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Microthermal Actuators

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Collaborators

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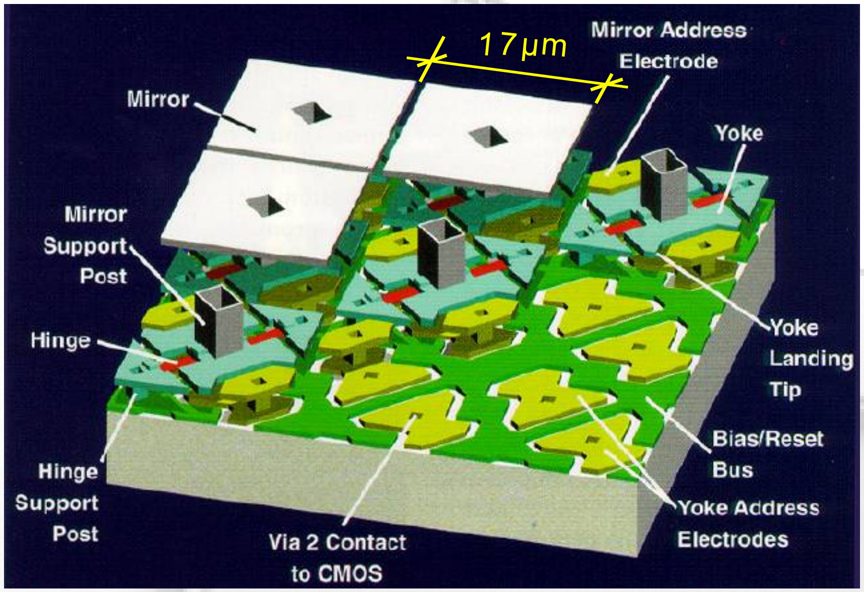
Microscale Thermal Sciences and Fluid Mechanics Projects

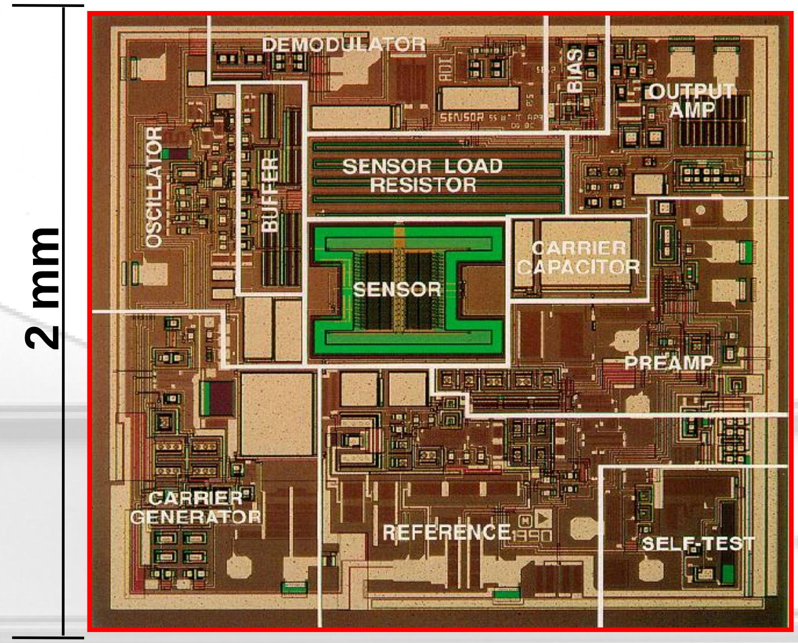
- Diagnostics, Metrology, and Imaging at Small Scales
  - Temperature measurement, Raman and thermal reflectivity
  - Micro-PIV, velocity and temperature measurements for liquid and gas microflows
  - Measuring transient dynamics
  - Thermomechanical effects
- Material Property Characterization
  - Thermal conductivity measurements
  - Optical properties
- Wetting and Interfacial Phenomena
  - Interfacial adhesion measurements, modeling
- Multi-Phase Microflows
- Laser Interactions with MEMS
  - Optical actuation
  - Damage characterization
  - Laser repair of adhered microstructures

Microthermal Actuators

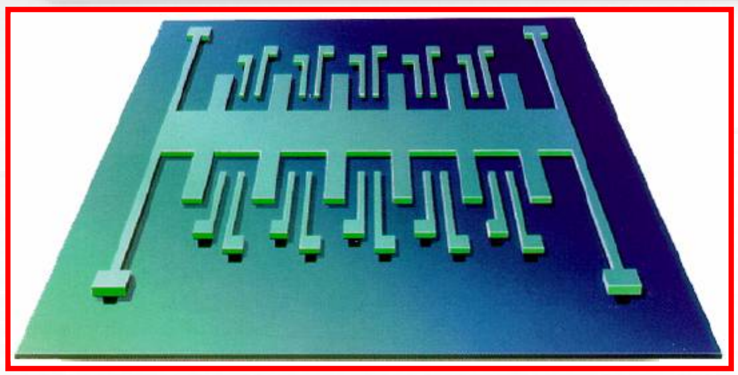
1. Introduction to MEMS
   - Applications
2. Microthermal actuators
   - Designs
   - Temperature measurements for Joule heated actuators
3. Optical Microthermal Actuators
   - Bent-beam actuator design and fabrication
   - Experimental results/laser damage
   - Failure analysis
   - Flexure-style actuator design
   - Experimental results/laser damage
   - Temperature measurements
4. Conclusions

MEMS Products





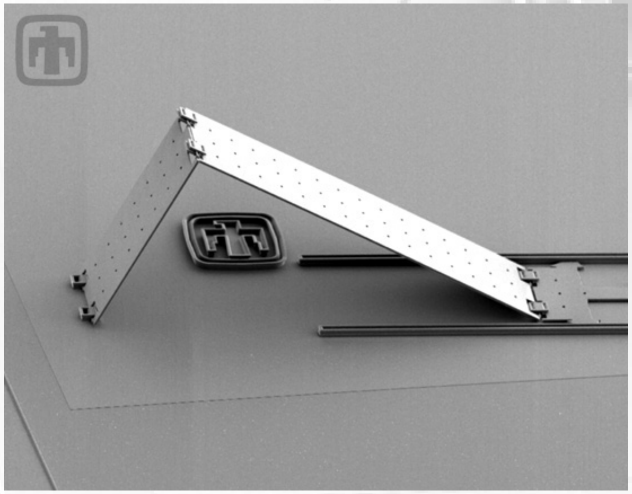
Digital Micromirror
Texas Instruments, Austin, TX
Larry J. Hornbeck,
SPIE Conference, Oct. 23-24, 1995.



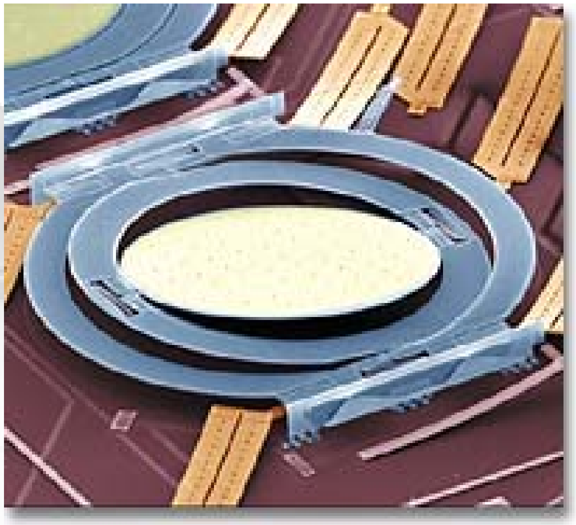
Accelerometer
Analog Devices

Optical MEMS or MicroOptoElectroMechanical Systems (MOEMS)

- Allows integration of increased system functionality for a given volume
- Includes optical mirrors, switches, cross connects, optical bench on a chip, etc.
- At high input powers, thermal management is a challenge

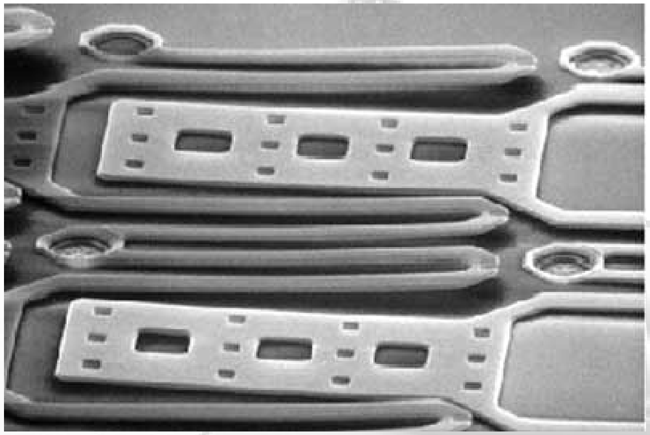


Micromirror
Sandia National Laboratories

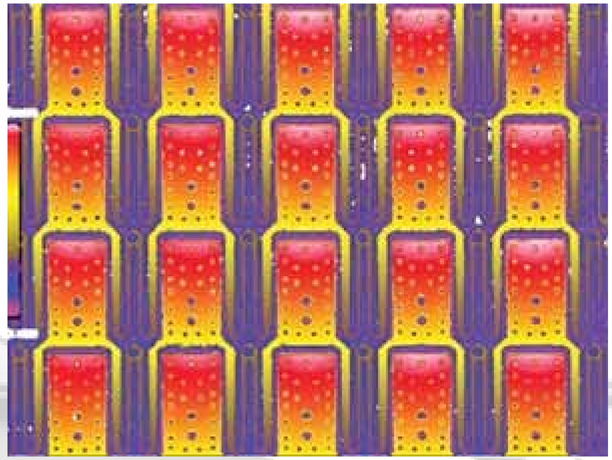


Optical Cross Connect
WaveStar™ Lambda Router, Lucent Technologies array of micromirrors route information to and from any of 256 input/output optical fibers

MEMS Based IR Imaging



50 μm long MEMS cantilevers in IR imaging system



Array of MEMS cantilevers

Each MEMS cantilever corresponds to a pixel.

The bimetal cantilevers are heated by incident infrared radiation causing them to bend, changing the capacitance between the cantilever and an electrode on the substrate. The capacitance change is converted into an electrical signal that is proportional to the amount of absorbed IR light.

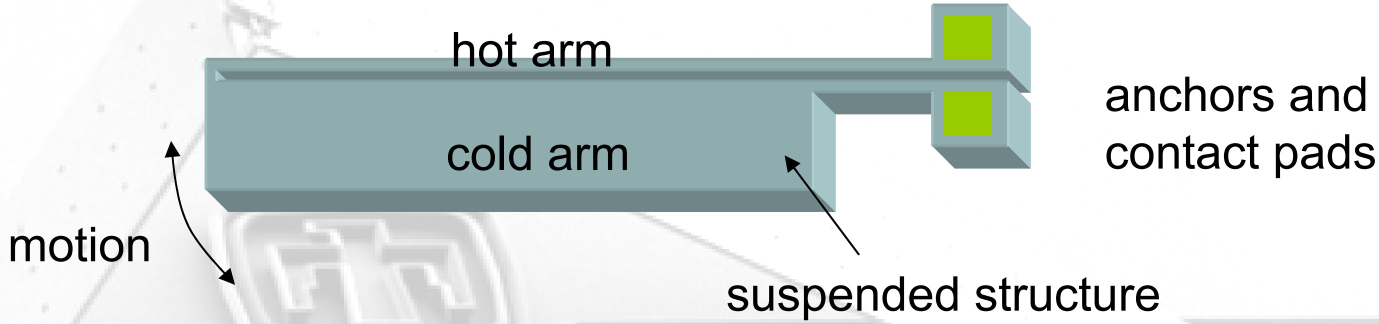
Hunter, S. R., et al., *Proc. of SPIE*, 5074, pp. 469-480, 2003.

Sarcon Microsystems, Knoxville, TN and Sarnoff Corporation, Princeton, NJ

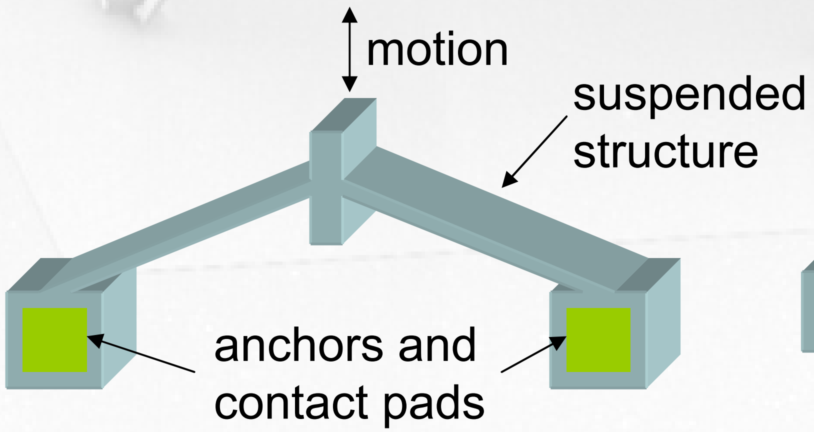
Opto & Laser Europe, June 2003.

MEMS Thermal Actuators

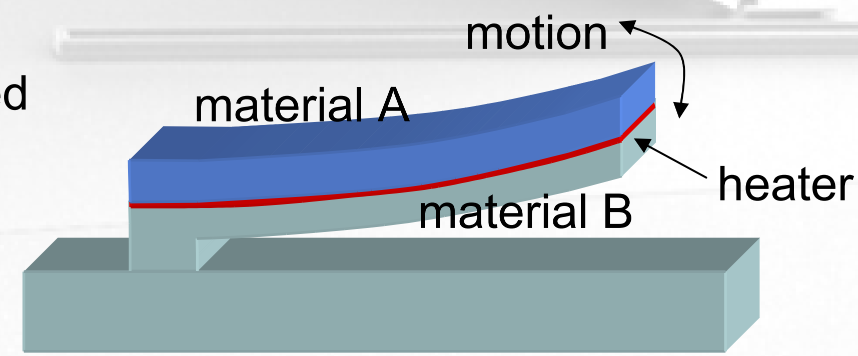
Comtois actuators, J. H. Comtois et al., *Sensors and Actuators A*, 70, pp. 23-31, 1998.



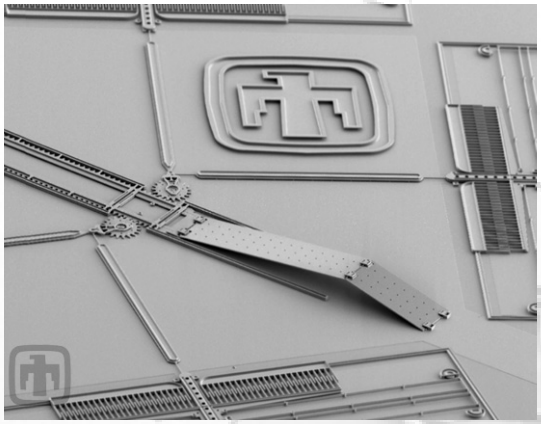
Bent-beam actuators, Que et al., *J. MEMS*, 10, pp. 247-254, 2001.



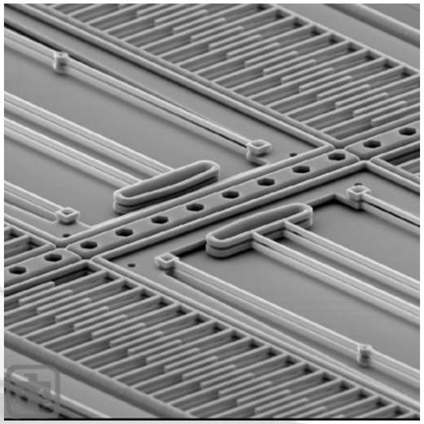
Multiple material actuators, Ataka et al., *J. MEMS*, 2, pp. 146-150, 1993.



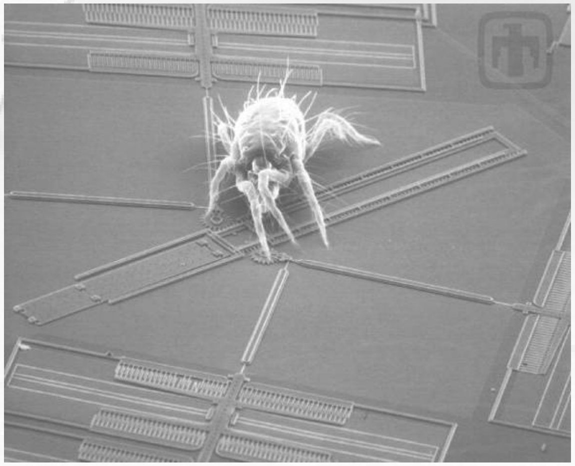
Surface Micromachined MEMS Devices



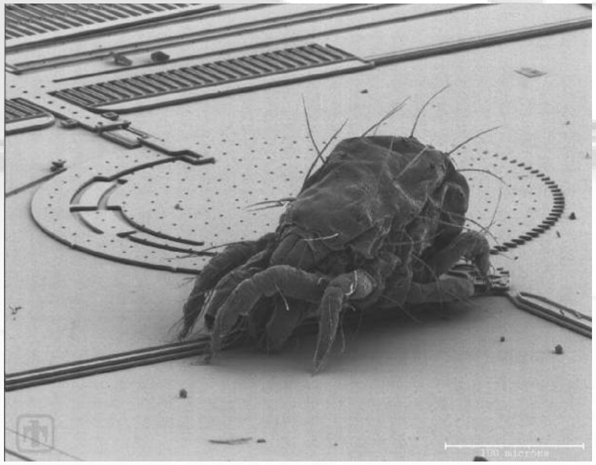
Hinged Silicon Mirror and Drive Motors



Comb Drive Detail



Spider Mite on a Mirror Assembly



Spider Mite on a Microlock Mechanism

http://mems.sandia.gov

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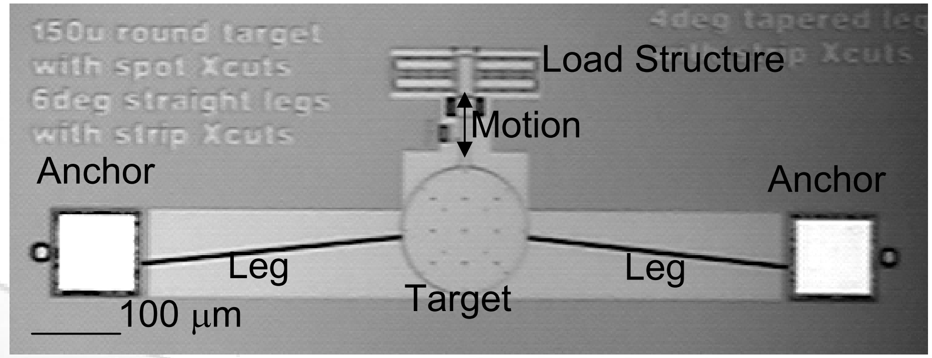
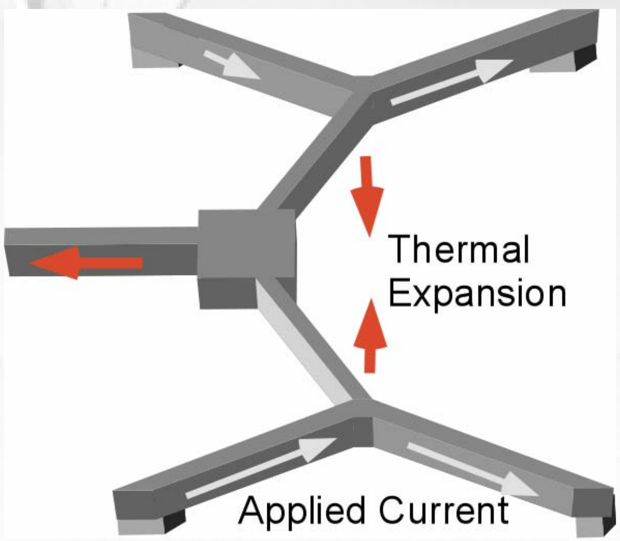
Microthermal Actuators for Microsystems

- Thermal Actuators (TAs) have much higher forces (200 μN) than electrostatic comb drives (20 μN).
- 100% compatible with SUMMiT-V™ process
- More resistant to stiction than lower force actuators.



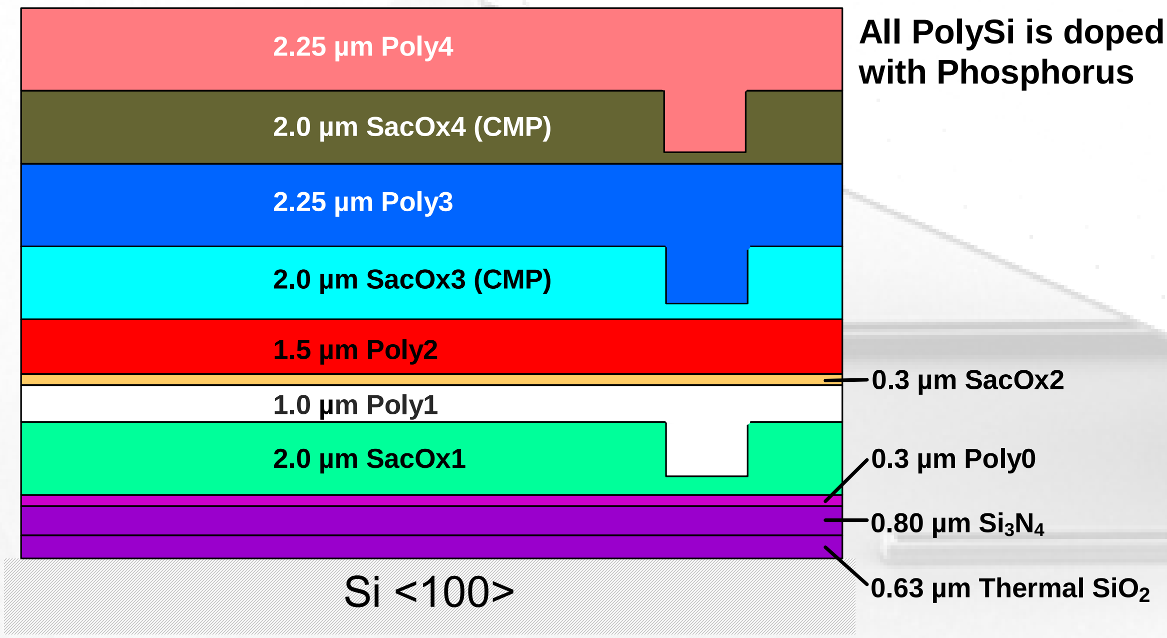


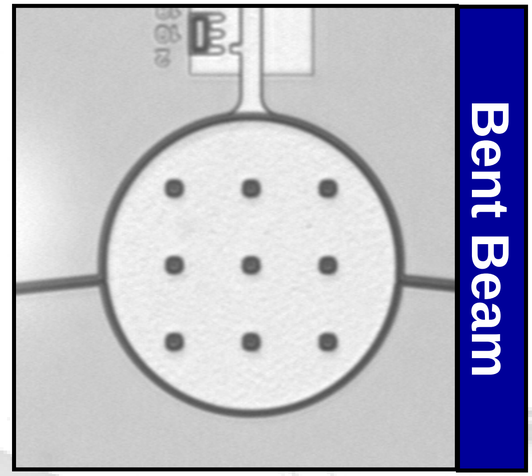
- Opto-Thermal Actuators (OTAs) use optical energy instead of electrical energy.
- Have no electrical connections to the outside world
- Compatible with radiation and high temperature environments
- Will not electrostatically attract particles.

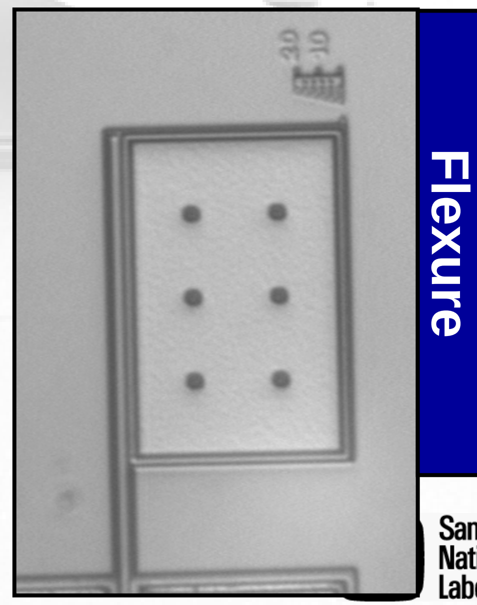
SUMMiT™ V

Sandia's Ultra-planar Multi-level MEMS Technology

SUMMiT™ Layer Descriptions







- 5-level sacrificial micromachining
- Actuators use top two layers (Poly3 and Poly4)

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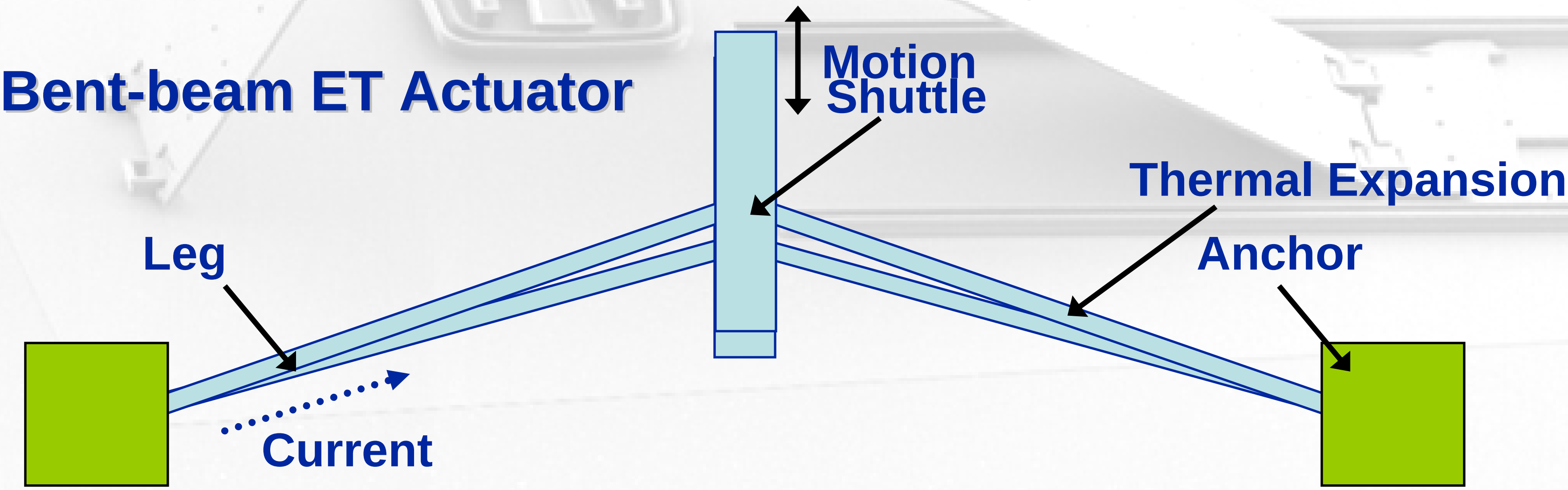
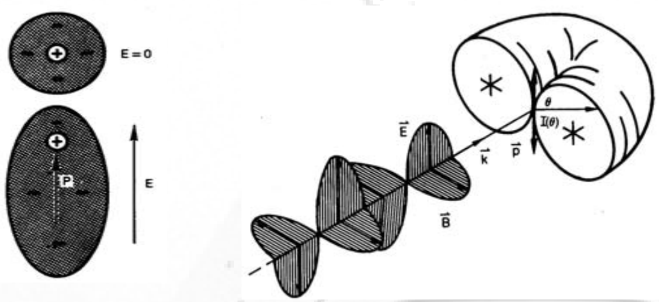
MEMS Electrical Bent-beam Microthermal Actuator

- Bent-beam (“Chevron,” “V-shaped”, symmetric)
  - L. Que, J.-S. Park, and Y.B. Gianchandani, *IEEE Conf. on MEMS*, pp. 31-36, 1999.
  - R. Cragun and L.L. Howell, *ASME IMECE MEMS Symp. Proc.*, pp. 181-188, 1999.

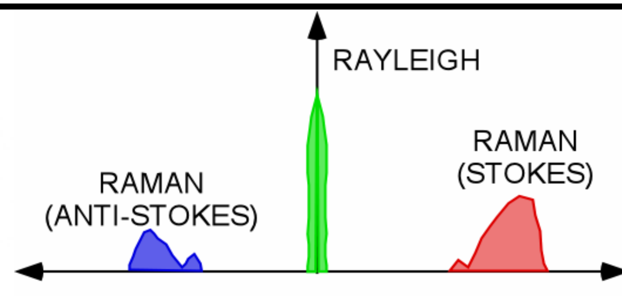
Bent-beam ET Actuator



Temperature Measurements Using Raman Microscopy – Description



Light Scattering by a Laser-Induced Dipole



Light Scattering Spectrum

- Light is scattered by <u>inducing</u> a <u>radiating dipole</u> in the scattering medium. $E_s \sim P$
- The scattered light field, E_s is proportional to the strength of the induced dipole moment, *P*.

$$E_s \sim P \sim \alpha\, E_L \sim \alpha \cos \omega t$$

- The polarizability, α, is a measure of how readily a medium is "polarized" (how easily light induced dipoles) and α can be expanded in terms of the equilibrium and 'vibrating' positions of the molecules in the scattering medium, in this case a solid-state lattice.

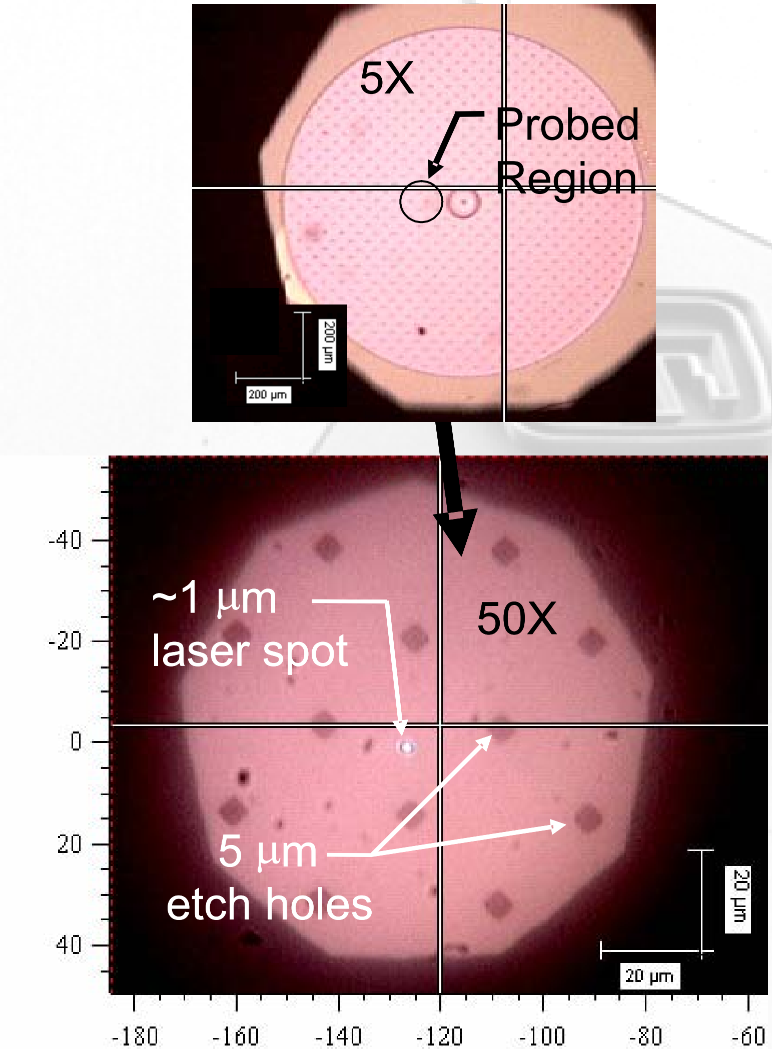
$$\alpha = \alpha_o + (\partial\alpha/\partial Q)Q$$

- If the lattice vibrates at a certain allowed phonon frequency, Ω, then $Q \sim \cos \Omega t$ and

$$E_s \sim \alpha_o \cos \omega t + (\partial\alpha/\partial Q)\,[\cos(\omega+\Omega)t + \cos(\omega-\Omega)t]$$

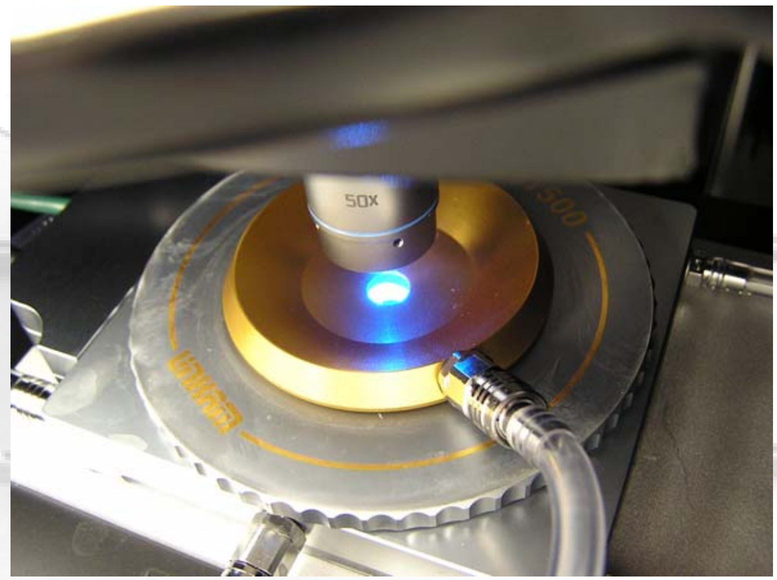
Rayleigh Scattering — Raman Scattering

Micro-Raman Probing of Polysilicon

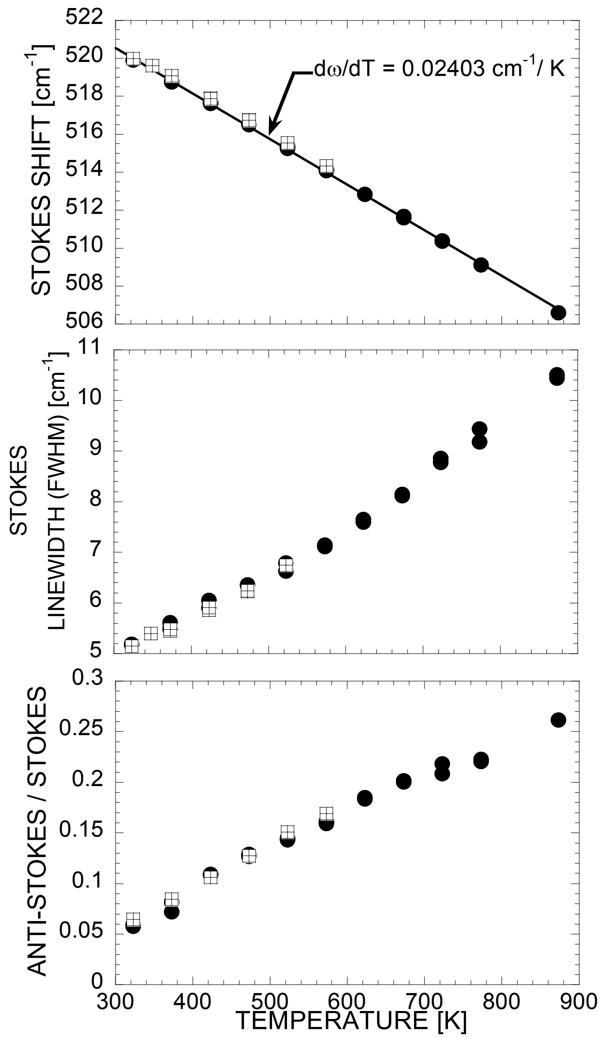


Polysilicon Surface under Raman Microscope

Laser-Illuminated Sample in Hot Stage

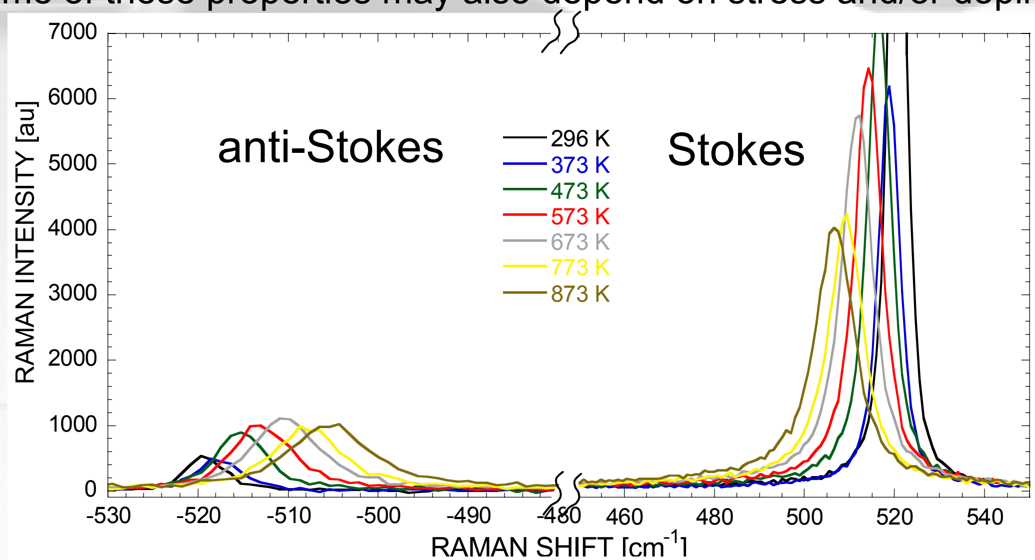


Polycrystalline Silicon Raman Spectra: Temperature Sensitivity



Temperature Sensitive Properties

- Temperature-dependent information extracted from PolySi Raman Spectra.
- Stokes (red-shifted) peak position – Shifts with increasing temperature due to lattice expansion.
- Stokes linewidth (full-width at half maximum) – increases with temperature due to increased optical phonon relaxation time.
- Ratio of Stokes to anti-Stokes (blue-shifted) areas -- Increased with temperature as a result of increasing population of thermally excited optical phonons.
- Some of these properties may also depend on stress and/or doping.



Raman Spectra from PolySi Part

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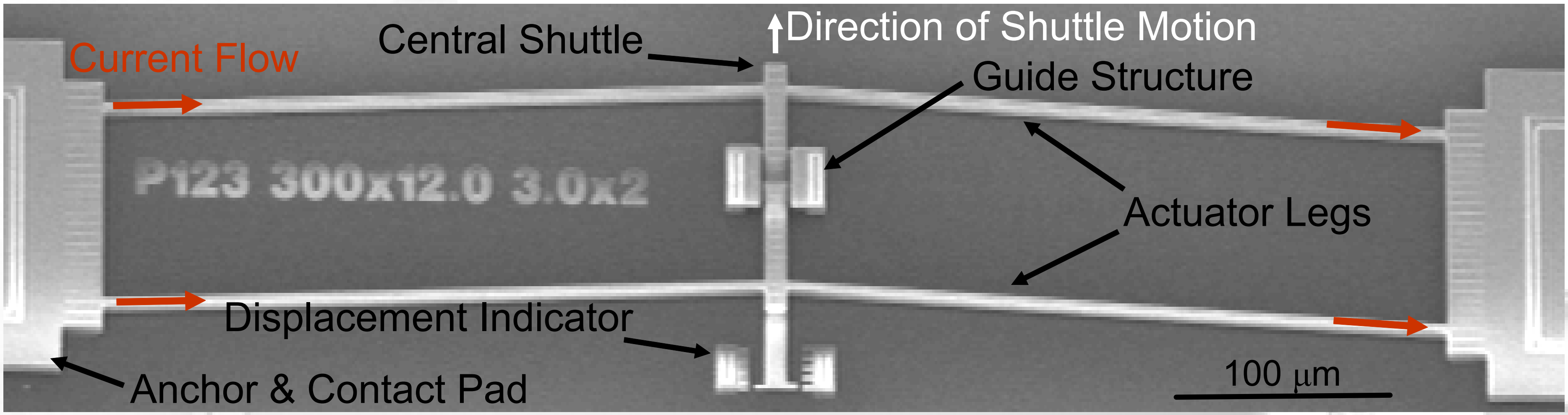
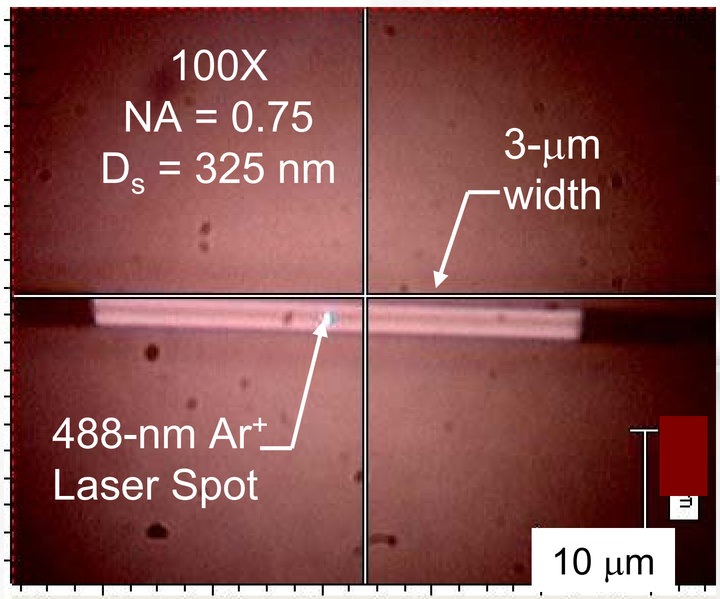
MEMS Thermal Actuators



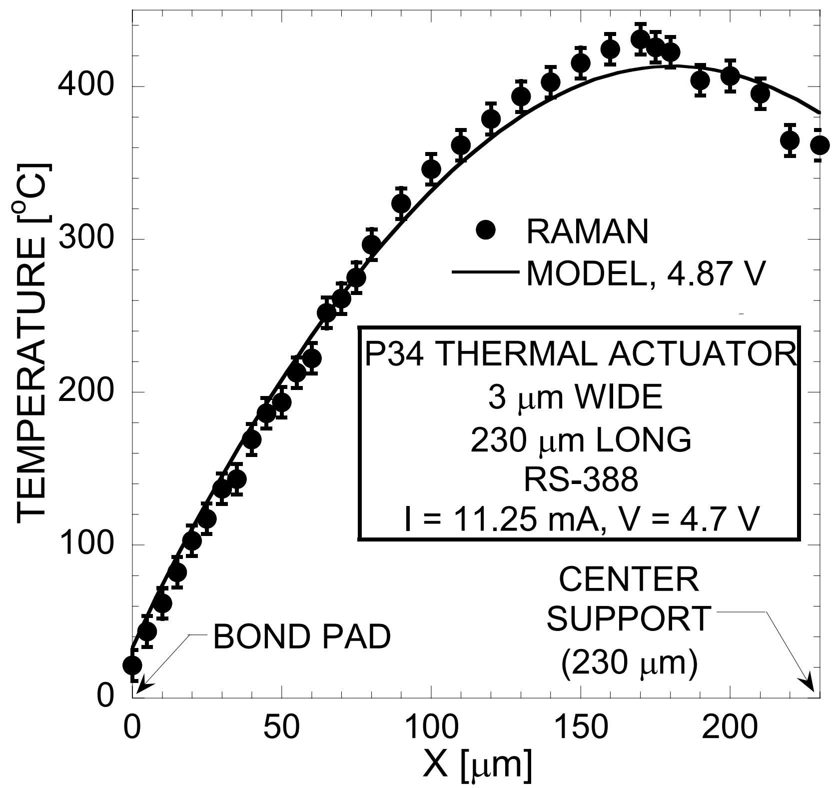
- Utilizes constrained thermal expansion due to Joule heating to achieve motion.
- Operates at low voltages and higher currents (12 V 20 mA typical) compared to other MEMS actuators.
- Capable of relatively high output forces (2.5 mN) and displacements (over 50 μm).

(M. Baker, Sandia National Laboratories, NM)

Raman Thermometry of a Thermal Actuator



Actuator Linkage Under Raman Microscope



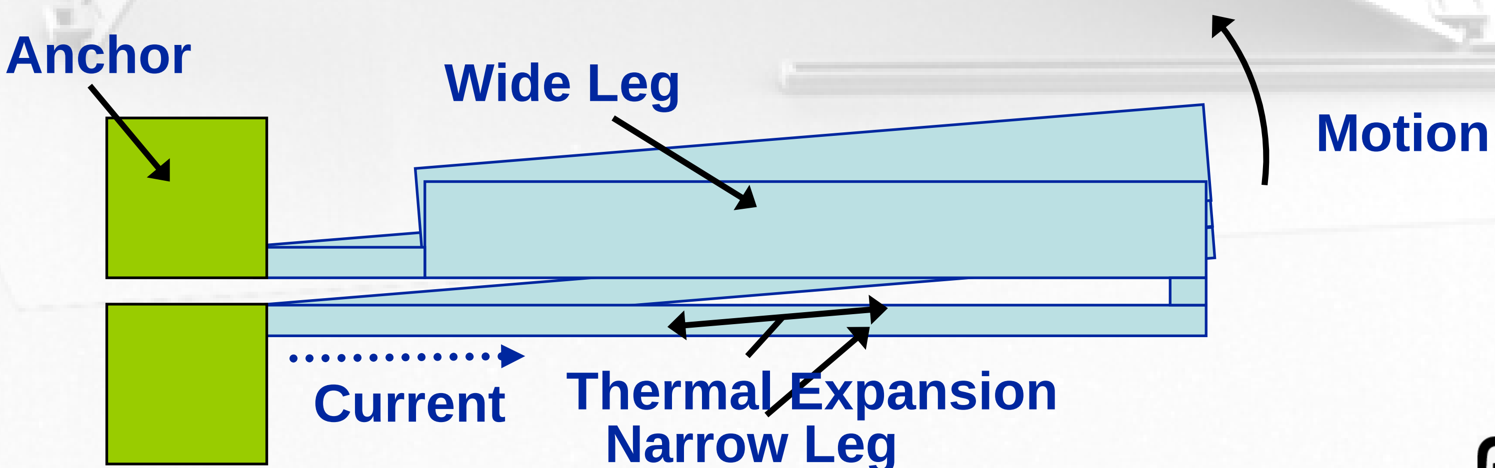
- To our knowledge, these were the first known data for such actuators, which are being studied in parallel by research groups at Brigham Young and Wisconsin
- The outstanding spatial resolution and unambiguous nature of the Si Raman signature are a significant improvement over IR methods

Kearney, Phinney, and Baker, *JMEMS*, **15**, pp. 314-321, 2006.

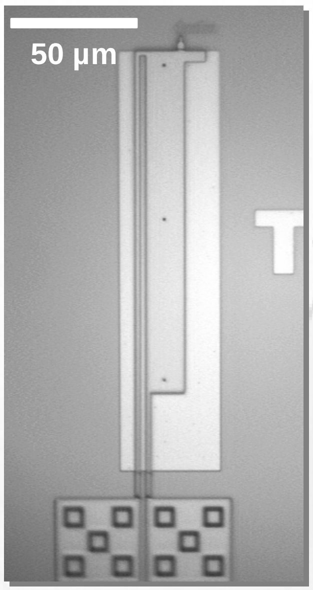
MEMS Electrical Flexure Microthermal Actuator

- Flexure (“Guckel,” “Comtois”, asymmetric)
  - J.H. Comtois, M.A. Michalicek, and C.C. Barron, *Sens. and Act. A*, **70**, pp. 23-31, 1998.
  - Q.A. Huang and N.K.S. Lee, *J. Micromech. and Microeng.*, **9**, pp. 64-70, 1999.
  - H. Guckel, J. Klein, T. Christenson, K. Skrobis, M. Laundon, and E.G. Lovell, 1992 IEEE Solid State Sensor and Actuator Wksp, pp. 73-75.

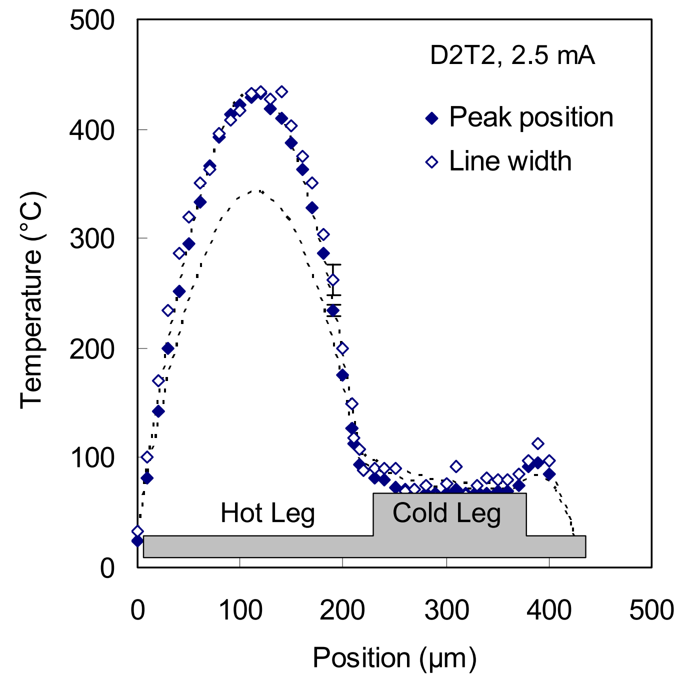
Standard ET Actuator



Raman Thermometry of Flexure Thermal Actuators



- Hot leg length = 200 μm
- Hot leg width = 2 μm
- Cold leg length = 160 μm
- Flexure length = 50 μm
- Leg separation distance = 3 μm
- Thickness = 2.5 μm
- Gap height = 2.0 μm



- Micron-scale resolution of instrument allows for temperature profiles to be obtained with 10 μm resolution. Displacement was 4.75 μm.
- Results are then used to validate numerical models of actuator temperature and displacement

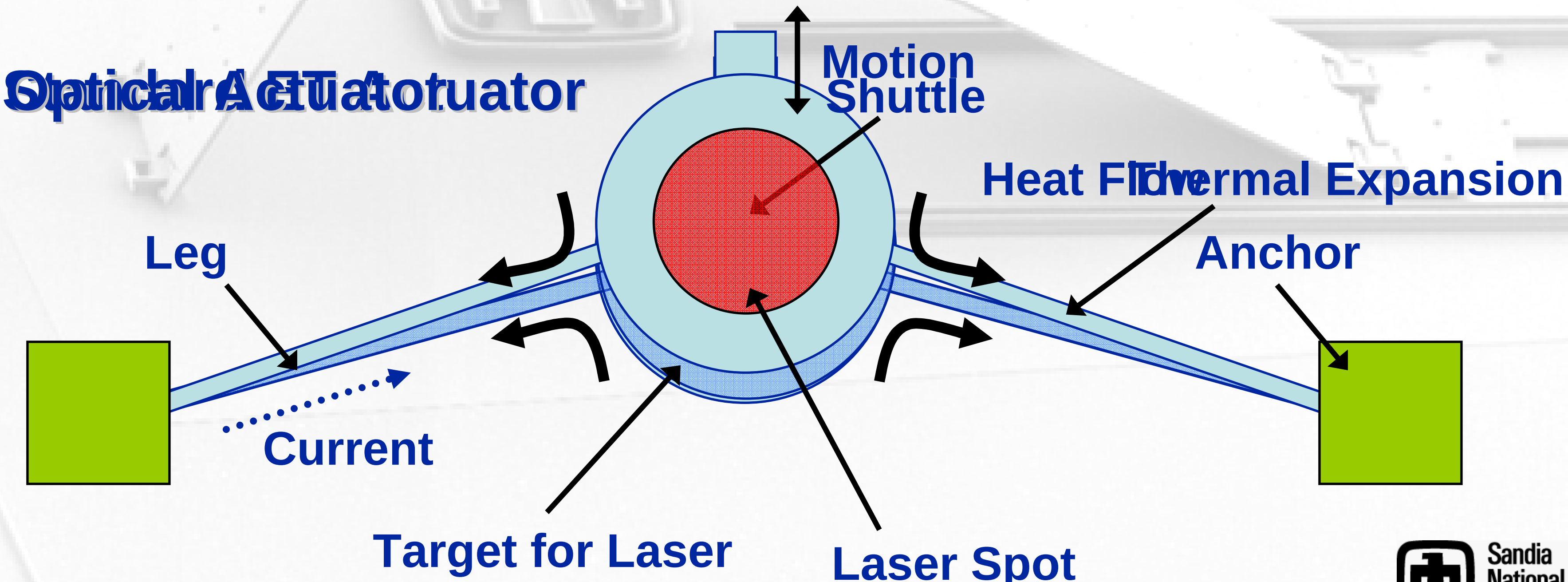
Serrano, Phinney, and Kearney, *JMM*, **16**, pp. 1128-1134, 2006.

Why Optical Actuation?

- Requires no electrical connections → intrinsic electrical isolation
- Compatible with harsh environments (radiation, high temperature, etc.)
- Enabling technology for all-optical MEMS devices
- Different actuation schemes possible, including radiation pressure, use of photostrictive materials and photothermal processes

MEMS Optical Bent-beam Microthermal Actuator

- Leverage knowledge of electrically powered MEMS actuators for optimizing design
- Two designs:
  - ➢ Bent-beam
  - – Flexure



MEMS Optical Flexure Microthermal Actuator

- Leverage knowledge of electrically powered MEMS actuators for optimizing design
- Two designs possible:
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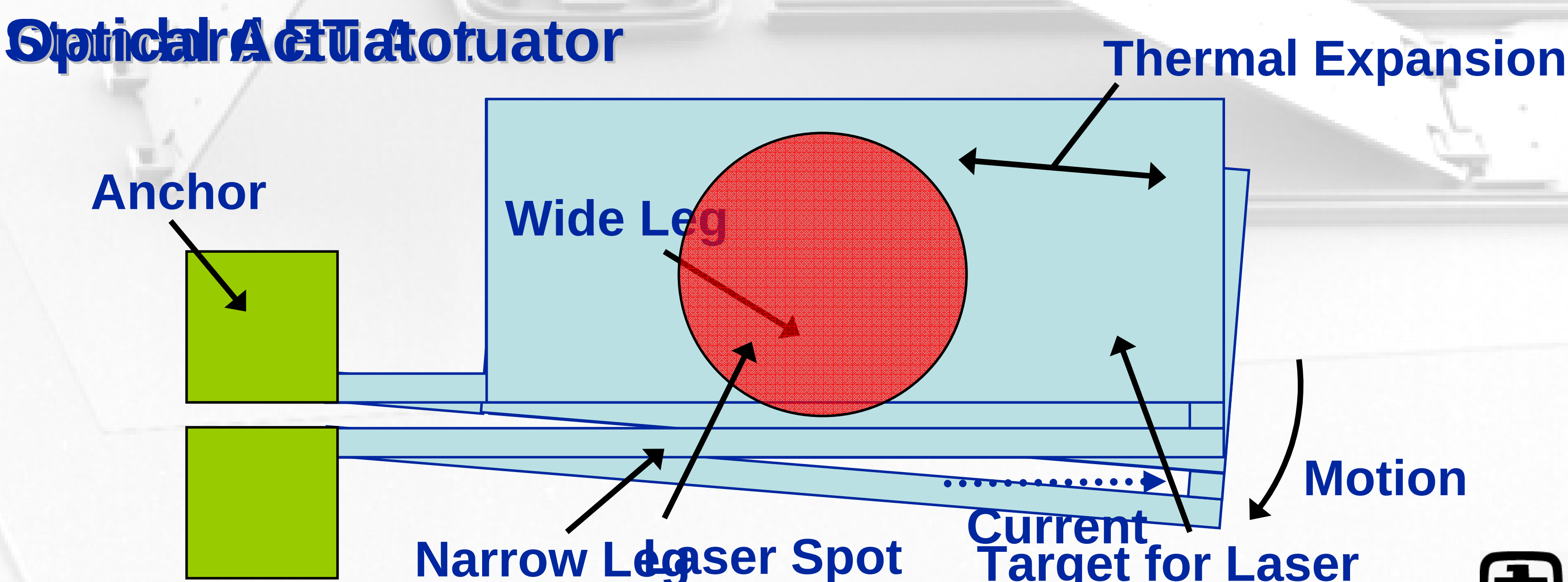

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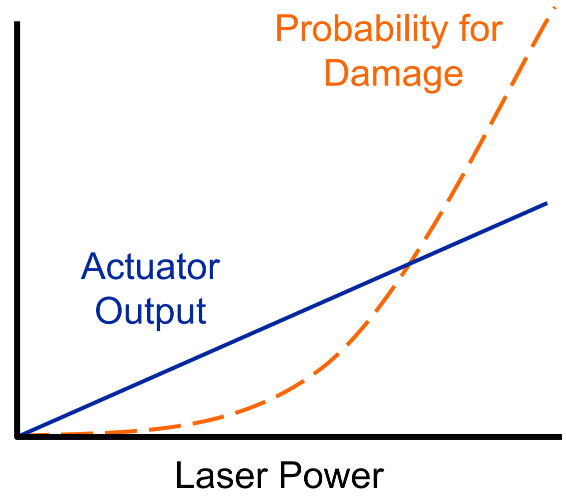
Optical Actuation

- Actuator output typically increases with input optical power
- Unfortunately, so does the risk of damage and device failure
- Improved performance obtained by:
  - **maximizing output**
  - **reducing damage risk**
- We must have a fundamental understanding of device behavior in order to improve designs



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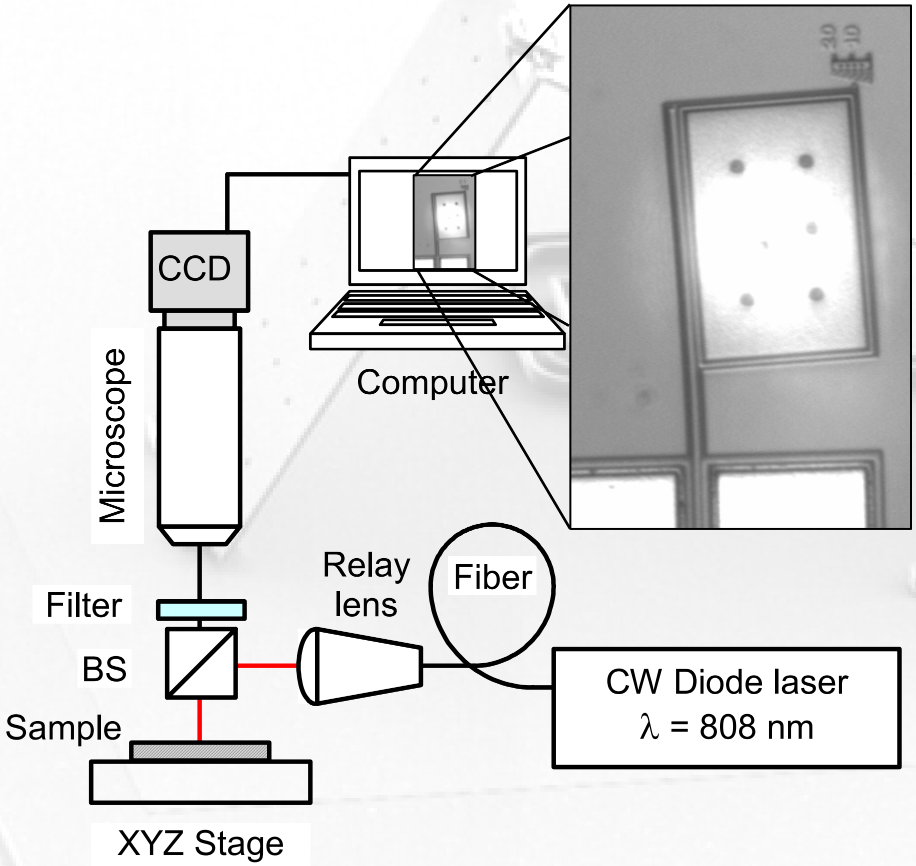
Experimental Details



- 808 nm CW fiber coupled laser powers actuators
- 100 μm diameter spot on sample
- Variable laser power
- Different actuator design variations tested
- Displacement performance and robustness evaluated through image analysis

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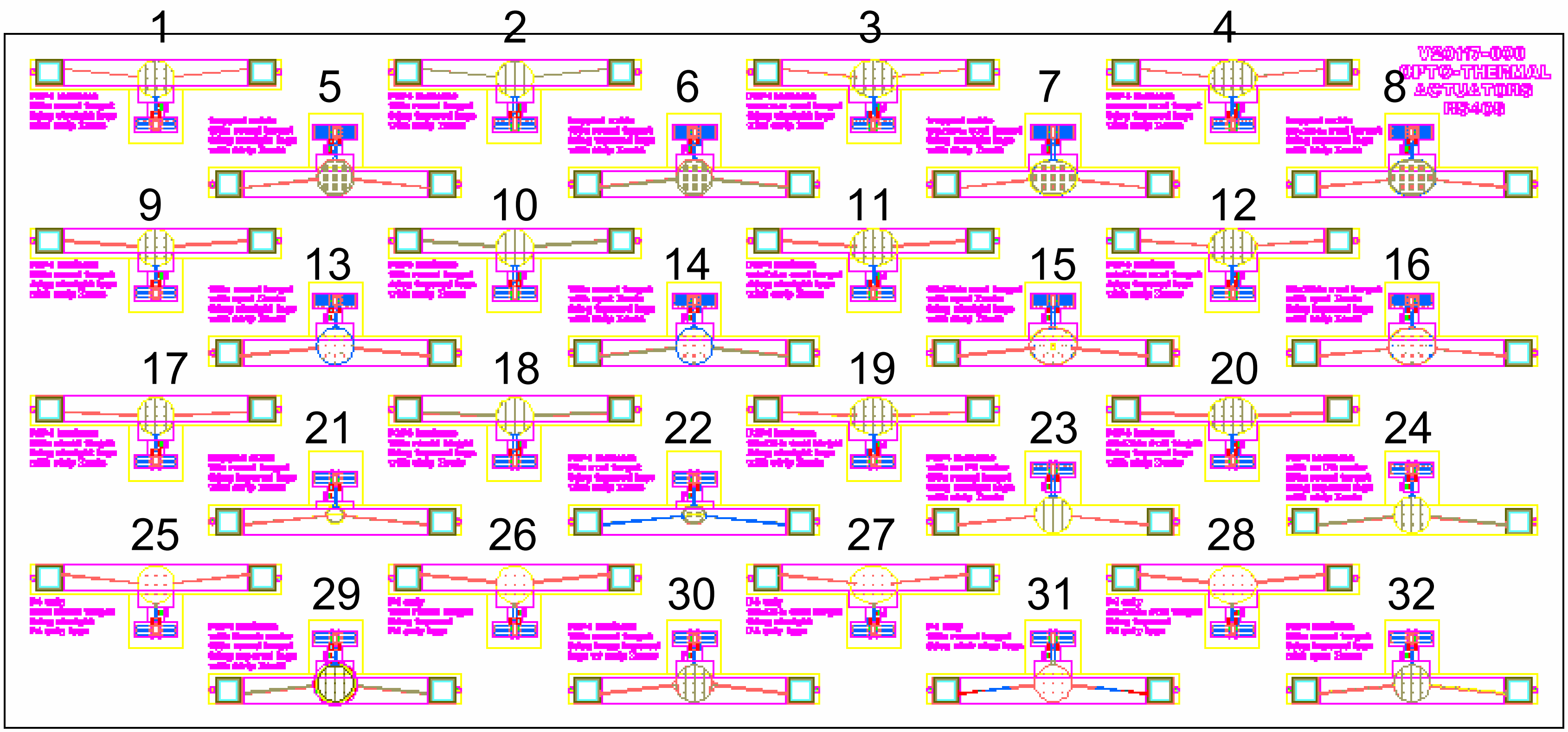
Optically Powered Thermal Actuators
Design of Experiments



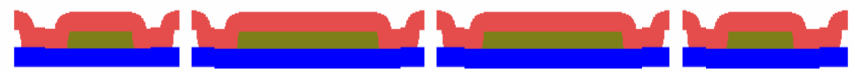
- Varied target design, target size, leg design and composition, and leg angle

Phinney et al., *Proc. of SPIE*, Vol. 5343, pp. 81-88, 2005.

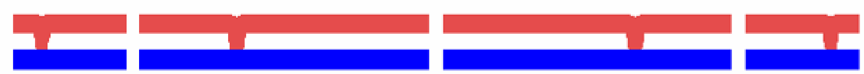
Optically Powered Thermal Actuator Target Cross Sections

- 4 different target designs were fabricated
- Poly3 and Poly4 are each 2.25 μm thick
- Oxide layer is 2.0 μm thick
- Distance to Poly3 layer to substrate is approx. 6.75 μm
- Distance to Poly4 layer to substrate is approx. 11.0 μm

Poly3-Poly4 laminate



Poly3-Poly4, trapped oxide



Poly3-Poly4, no trapped oxide

Poly4 only

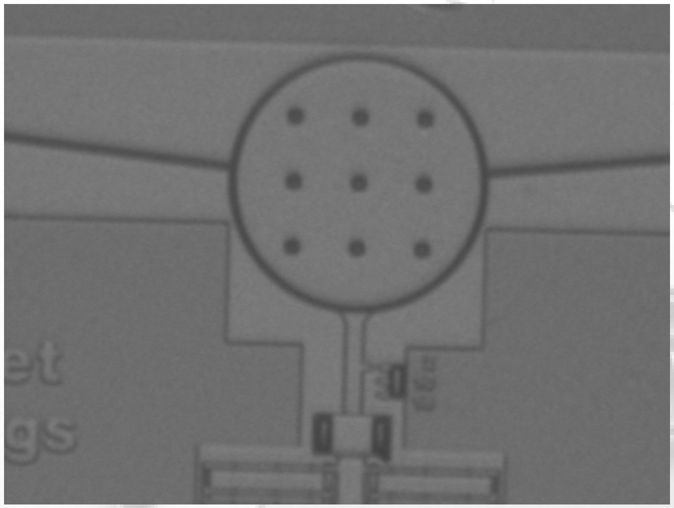
Phinney and Serrano, *Sensors and Actuators A*, **134**, pp. 538-543, 2007.

Experimental Details
First Round of Testing

- Two dice were tested for a total of 64 actuators tested (two of each design).
- Displacement was measured for the opto-thermal actuators from the images taken by the computer.
- Displacement was roughly the same (around 6 μm) for all actuators.
- However, damage levels varied substantially from essentially no damage to high amounts of damage.

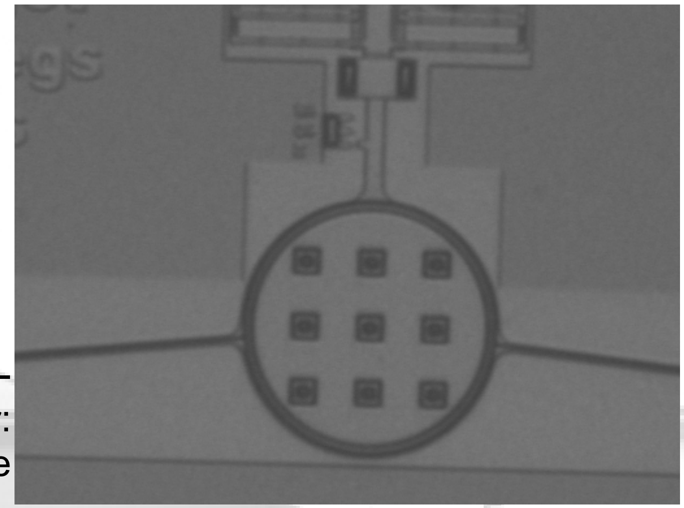
Phinney et al., *Proc. of SPIE*, Vol. 5343, pp. 81-88, 2005.

Optically Powered Thermal Actuator Damage Characteristics

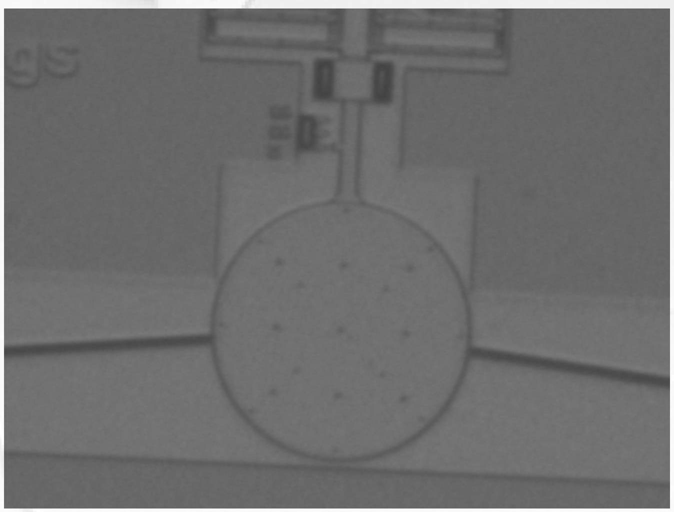


Poly3-Poly4 laminate actuator: No Damage

Poly3-Trapped Oxide-Poly4 actuator: Low Damage



150 µm



150 µm

Varying amounts of damage observed when actuator targets irradiated by a laser at 808 nm at three power levels: 150 mW, 250 mW, and 350 mW

Poly3-Air Gap- Poly4 actuator, connecting posts are 2 µm by 2 µm: High Damage

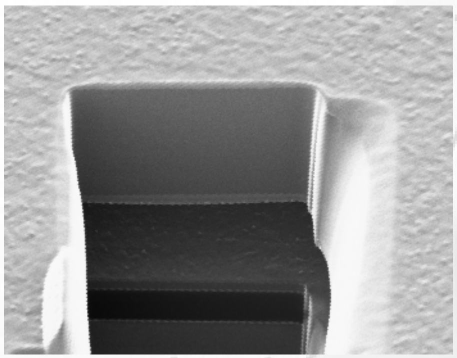
Summary of Laser Damage

Target Design	Number of Actuators Tested	Level of Detectable Post-Test Damage		
		None	Low	High
P3P4 laminate	36	23	11	2
P3P4 with trapped oxide	10	4	6	0
P3P4 with air gap	8	0	0	8
P4 only	10	0	0	10

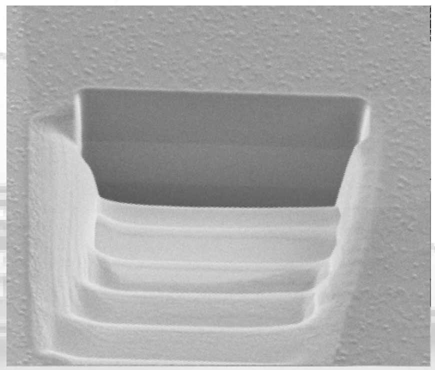
Phinney et al., *Proc. of SPIE*, Vol. 5343, pp. 81-88, 2005.

FIB Cross Sections of Parts

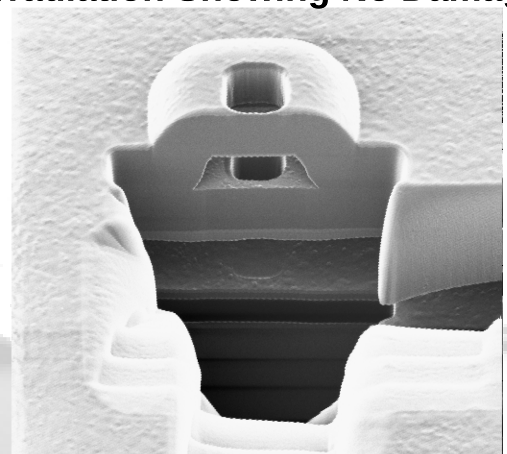
P3P4 Laminate Prior to Laser Irradiation



P4-Trapped Oxide-P3 Prior to Laser Irradiation

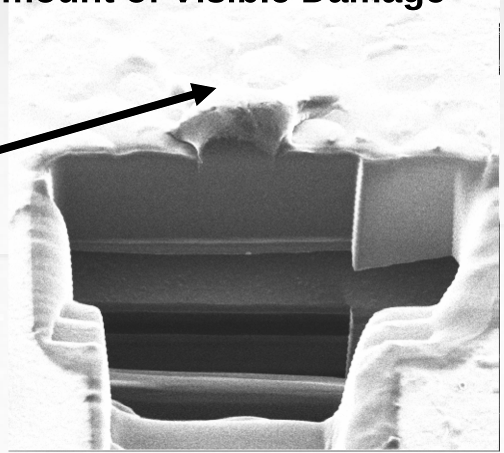


P3P4 Laminate After Laser Irradiation Showing No Damage

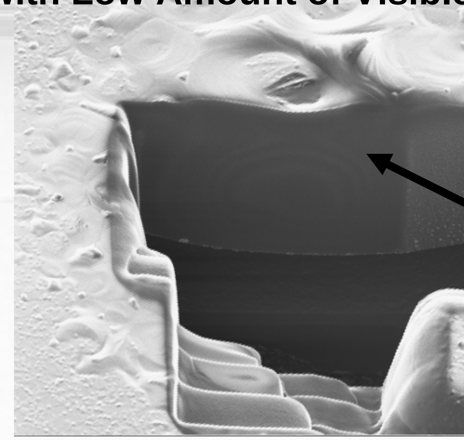


P3P4 Laminate After Laser Irradiation with Low Amount of Visible Damage

Damage is mostly superficial in this area (depth is less than a micron)



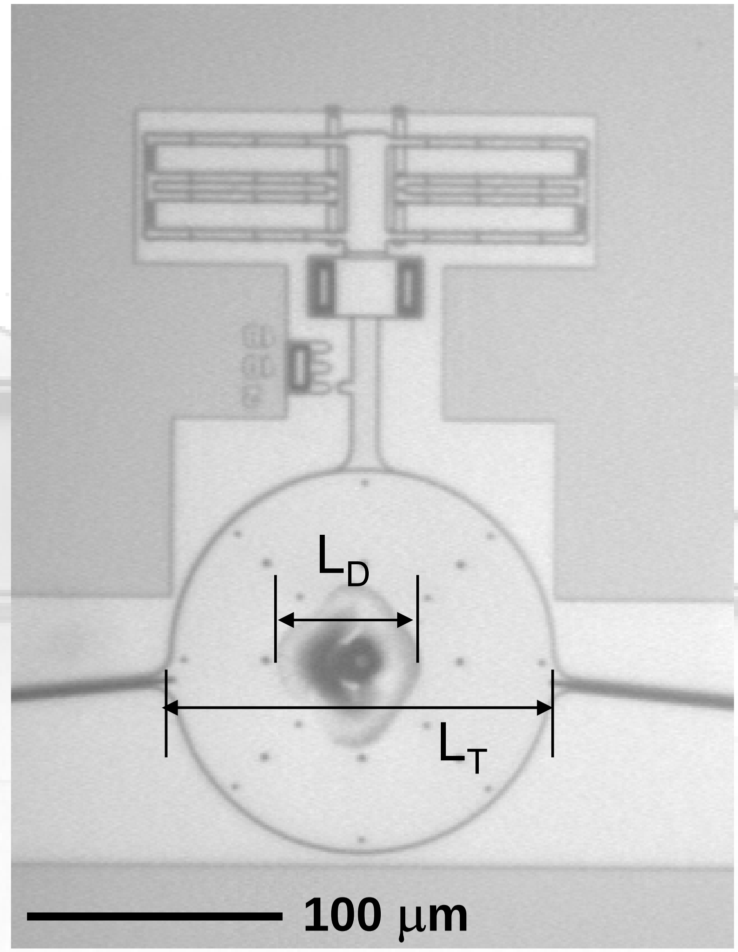
P4-Trapped Oxide-P3 After Laser Irradiation with Low Amount of Visible Damage



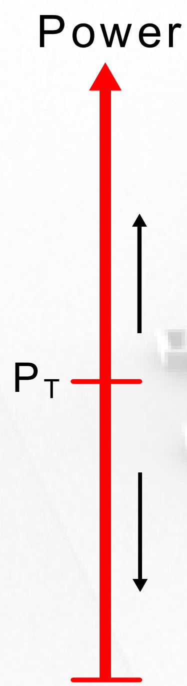
Damage and apparent bending is observed all the way through the poly layer

Damage Characterization

- Extent of damage on target surface critical for device reliability
- To compare ovals and circles, normalize damage width, L_D, by target width, L_T
- Evaluate damage extent as a function of power, irradiation time

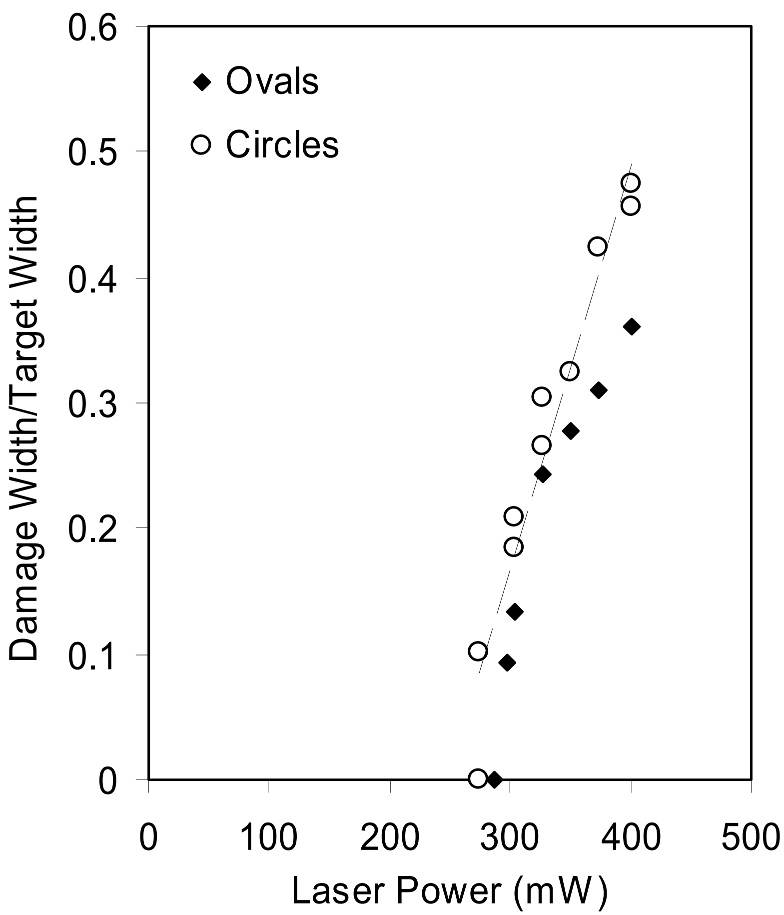


Laser Damage: Two Regimes

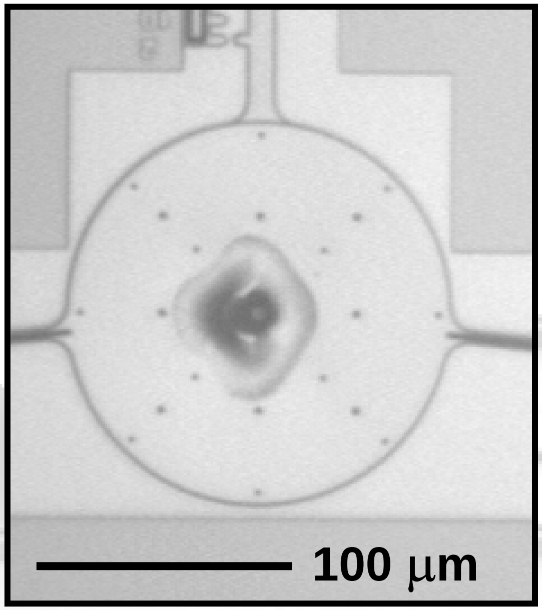


- Occurrence of damage depends on laser power
- Two regimes of damage were observed
  - Immediate damage: damage occurs immediately upon irradiation; higher laser powers
  - Prolonged exposure: damage occurs after irradiation over a period of time; lower laser powers
- Indication of both short- and long-term phenomena occurring during laser irradiation

Immediate Damage



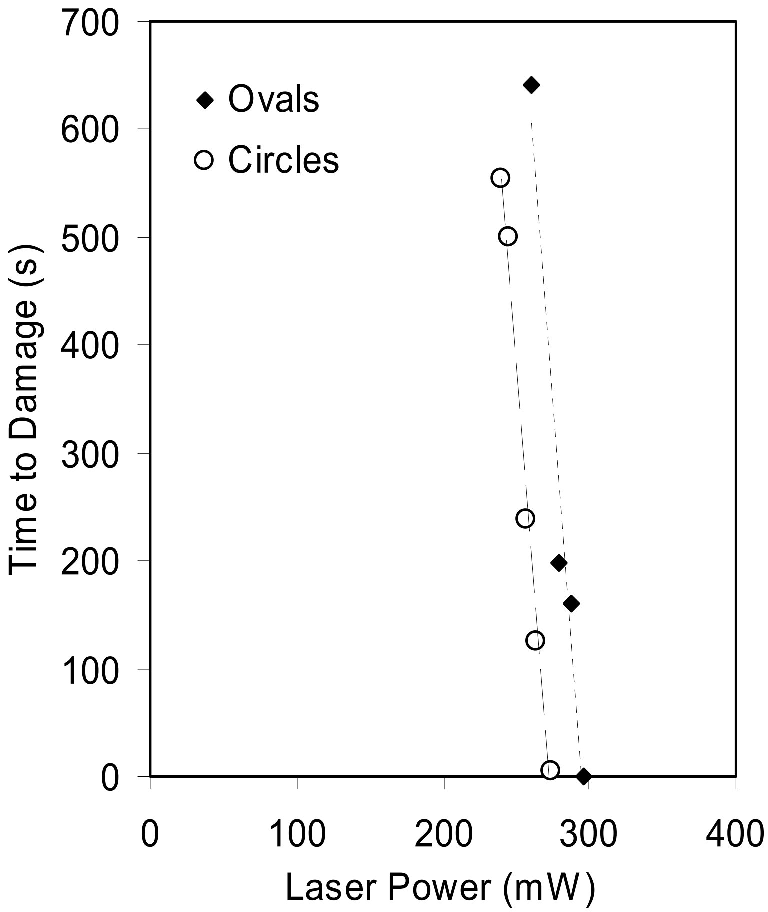
- No detectable delay between laser irradiation and surface damage
- Damage extent increases linearly for laser powers greater than 300 mW on circular and oval targets



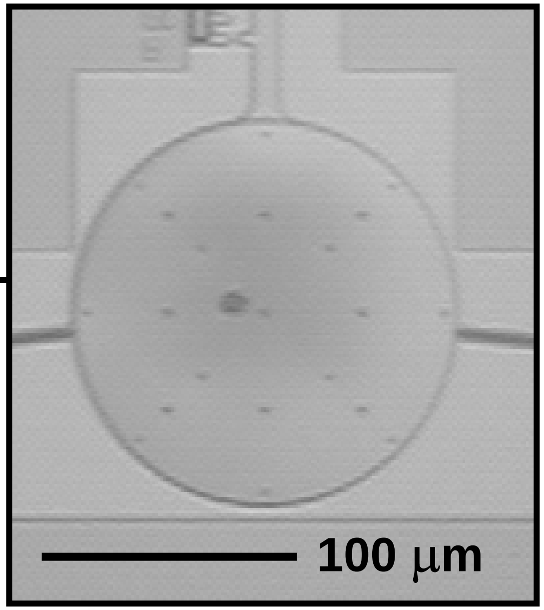
- Threshold power for immediate damage:
  - ~275 mW (circular)
  - ~295 mW (oval)

Serrano et al., 2005, *Proc. of InterPACK'05*, ASME, IPACK2005-73322, pp. 1-6.

Prolonged Exposure Damage



Serrano et al., 2005, *Proc. InterPACK'05*, ASME, IPACK2005-73322, pp. 1-6.



- Damage extent is small compared to immediately damaged OTA
- Exposure time before damage critical for device survivability
- Sharp increase in damage time as power is lowered
- Exposures times beyond 5 minutes result in warping/discoloration of target surface
- Damage possibly caused by material and/or property changes due to surface annealing

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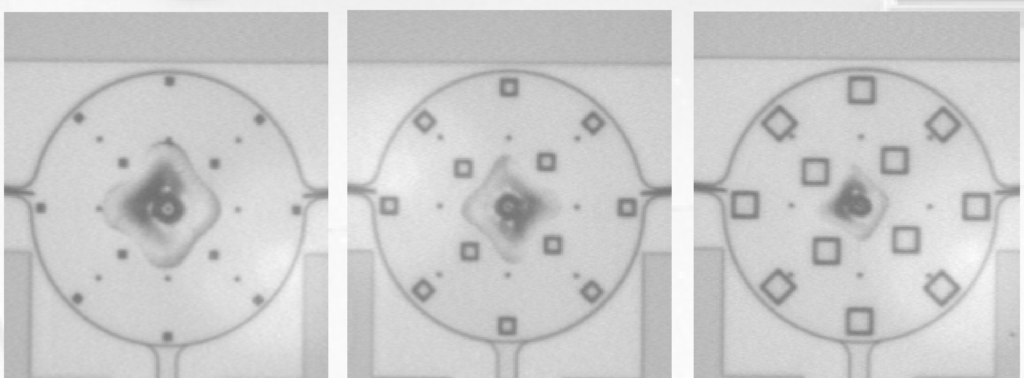
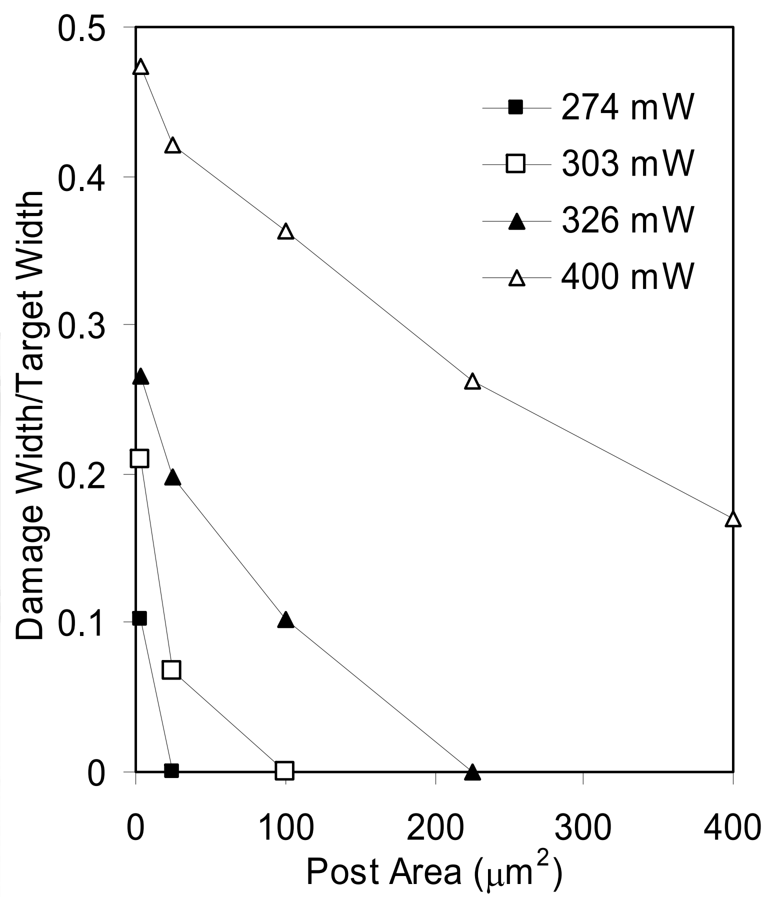
Effect of Post Size

- Larger connecting posts:
  - Increase thermal mass
  - Improve heat transport out of irradiated zone
  - Less damage on target surface for same power levels
- Damage not prevented entirely, but greatly suppressed

400 mW



5 μm posts | 10 μm posts | 15 μm posts



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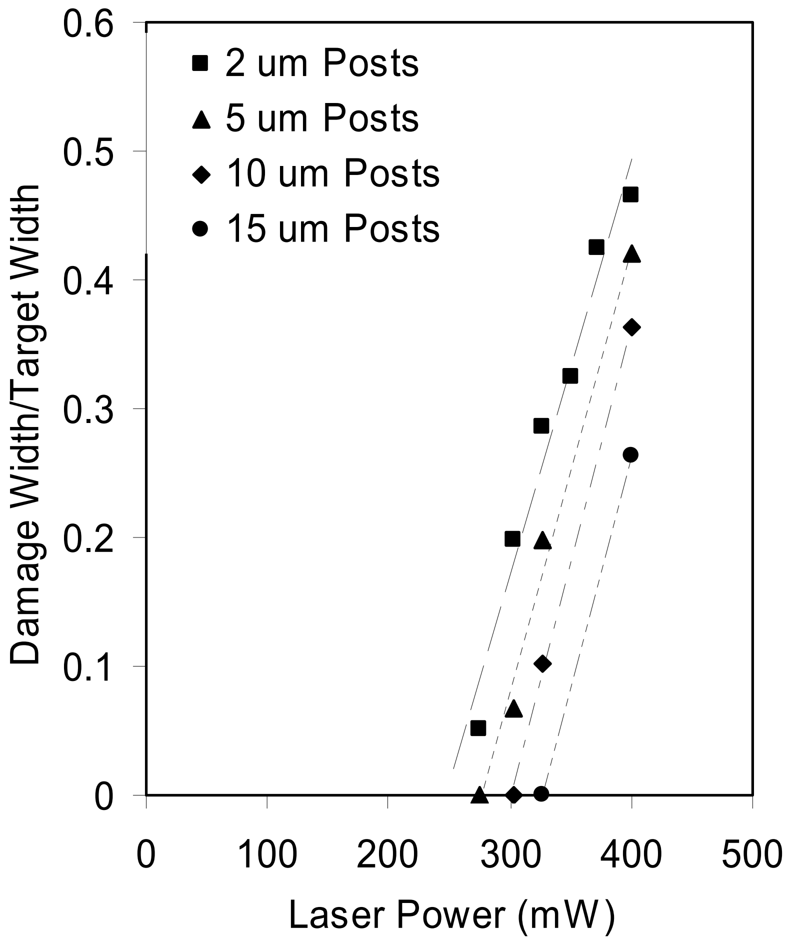
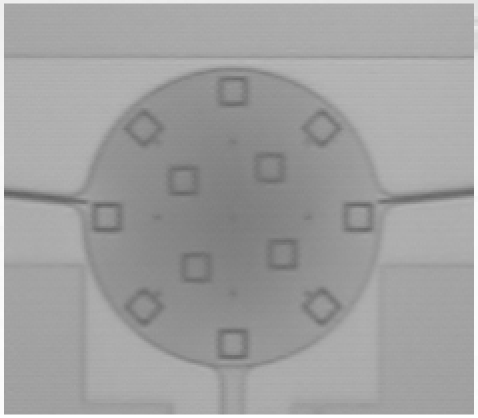
Effect of Post Size

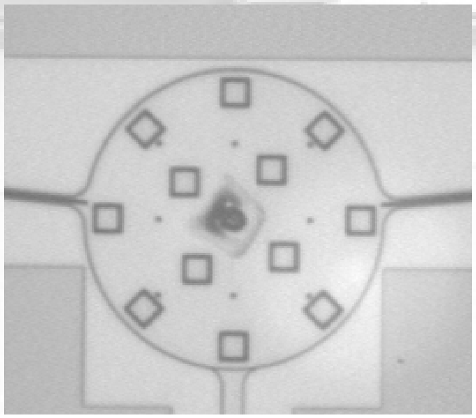


Serrano et al., 2005, *Proc. InterPACK'05*, ASME, IPACK2005-73322, pp. 1-6.

- Threshold power for immediate damage shifted to greater laser powers and longer time-scales
- Targets with 15 x 15 μm^2 posts withstood 16 min. w/o damage



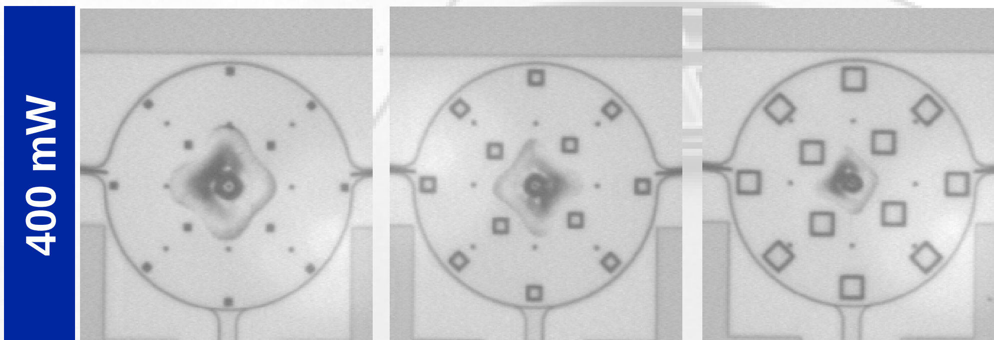
P=326 mW, t_D ~ 600 s



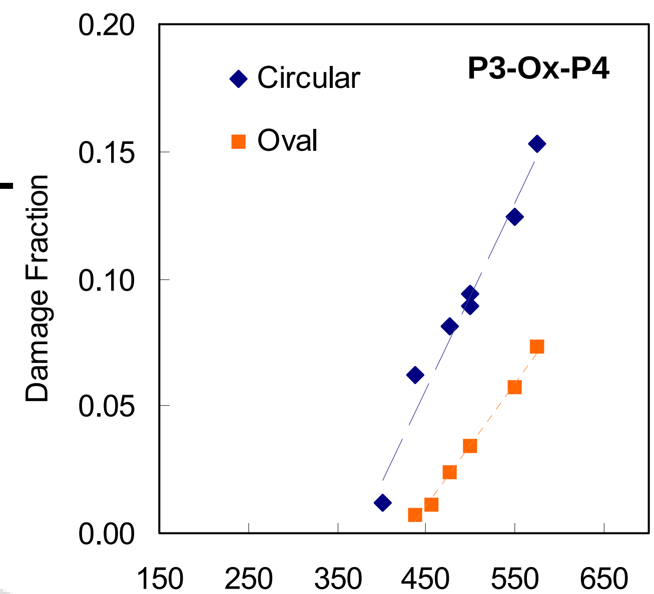
P=400 mW, t_D ~ 0 s

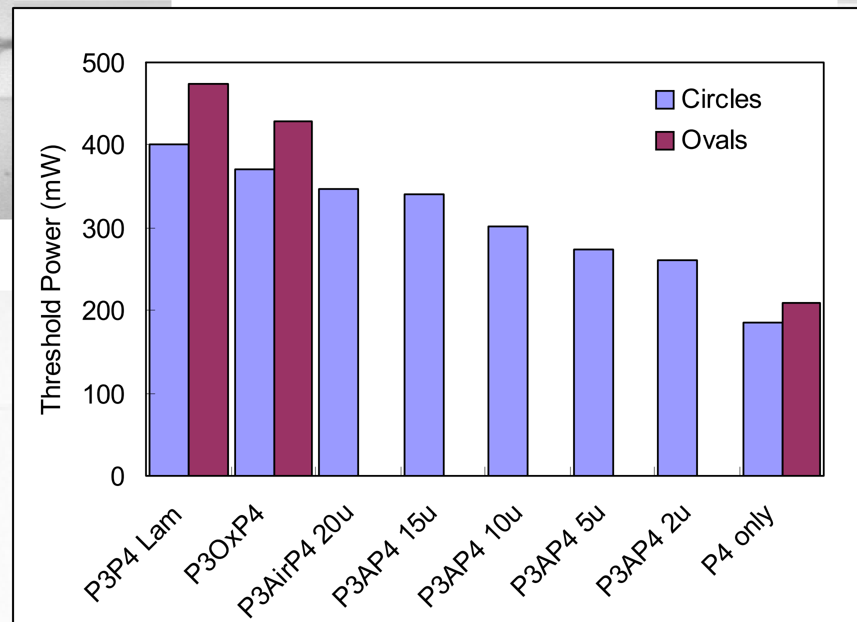
Bent-Beam Actuators

- Displacement is ~5-6 µm with minimal dependence on laser power
- Robustness to damage is key for device reliability



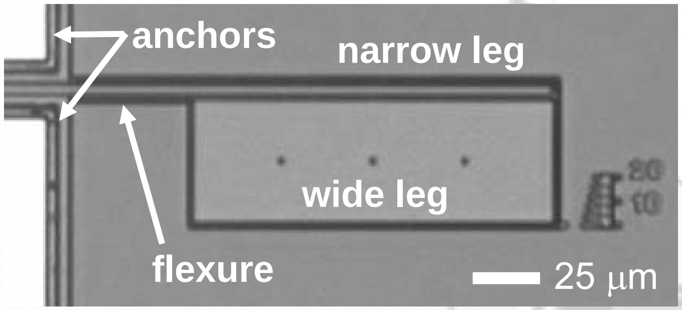
5 µm posts | 10 µm posts | 15 µm posts





- Increasing target thermal mass shifts damage to higher powers; cannot prevent it entirely
- Threshold power for damage can be estimated from damage size

Flexure-style Optical Actuators

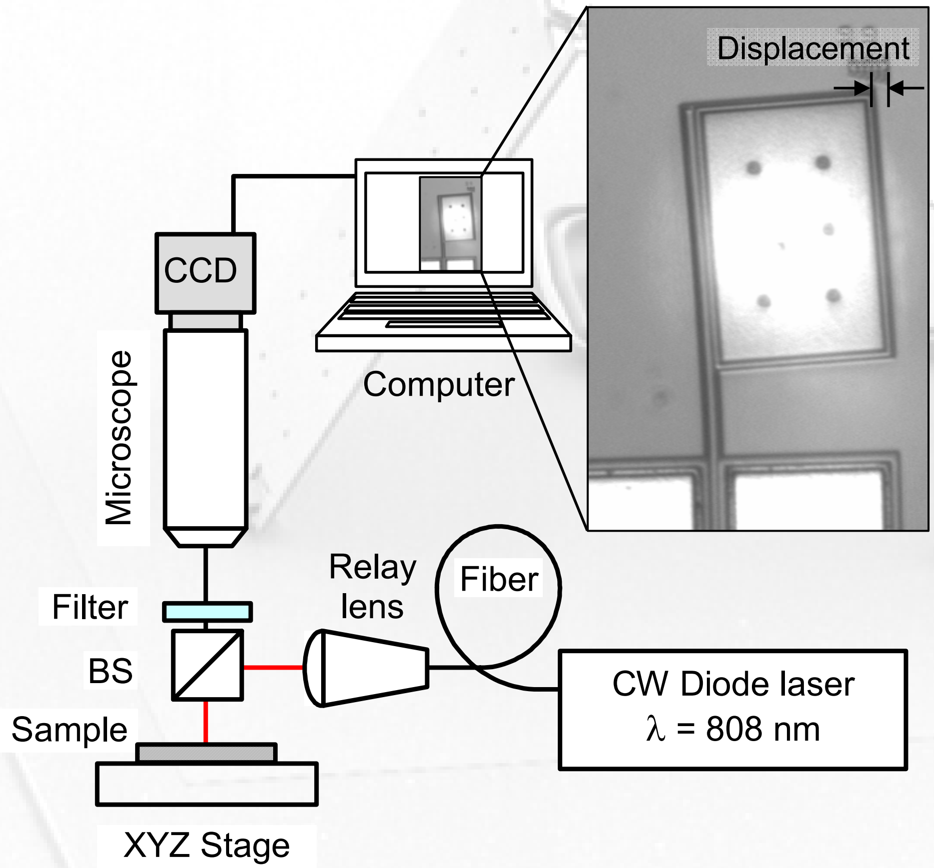


- Dissimilar thermal expansion between hot and cold sides used to generate motion
- Compared to ET flexure actuators
  - Larger wide leg which serves as target for laser
  - Wide leg is “hot” side of actuator
  - Motion is in the opposite direction
  - Different failure mechanism

- Actuator designs
  - **Composition: P4-only or P3-P4 laminate**
  - **Narrow leg: 2.5 x 200 µm**
  - **Wide leg: 2.5 x (50/100) µm**
  - **50 µm flexure element**
  - **2.5/5.0 µm leg-leg distance**

Serrano and Phinney, 2006, *Proc. ASME IMECE*, IMECE2006-14950, pp. 1-6.

Experimental Details



- Actuators irradiated with 808 nm, fiber-coupled, CW diode laser; 100 µm diameter spot
- Laser power varied from 100-650 mW
- Images of actuators captured before, during and after irradiation

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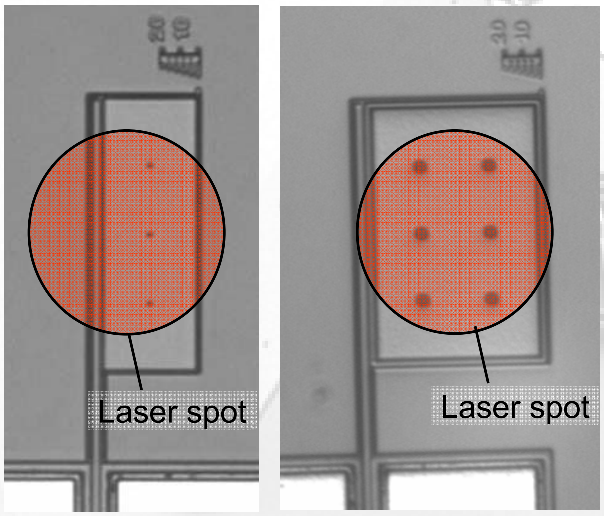
Experimental Details

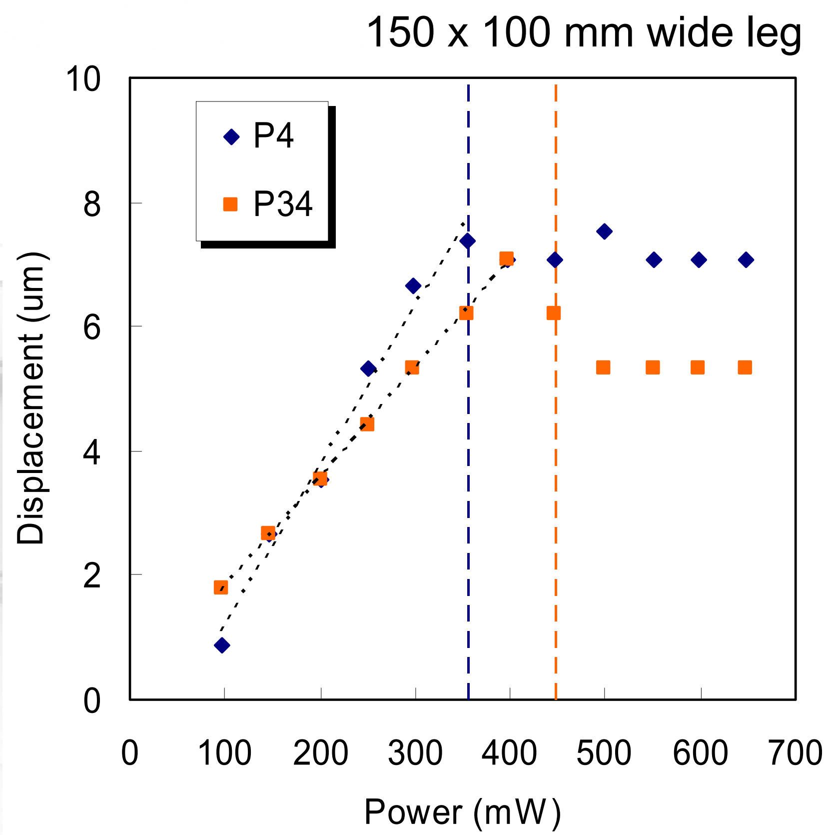


Laser spot centered on 100 µm wide leg; offset on 50 µm wide leg

- Displacement measured at the top-right corner of device; determined with image analysis
- Displacement determined to ± 1 pixel (0.65 µm)
- Irradiation schemes:
  - Power ramp: **laser power always incident on actuator, increased slowly; images captured at regular power intervals**
  - On/off irradiation: **images captured, laser power increased with each on/off cycle**
  - Prolonged exposure: **laser incident on actuator for extended period; images captured at regular time intervals**

Target Composition

- Displacement is linear with power up to initiation of surface damage
- Maximum displacement similar for both compositions
- After damage, displacement recedes slightly (P34) or remains constant
- P4-only actuators significantly more robust than previous studies; possibly due to interference



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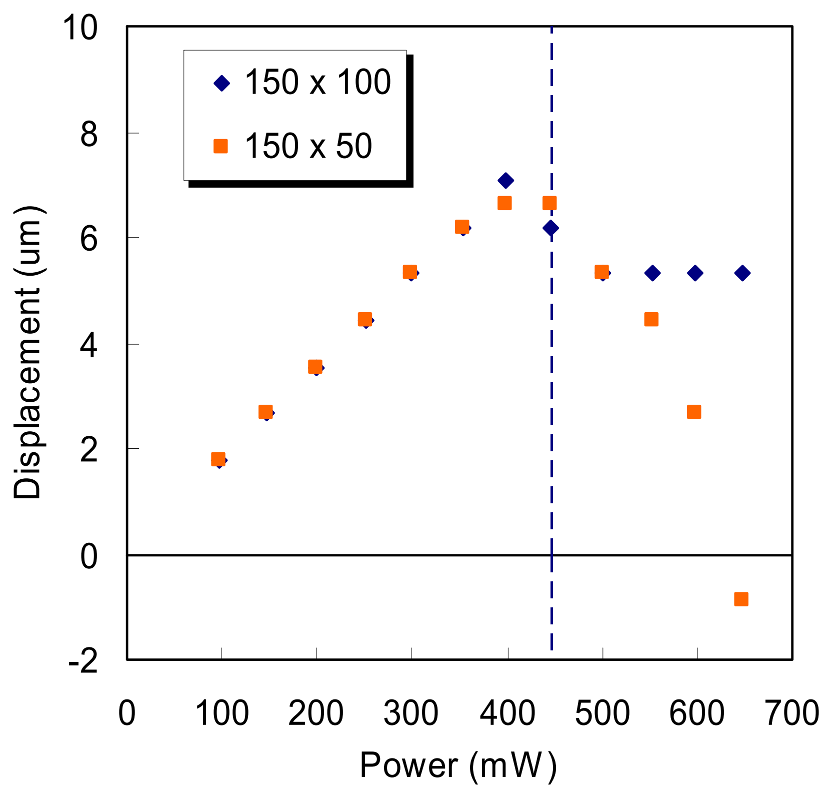
Displacement Recession



- Narrower actuator shows significant recession in displacement after damage regardless of composition
- Displacement loss due to softening of the poly at elevated temperatures responsible for damage
  - **"Softening" compromises more of the actuator structure in the narrower device**

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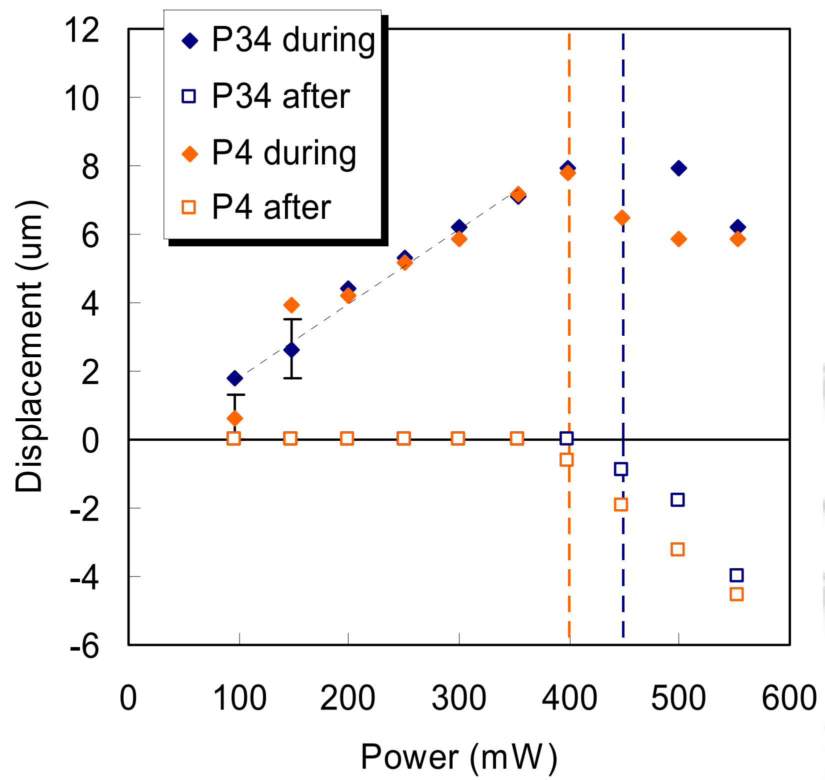
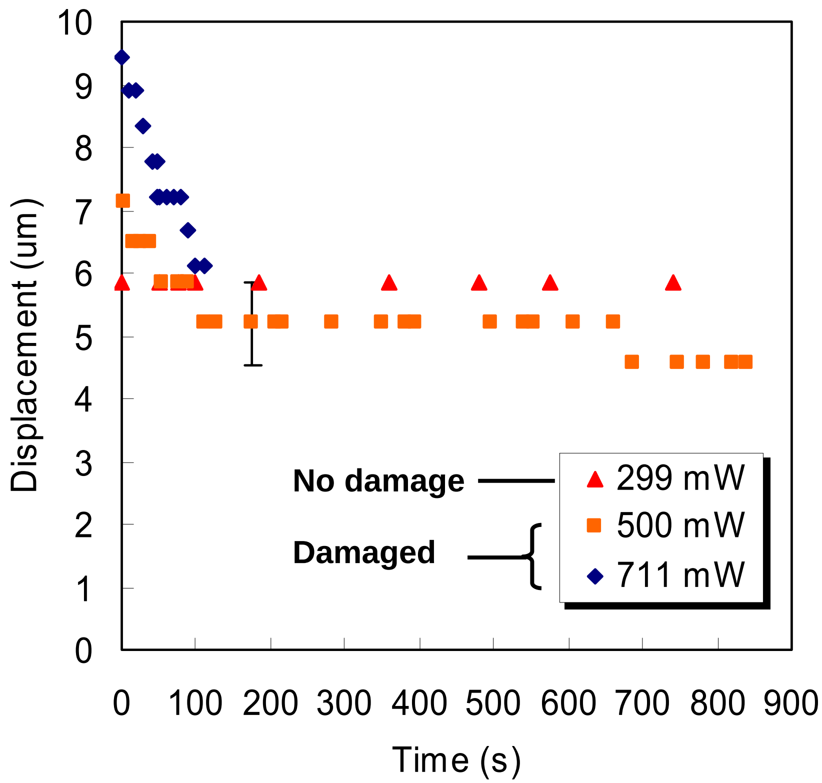
On/Off Cycling

- Cycling laser power on/off results in repeatable displacement in undamaged surface
- After damage, displacement recession is clearly evident after irradiation
  - **initial position recedes with increasing laser power**
  - **relaxation during the damage event results in thermal contraction upon cooling**



Prolonged Exposure: More Recession

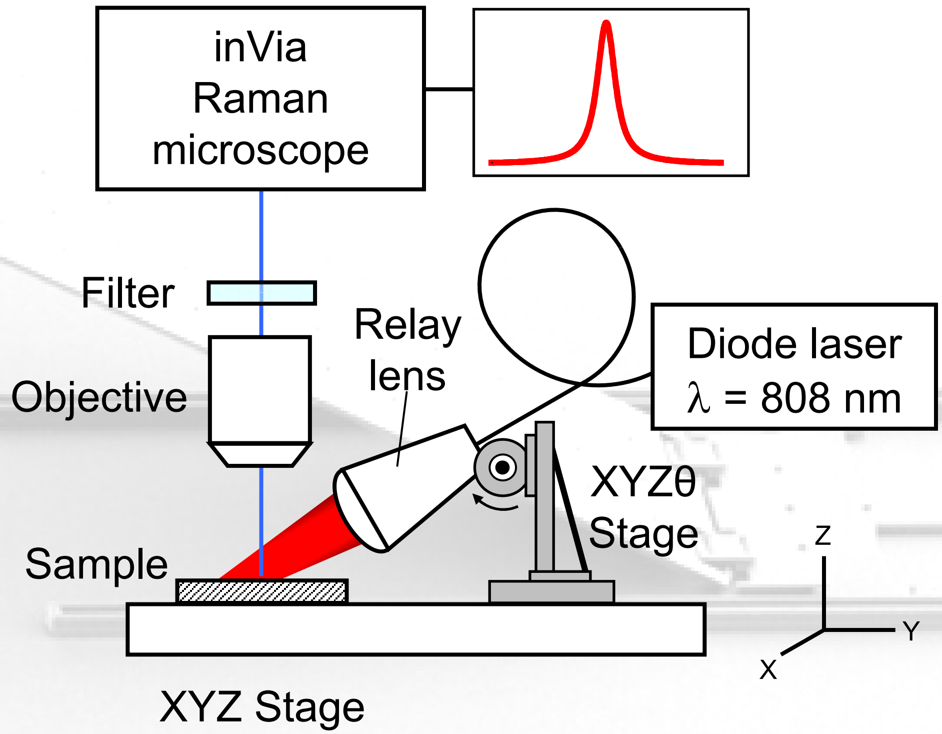


- At powers below damage, displacement holds constant
- If the surface is undamaged prior to irradiation, powers that produce damage:
  - Result in large displacement recession within first 200 s of irradiation;
  - Slight increase in surface damage size during first 60 s; minimal afterwards

Experimental Setup

Heating Laser

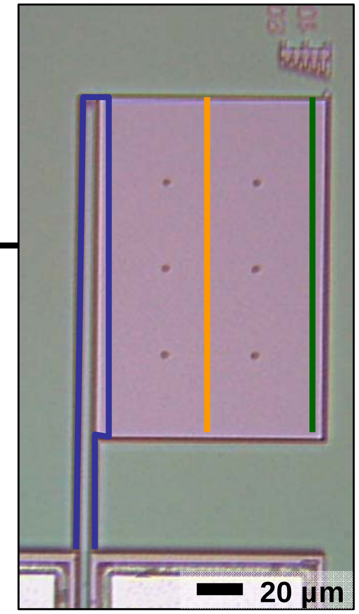
- 808 nm CW laser, fiber-coupled to a 100 µm core fiber
- Laser focused with 1:1 relay lens mounted on XYZθ stage
- Angle of incidence fixed at 60° to the sample normal; results in 200 µm x 100 µm elliptical spot



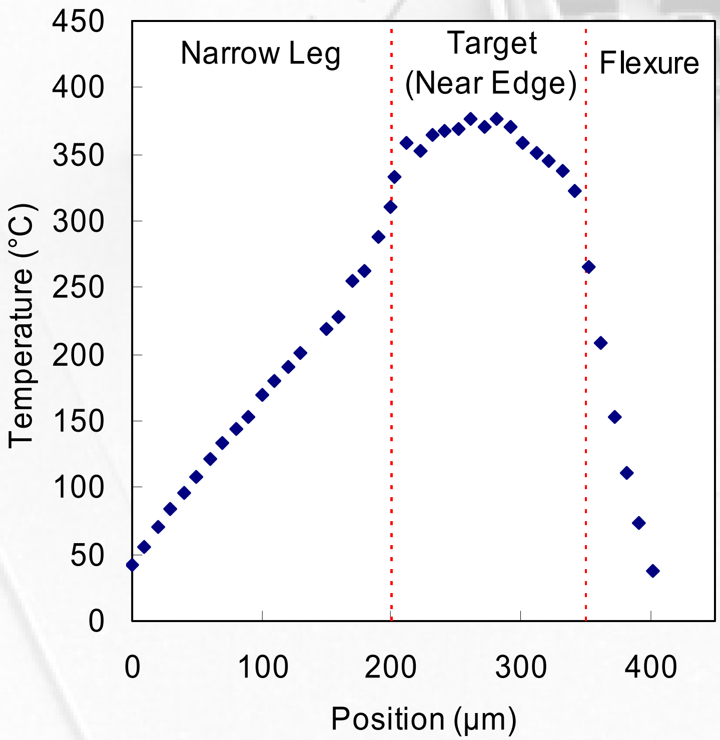
Raman microscope

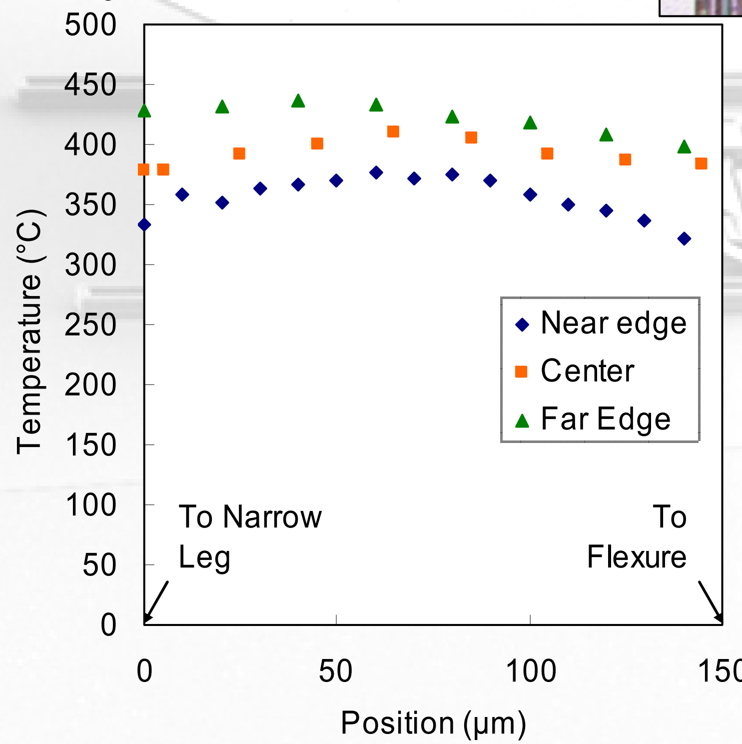
- 488 nm Ar^+ laser focused with 20x, 0.42 NA objective; resolution better than 1.5 µm
- IR filter blocks scattered IR light with minimal loss to Raman signal from sample (λ_{Raman} ~ 500 nm)
- Laser heating set-up designed to operate within physical constraints of Raman microscope

Optically-Powered Flexure Actuator



- Steady temperature increase along narrow leg
- Target temperature uniform at ~375°C up to middle, then decreases as flexure is approached
- Upper-right corner is hottest point on actuator due to device motion and longest conduction pathway





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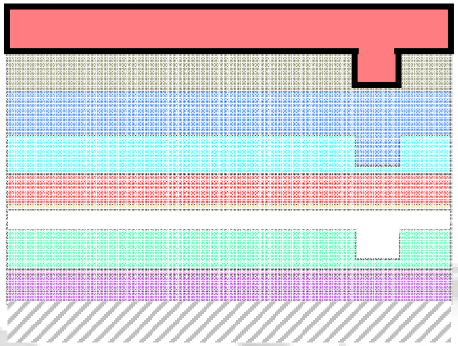
Cantilever Plate Description

Cantilever plate (springboard)

- 500 µm long x 250 µm wide
- Single Poly4 layer (2.25 µm thick)
- 10.75 µm from the substrate
- Anchored to substrate at one end; opposite end is free
- Surface covered with 2 µm square etch-release holes spaced 25 µm apart



Serrano and Phinney, 2007, *Proc. InterPACK'07*, ASME, IPACK2007-33571, pp. 1-7.

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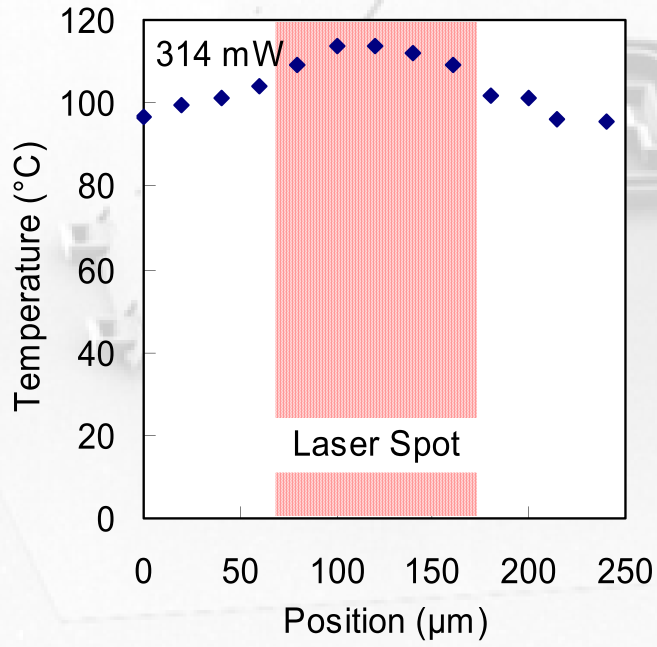
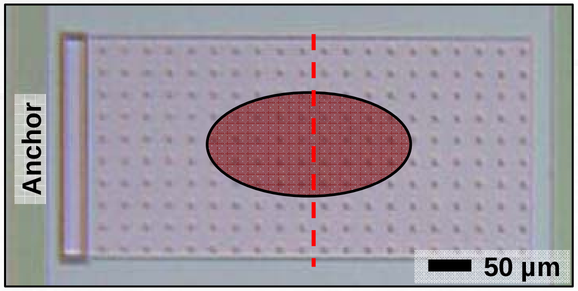
Cantilever Plate

- Irradiated with 314 and 532 mW, with the laser spot centered on the plate
- Temperature measured across width and length of plate at 20 µm intervals



Across width

- Symmetric temperature profile
- Almost uniform temperature across plate with slight increase within laser spot
- Peak temperature of 115°C at 314 mW



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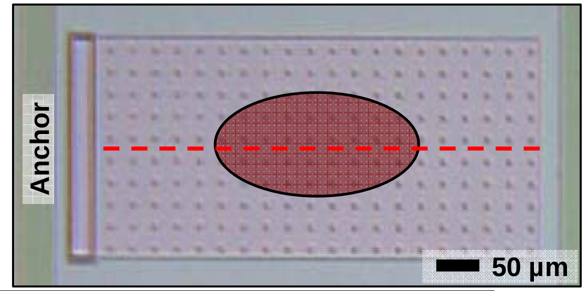
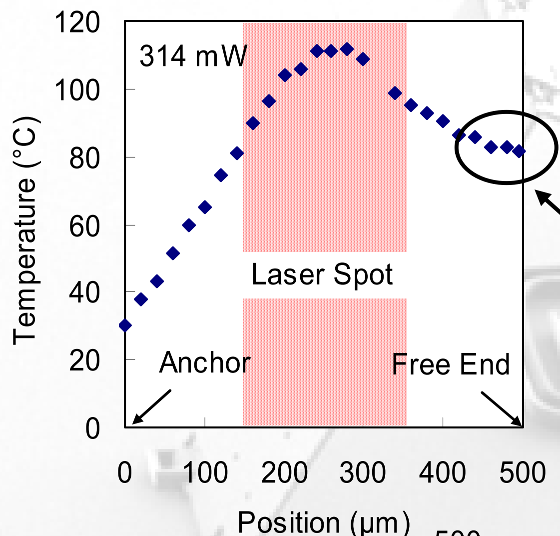
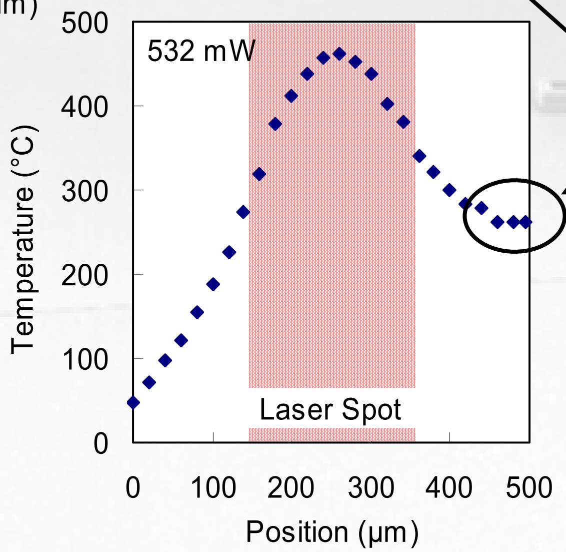
Cantilever Plate







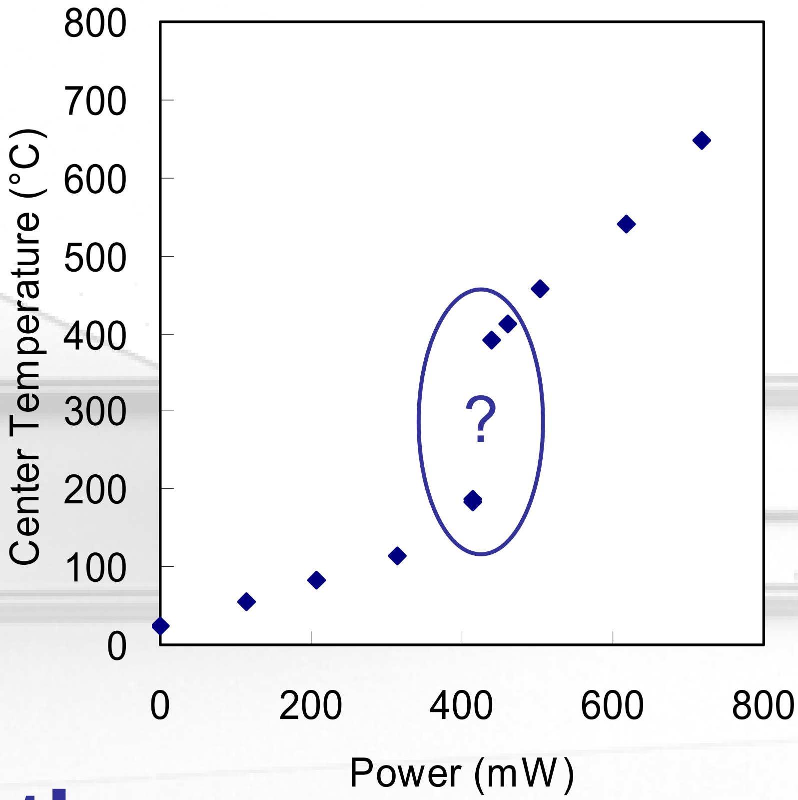
Across length

- Effect of different boundary conditions clearly evident
- Pronounced increase within irradiated region
- Peak temperature of 460°C at 532 mW

Adiabatic edge observed at free end, validating extended surface model assumptions

Optical-Thermal Phenomena

- Center temperature is ~linear with power < 400 mW and temperatures < 200°C
- In the vicinity of 440 mW, temperature “jumps” by 200°C to over 400°C
- Temperature remains linear with power for higher powers



Why the abrupt jump?

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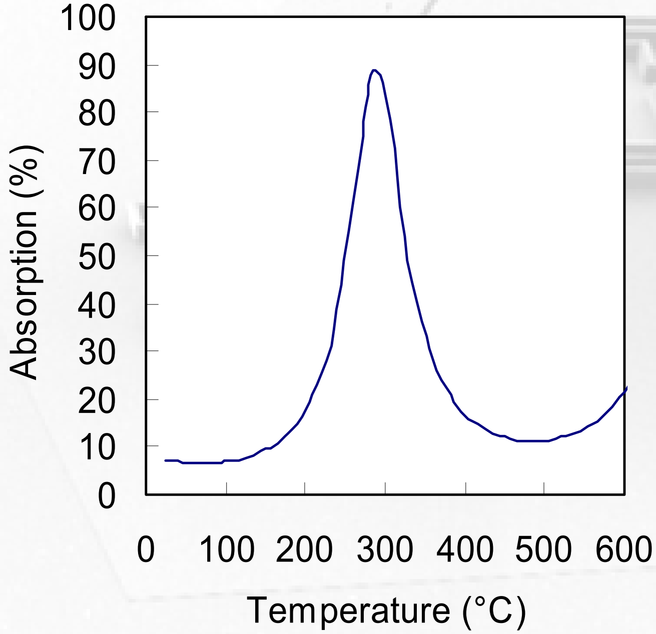
Optical-Thermal Phenomena

- Optical constants are dependant on temperature; $n \propto T$; $k \propto \exp(T)$
- Thin film interference; absorption strongly affected

Poly4 absorption from Fresnel calculations



- Flat absorption curve at lower temperature leads to initial linear temperature increase
- Sharp absorption peak leads to a "positive feedback" effect
  - increased temperature → increased absorption → increased temperature → increased absorption ...
  - temperatures in the region of the absorption peak are "forbidden" in steady state

Cantilever plate: 60° incidence; 808 nm; literature temperature dependence for optical constants

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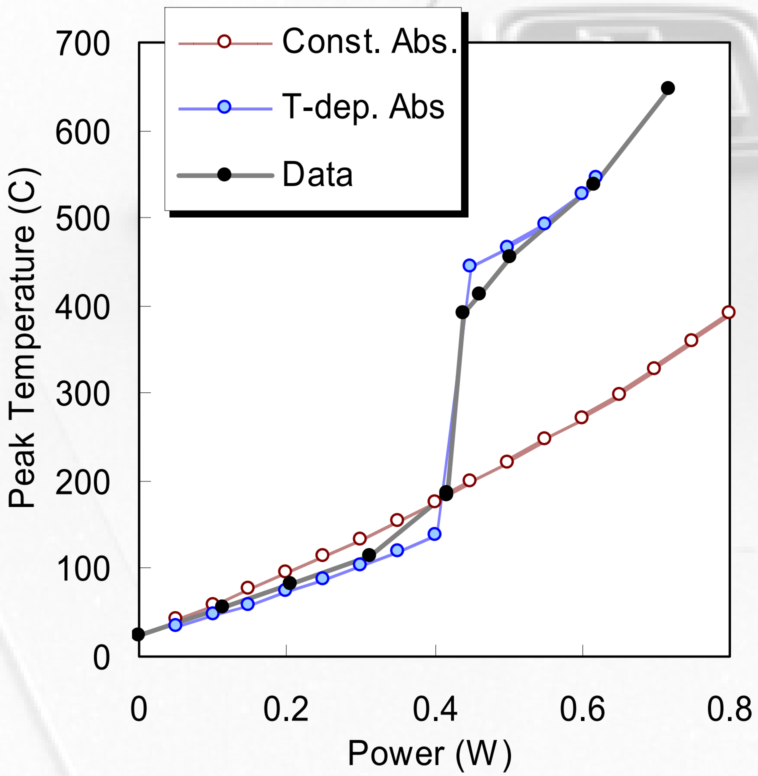
Simulating Optical-Thermal Phenomena

- Coupled optical-thermal phenomena must be considered for accurate device modeling
- Requires knowledge of *n*(T) and *k*(T)



- With fixed absorption, model fails to reproduce temperature jump and under-predicts peak temperature at higher powers
- Including optical effects into thermal model improves model results and also predicts temperature jump

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Summary and Conclusions

- A complete understanding of thermal phenomena in microsystems is necessary to improve the design, operation, and reliability of MEMS devices for a variety of applications.
- Raman thermometry was used to make high spatial resolution temperature measurements on microthermal actuators.
- Bent-beam and flexure-style polysilicon actuators were designed, fabricated, and tested to evaluate laser-based actuation for microsystems.
- For optically powered MEMS devices, target design has a significant impact on the likelihood for damage due to laser heating since it affects the distribution of energy within the target.
- **There are plenty of technical challenges and opportunities at the boundary of thermal sciences and microsystems.**

Summary and Conclusions

- Different variations of two types of polysilicon optically-powered actuators were tested
- Actuator performance evaluated in terms of displacement and robustness to laser-induced damage

Bent Beam Actuators

- **Performance limited by heat flow; laser power has minimal impact on displacement**
- **Increased thermal mass of target surface shifts damage to higher laser powers**
- **Prolonged exposure near threshold can still cause damage due to changes in material properties**

Flexure Actuators

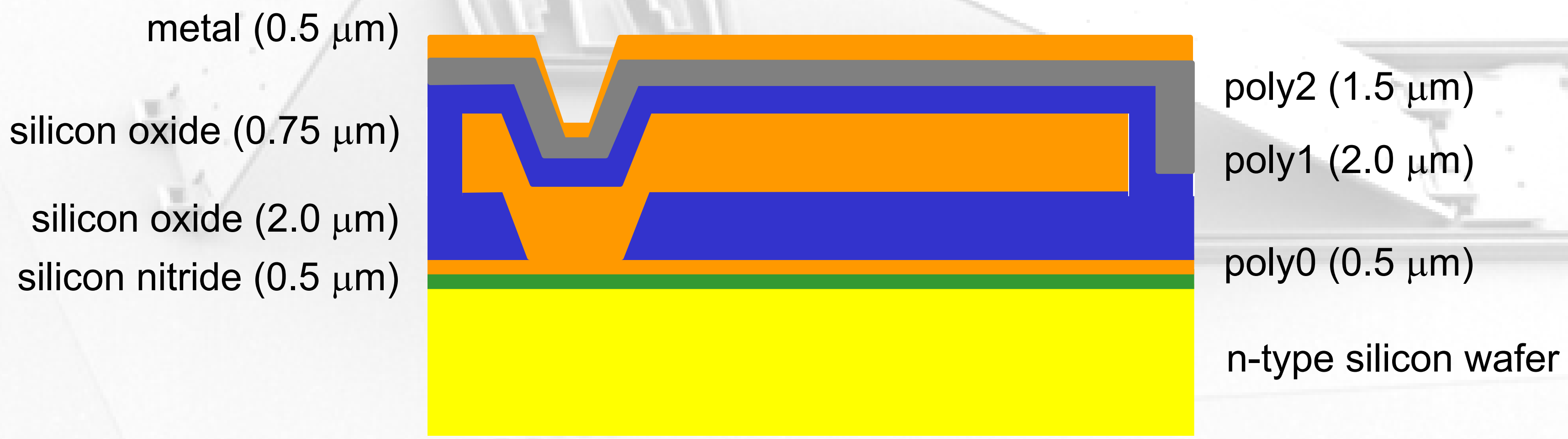
- **More effective use of laser power; displacement is linear with applied power below damage threshold**
- **Damage causes recession in displacement while powered due to structural relaxation of polysilicon**
- **Prolonged exposure to elevated laser powers causes further recession in displacement**

Summary and Conclusions

- Polysilicon flexure type optical actuators were evaluated for performance and robustness to damage
- Because heating power is applied directly to members responsible for motion, displacement is linear with power for laser powers that do not produce damage ($P < 400$ mW)
- Maximum displacement is 8-9 μm
- Increased incident power results in surface damage and recession in actuator displacement due to structural relaxation of the polysilicon layer
- Prolonged exposure to elevated laser powers further increases the recession in the displacement

Sacrificial Surface Micromachining

Multi-User MEMS Process (MUMPs^{TM})



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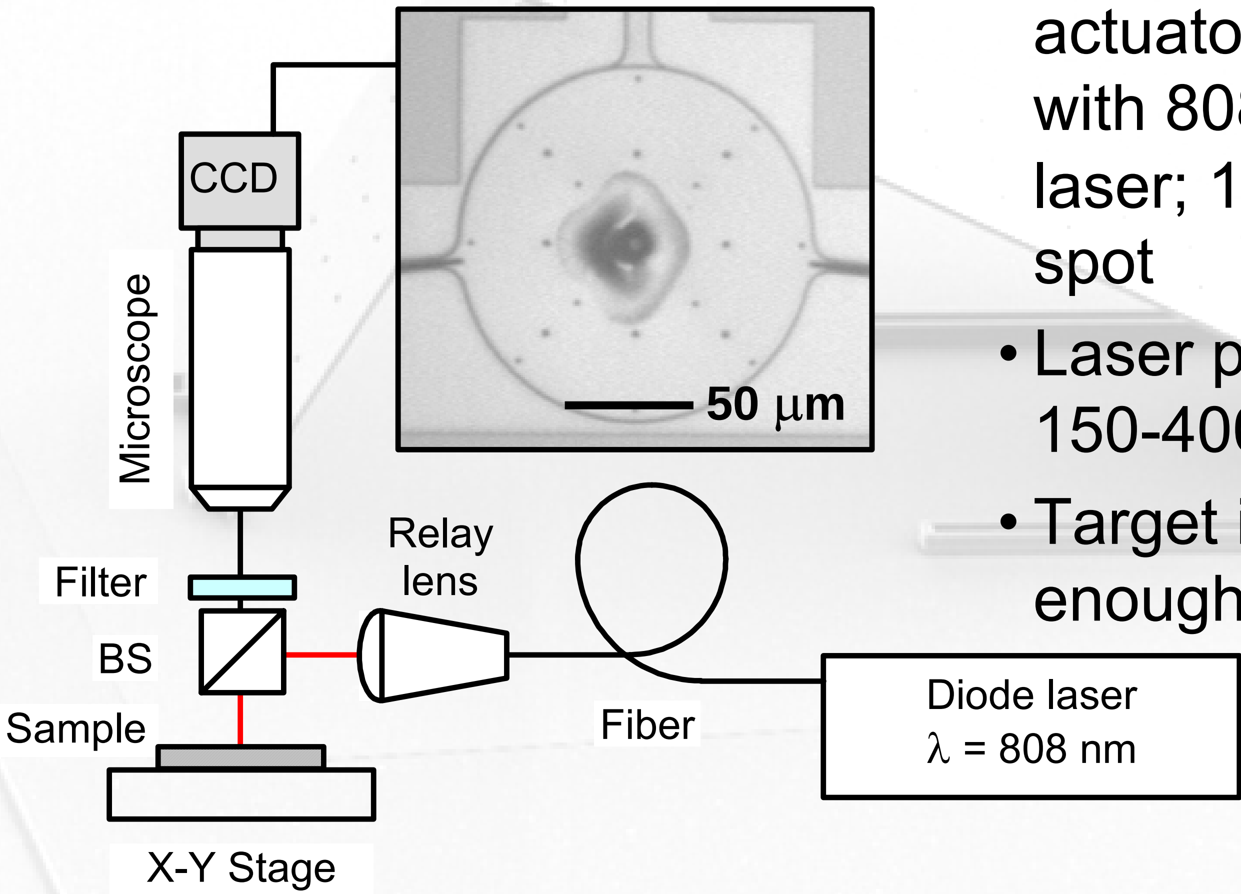
Experimental Methods

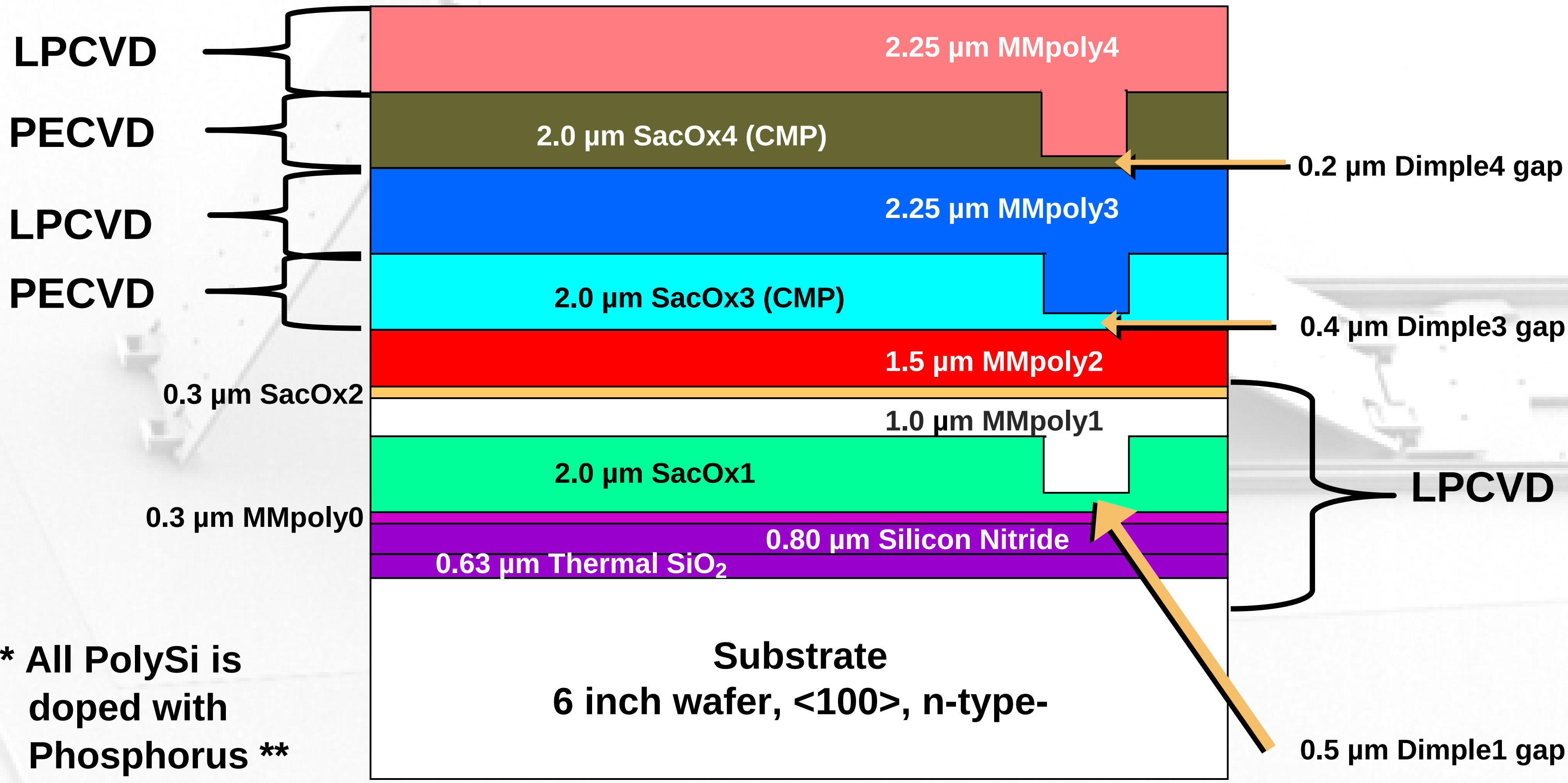


- Optically powered thermal actuator target irradiated with 808 nm CW diode laser; 100 μm diameter spot
- Laser power varied from 150-400 mW
- Target irradiated long enough to image device

SUMMiT™ V

Sandia's Ultra-planar Multi-level MEMS Technology

SUMMiT™ Layer Descriptions



** All PolySi is doped with Phosphorus **

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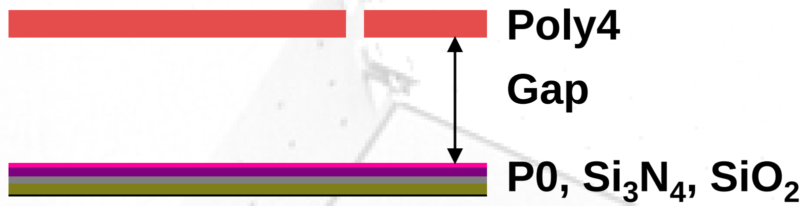
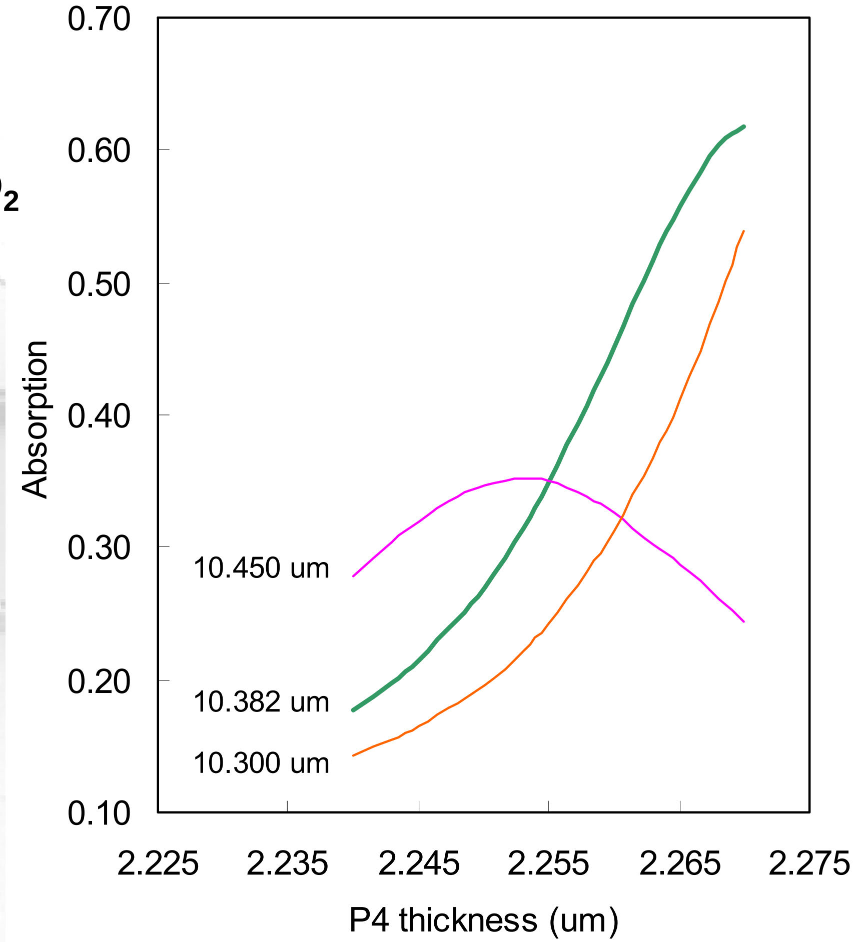
Optical Energy Absorption: Poly4 only

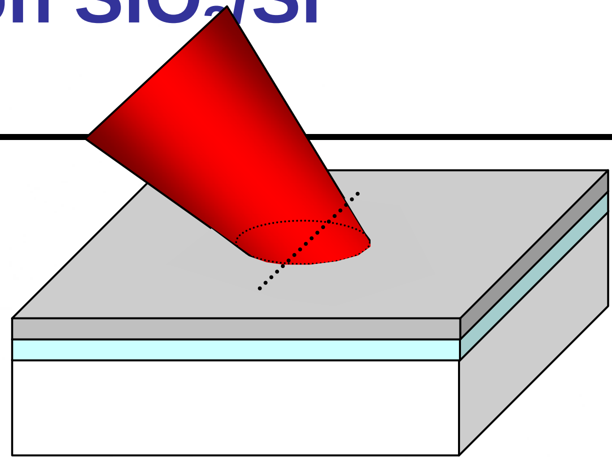


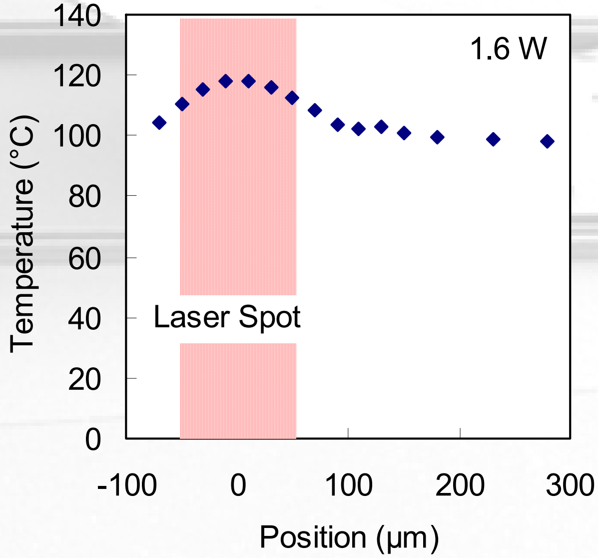
- Thin film interference affects absorption in multi-layered structure
- Absorption strongly dependent on film and gap thicknesses
- Nominal thickness fluctuations can lead to >100% change in optical energy absorption



Polysilicon Film on SiO_2/Si

- Laser power of **1.6 W** needed power to generate substantial heating due to large thermal mass
- Temperature measured along major and minor axes of elliptical laser spot at 20 μm intervals
- Along minor axis:
  - Peak temperature of 120°C
  - Strongest temperature gradient within beam spot
  - Uniform temperature outside immediate vicinity of laser spot





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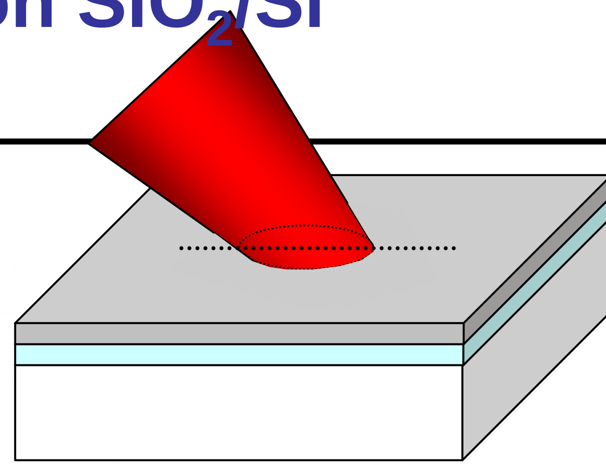
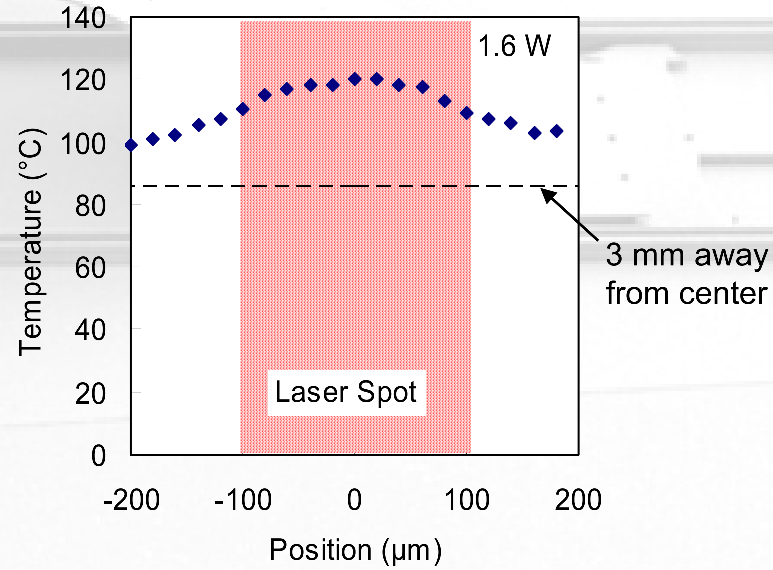
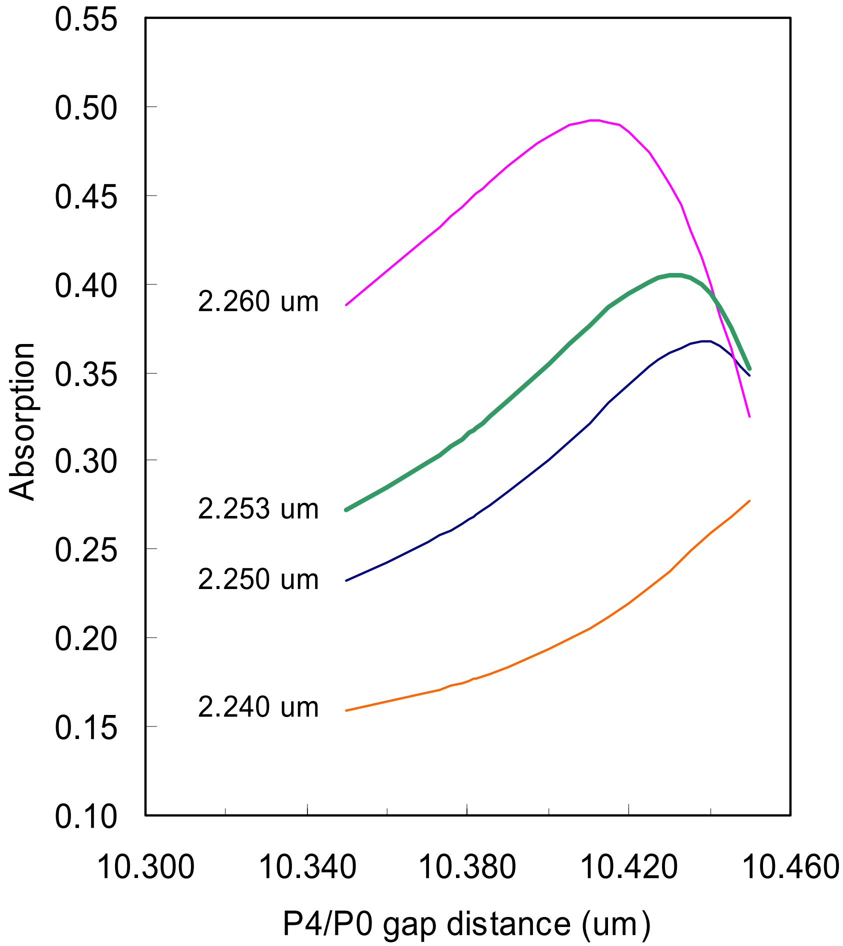
Polysilicon Film on SiO_2/Si

- Laser power of **1.6 W** needed power to generate substantial heating due to large thermal mass
- Temperature measured along major and minor axes of elliptical laser spot at 20 µm intervals
- Along minor axis:
  - Peak temperature of 120°C
  - Strongest temperature gradient within beam spot
  - Uniform temperature outside immediate vicinity of laser spot
- Along major axis
  - Weaker gradient within beam spot than along major axis
- Sample still at elevated temperature (85°C) three millimeters away from laser spot



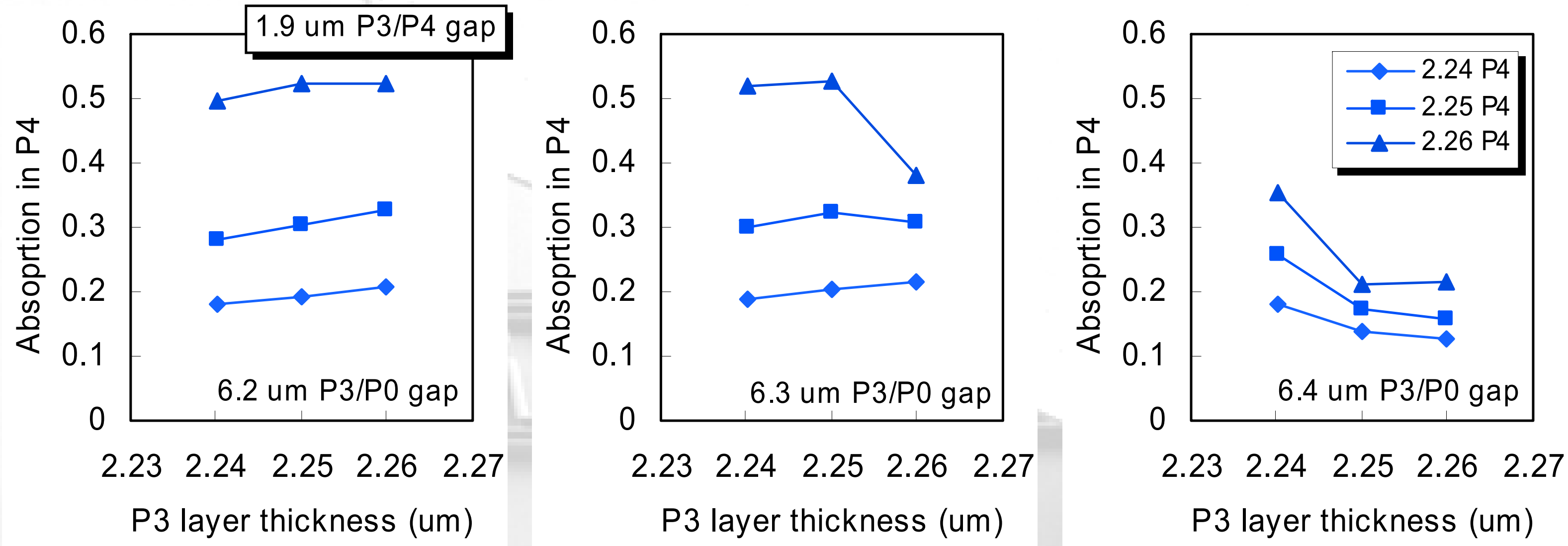


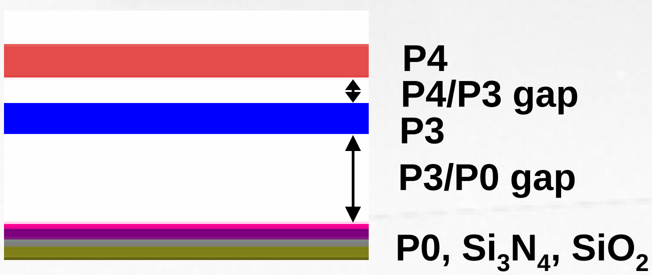
Optical Energy Absorption: P4 only



- As-fabricated gap values necessary to establish range of absorption during operation
- Energy absorption affected by component deflection during operation

Optical Energy Absorption: P3-Air Gap-P4





- Additional layers introduce more parameters that affect absorption
  - Multiple film thicknesses
  - Multiple gap distances

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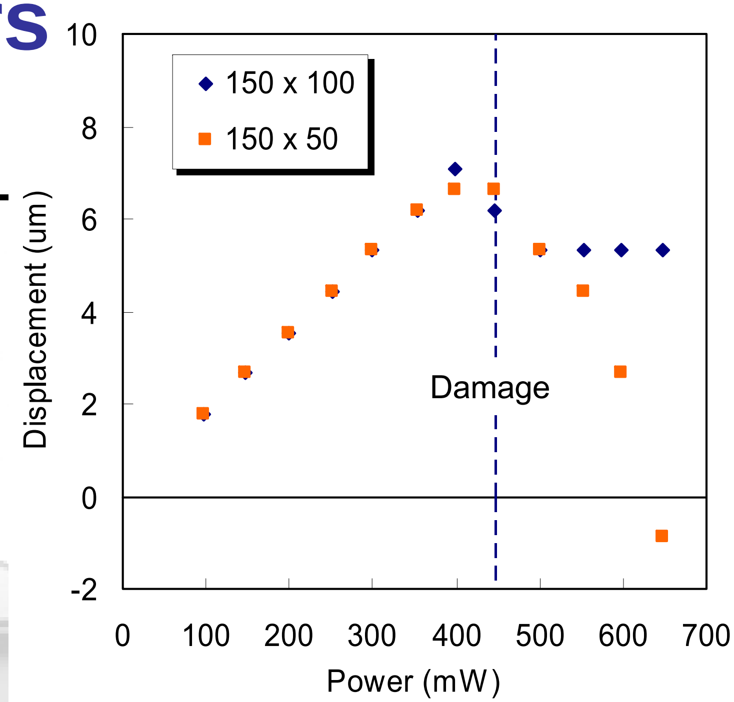
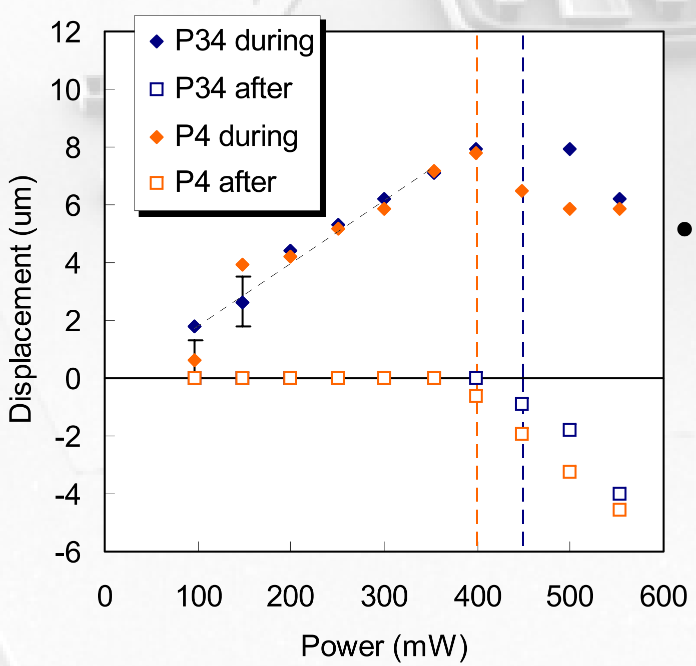
Flexure Actuators

- **Linear displacement with laser ~~power up to initiation of damage~~**
- **Damage compromises structural integrity of device**
- **Viscous relaxation leads to reduction in thermal strain and displacement recession**





- **Strain relaxation during damage results in additional thermal contraction when unpowered and recession of return position**

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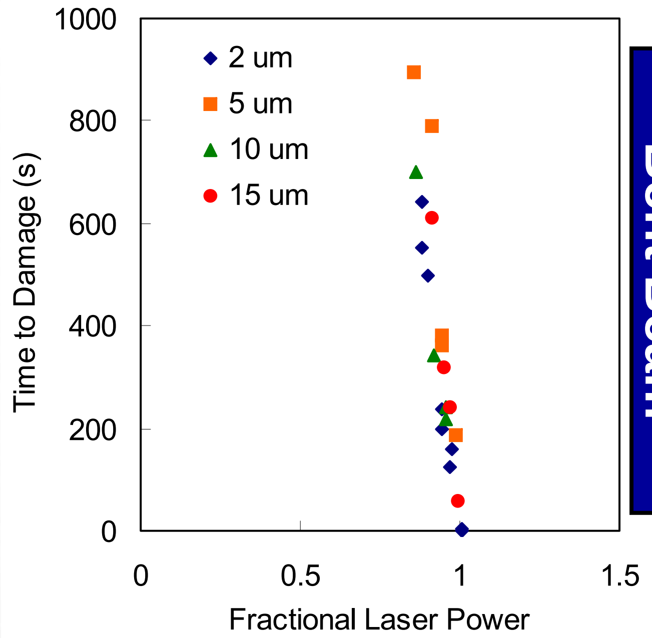
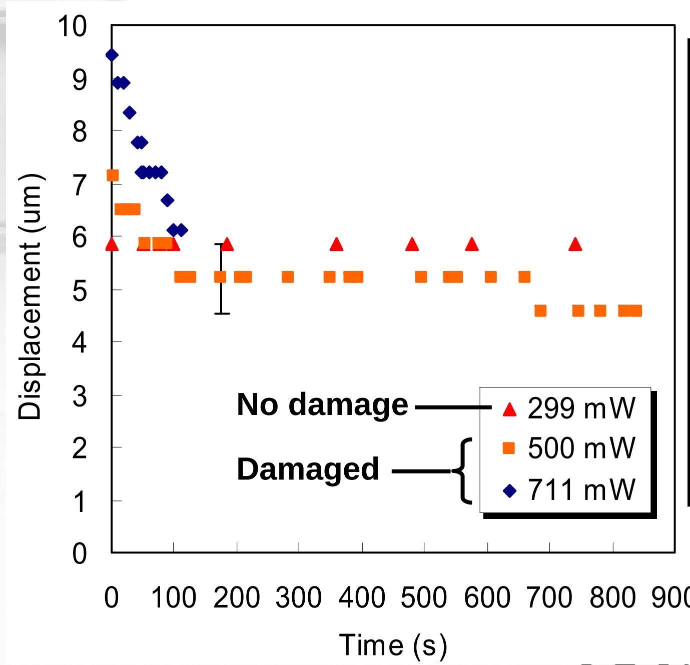
Timed Exposure



Bent Beam

- Bent beam actuators can still suffer damage if operated near the damage threshold
- Properties (n, k, Λ) can change enough near threshold to cause overheating and damage



Flexure

- Flexure actuators operated below damage threshold hold displacement
- If damaged, displacement recession can continue for several minutes