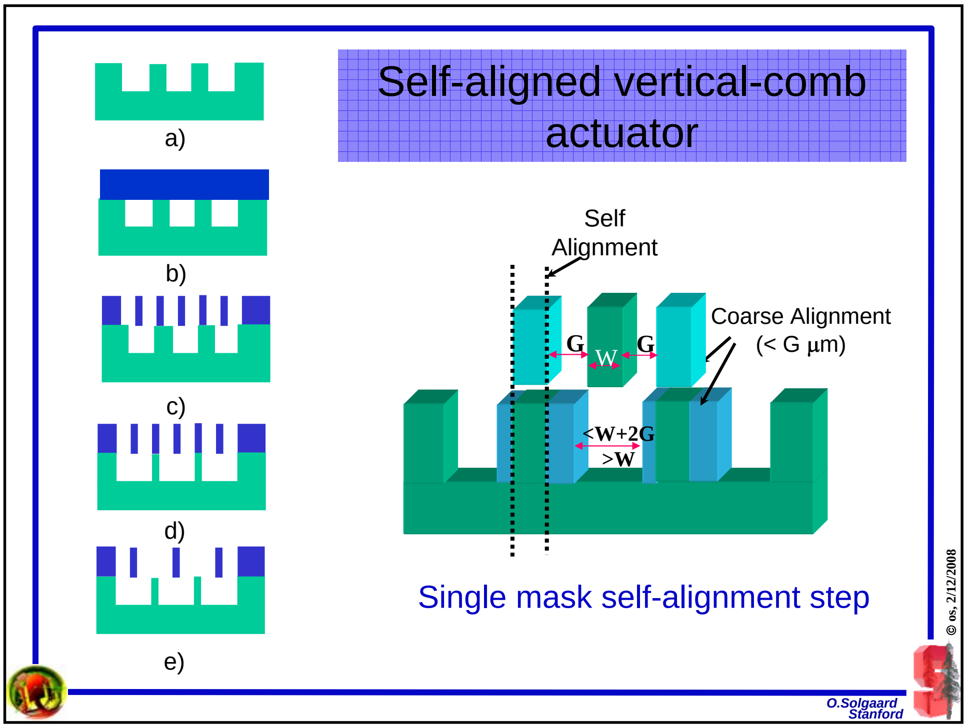
DRIE of device silicon

Release etch



2x2 switch – DRIE of SOI

Bryant Hichwa etal, OCLI/JDS Uniphase, "A Unique Latching 2x2 MEMS Fiber Optics Switch", Optical MEMS 2000, Kauai, August 21-24th, 2000.

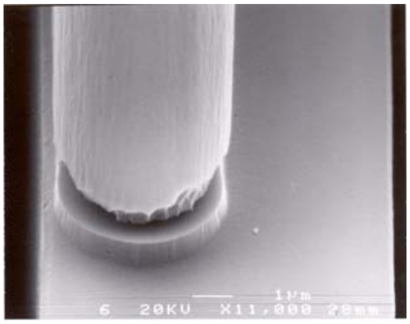


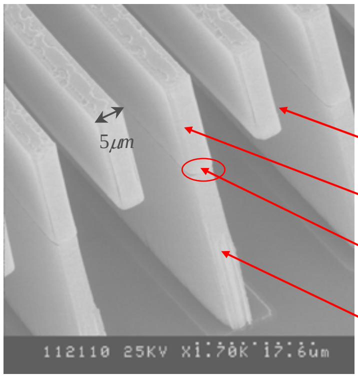
Self-aligned vertical-comb actuator

Single mask self-alignment step

Pattern Transfer with DRIE

- The SOI mask is reproduced in the substrate with high fidelity
- Misalignment is < 0.1μm
- Sidewall oxide on lower structure must be removed before DRIE





Movable combteeth

Fixed upper combteeth

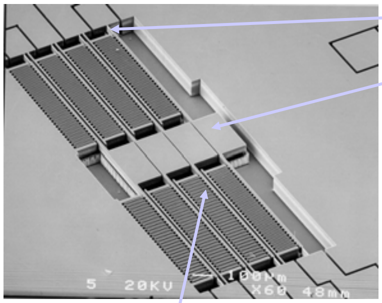
Oxide layer

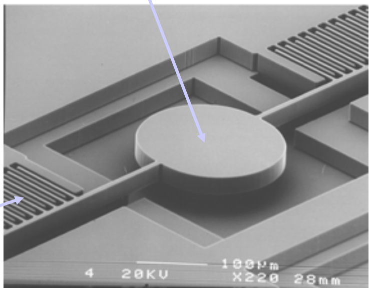
Fixed lower combteeth

SOI μMirrors

Torsional spring

Mirror surface





Vertical comb drive

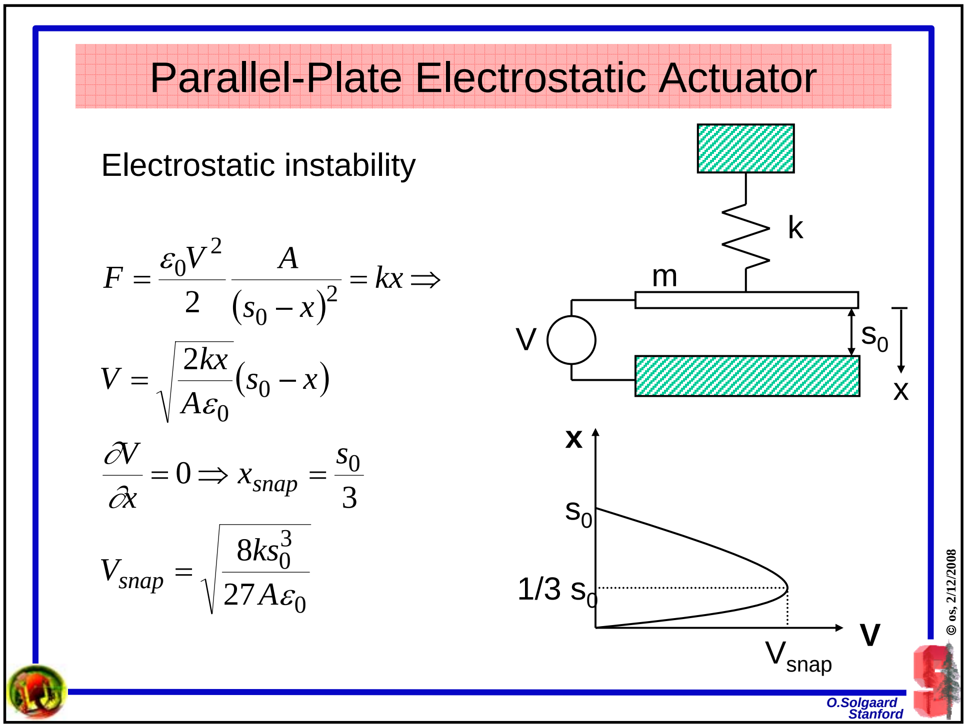
- DRIE etching of SOI materials
- High quality, flat, and stiff mirrors => Good beam quality!
- High force => high speed, Dual-mode actuators, Phased arrays
- High yield, high reliability operation at high voltage require self aligned combs

Summary –Micromachining

- Bulk Micromachining
  - Anisotropic etching creates precise mechanical structures and optical-quality surfaces by parallel processing
- Surface micromachining
  - IC compatible
    - Versatile, flexible technology with proven reliability
    - Large arrays are possible
    - Applications: Accelerometers, inertial sensors, probes resonators, micromirrors, microgratings, lenses, tunable VCSELs
  - Challenges
    - Dry release etch (necessary for commercial success?), Integration, Dimensional control
  - Several foundries exist, but still not commodity
- DRIE of SOI

Actuator Figures of Merit

	Force	Speed	Throw	Supply	Compatibility	Repeatability	Function
Piezo-electric	High	High	Low	Voltage /cont.	Low	High	Continuous
Magnetic	High	Low	High	Current /cont.	Low	High	Continuous
Thermal	High	Low	High	Current /cont.	High	Low	Assembly
Surface tension	High	Low	High	Temp./ latching	+/-	Low	Assembly
Electro-static	Low	High	+/-	Voltage /cont.	High	High	Continuous/ Assembly



Parallel-Plate Electrostatic Actuator

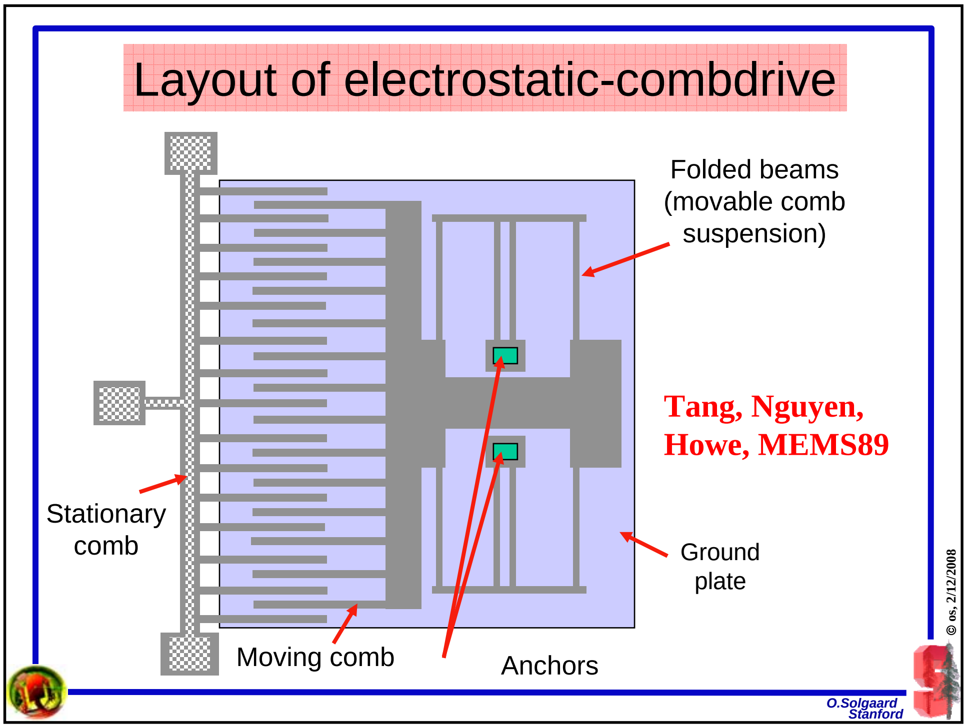
Electrostatic instability

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

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

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

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



Layout of electrostatic-combdrive

Folded beams (movable comb suspension)

Tang, Nguyen, Howe, MEMS89

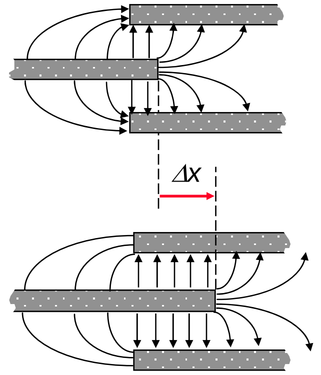
Stationary comb

Ground plate

Moving comb

Anchors

Electrostatic-comb drives



Electric field distribution
in comb-finger gaps

$$\frac{\partial C}{\partial x} = N \cdot \left(\frac{2\varepsilon_0 h}{d^{\beta}} \right) \cdot \alpha$$

N : number of comb-fingers
α, β : fitting parameters, values extracted from simulation
h : thickness of comb-fingers
d : width of gap between comb-fingers

$$F = \frac{1}{2} \frac{\partial C}{\partial x} \cdot V_{dc}^2 = \alpha \frac{N\varepsilon_0 h}{d^{\beta}} \cdot V_{dc}^2$$

$$\Rightarrow F \approx \frac{Nh}{d} \cdot \varepsilon_0 V_{dc}^2$$

Combdrive vs. parallel plate

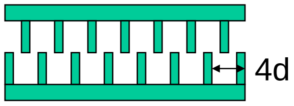
$$\text{Parallel plate: } F_{pp} = \frac{A_{pp} \varepsilon_0 V^2}{2s^2}$$

A_{pp}=wh

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

$$A_{cd} = 4Ndh \Rightarrow F_{cd} = \frac{A_{cd} \varepsilon_0 V^2}{4d^2}$$

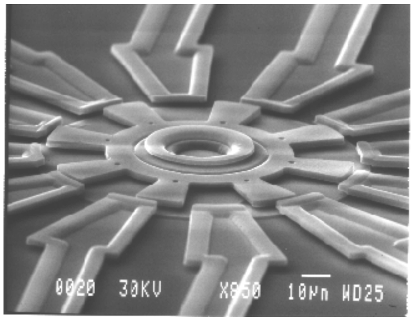
A_{cd}=4Ndh



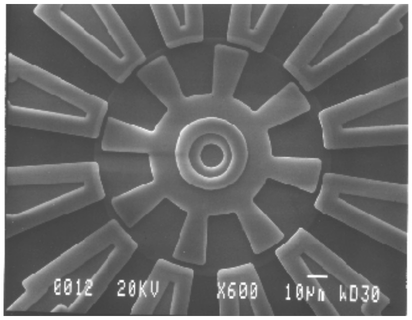
$$\boxed{\frac{F_{cd}}{F_{pp}} = \frac{s^2}{2d^2} \approx \frac{9}{2} \frac{(\text{Displacement})^2}{(\text{Lithographic limit})^2}}$$

Side Drive Motors

Side view of SDM

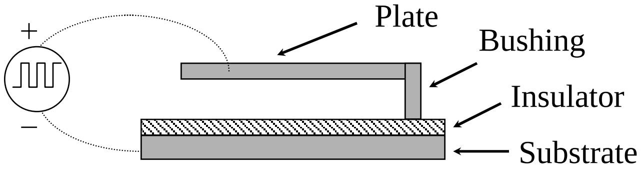


Top view of SDM



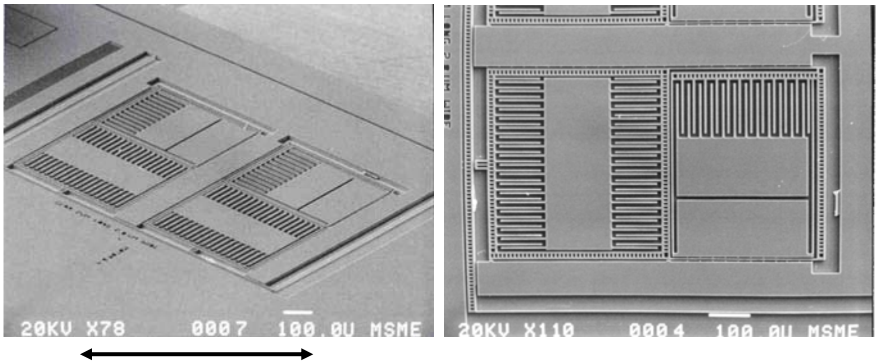
Source:MCNC
http://mems.mcnc.org/msems.html

Scratch Drive Actuator (SDA)



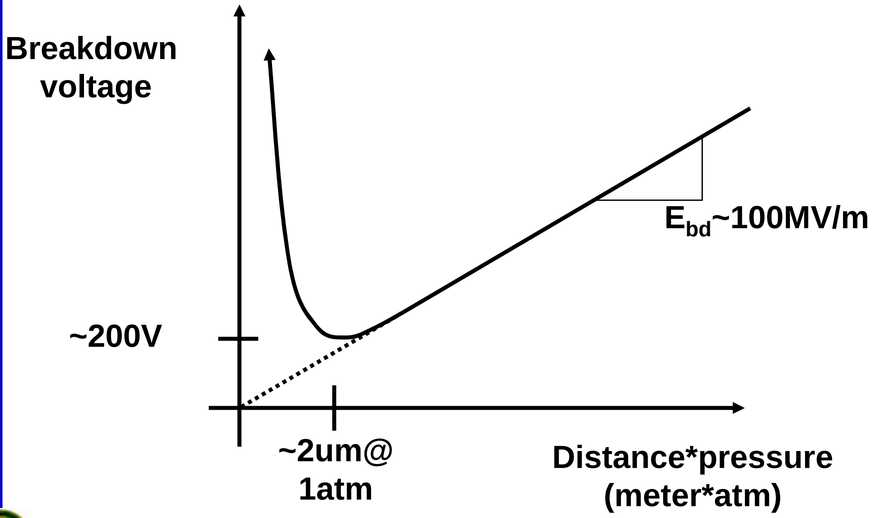
- Micro XYZ positioning stages
  (L. Y. Lin, et. al., 1997; Li Fan, et. al., 1997)
- Self-assembly of MEMS devices
  (A. Terunobu, et. al., 1997; Y. Fukuta, et. al., 1997)
- Free-space fiber optic cross/bar switch
  (Shi-Sheng Lee, et. al., 1997)

Silicon Inchworm Motors



Pister, UCB

Paschen Curve



Damping

- Two kinds of viscous (fluid) damping
  - Couette: $b = \mu A/g$; $\mu = 1.8 \times 10^{-5}$ Ns/m^2
  - Squeeze-film: $b \sim \mu W^3 L/g^3$
  - μ proportional to pressure
- Many MEMS devices are under damped
  - Complicates control
  - Slows down response (ringing)
  - Pay attention to vibration modes!

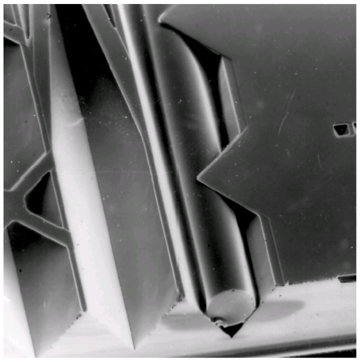
Summary - Microactuation

- Piezoelectric effect - unfulfilled potential
- Magnetic effect for special applications
  - Automotive
  - Fiber switches
- Thermal and surface tension actuators for assembly
- Electrostatic actuation
  - Favorable scaling, CMOS compatible materials, High speed
  - Long throw can be achieved at the cost of complex design
- Damping is important for the dynamic characteristics of Microactuators

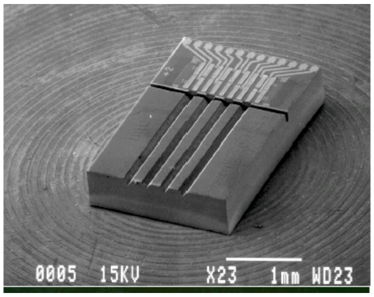
MEMS and Electronics Integration

- Process integration - MEMS and CMOS
  - CMOS first: thermal issues
  - MEMS first: topography problems
  - Mixed process: huge development
  - All have Y_i^N issues
  - Successfully commercialized by TI and Analog Devices
- Post-processing of CMOS
  - Limited flexibility, questions about mechaincal and optical quality
- Integration by Assembly
  - Wafer bonding
  - Self assembly

Silicon V-groove Technology



Silicon V-grooves with clamps to fix the fibers. C. Strandman and Y. Backlund.



Silicon v-grooves for fiber-to-laser alignment. The laser chip is attached to the silicon chip with solder bump technology. H. Ahfeldt 1997.

Future directions and Conclusions

- High-aspect ratio optical MEMS combines
  - Large forces and excellent mechanical and optical properties of bulk micromachining
  - Flexibility of surface micromachining
  - Applicable to fluidic-MEMS and bio-MEMS
- DRIE is more practical than LIGA and has become the standard for high-aspect ratio MEMS
  - DRIE of SOI allows functional devices based on a single mask!
- DRIE+Wafer bonding for functionality, reliability, packaging
- Integration of DRIE-MEMS and electronics
  - Through-the-wafer interconnects
- Bulk, surface and DRIE micromachining are complementary techniques
- The MEMS tools box is well stocked => we can make anything!