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Laser Heating of Silicon Microsystems

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Serrano and Phinney, "Optical-Thermal Phenomena in Polycrystalline Silicon MEMS during Laser Irradiation," chapter in *Microelectromechanical Systems and Devices*, InTech Open Access Publisher, 2012.

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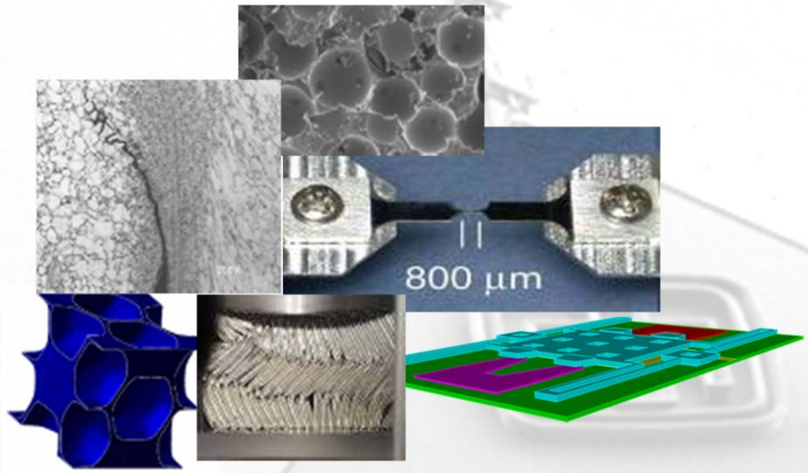
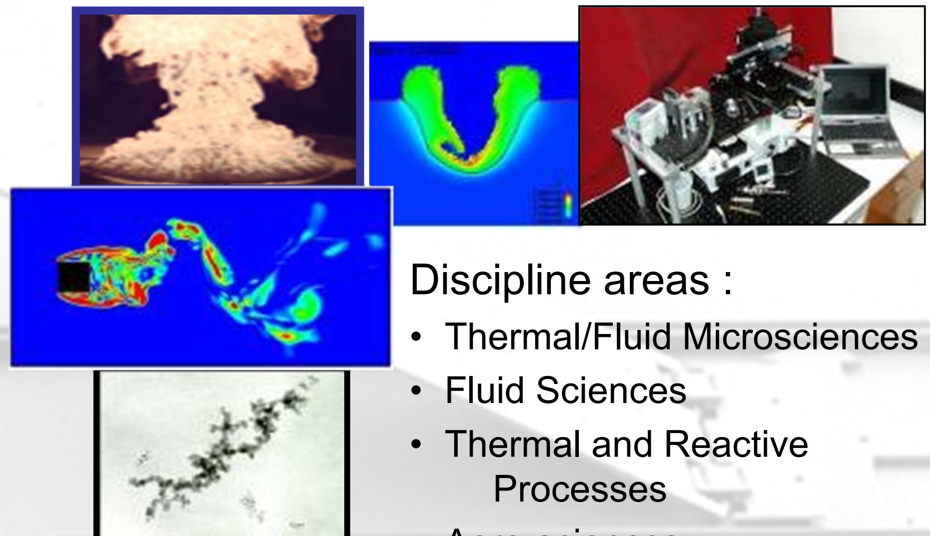
Engineering Sciences Center at Sandia National Laboratories



Thermal, Fluids & Aero-sciences



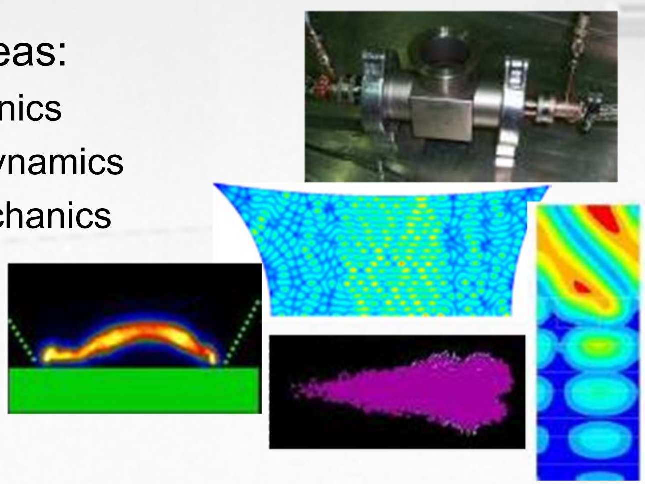
Discipline areas :

- Thermal/Fluid Microsciences
- Fluid Sciences
- Thermal and Reactive Processes
- Aero-sciences

Solid/Material Mechanics & Structural Dynamics

Discipline areas:

- Solid Mechanics
- Structural Dynamics
- Material Mechanics



Electrical Sciences

Discipline areas:

- Electromagnetics and Plasma Physics
- Electrical Processes

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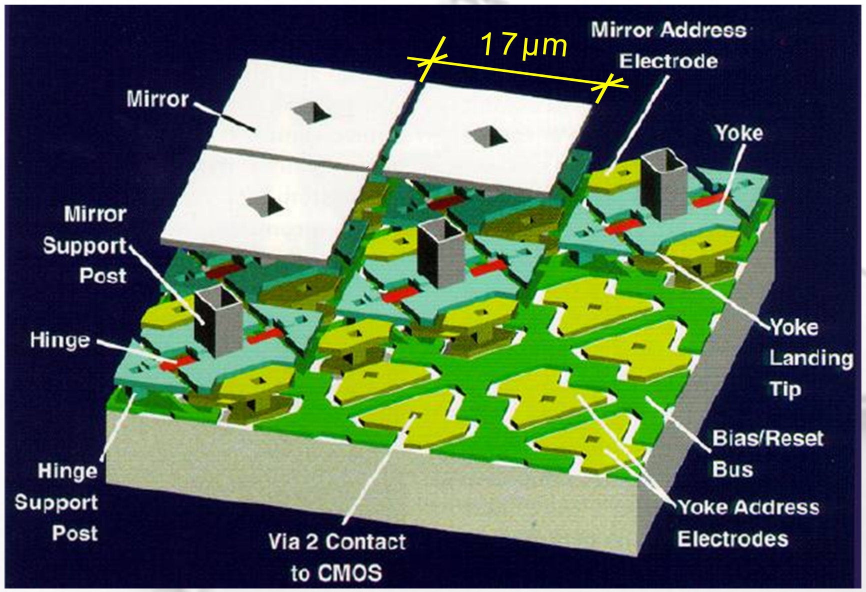
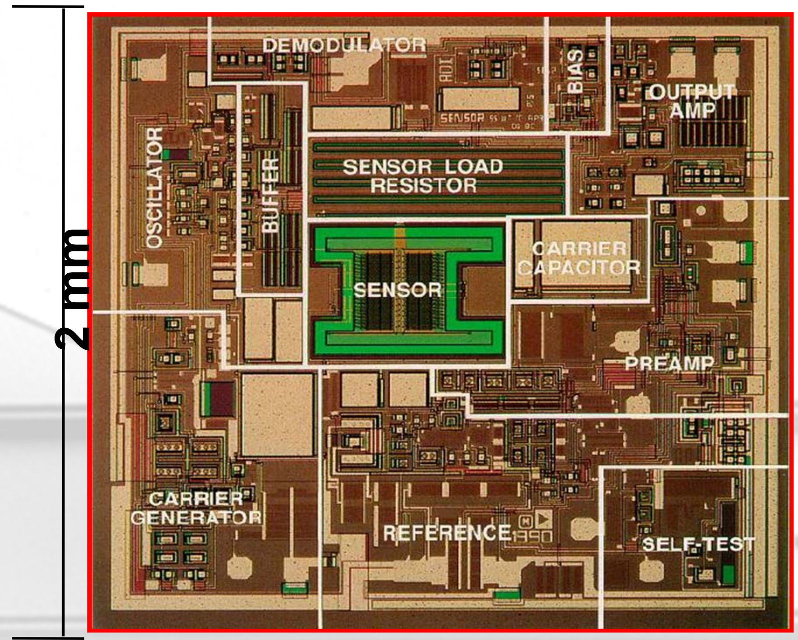
Thermal Phenomena in Polycrystalline Silicon MEMS during Laser Irradiation

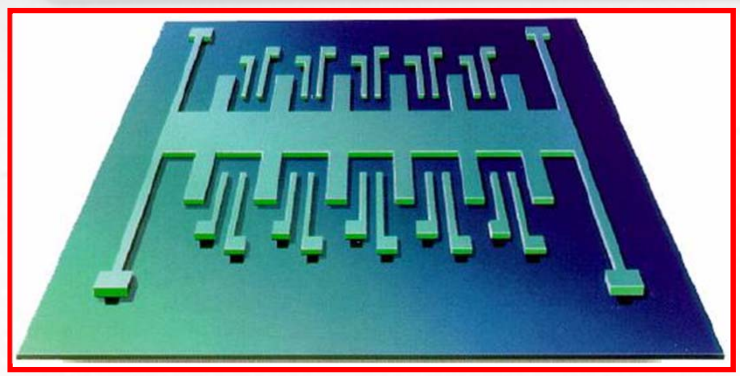
1. Motivation
   - Laser Powered Thermal Microactuators
2. Test Structures and Devices
   - Surface Micromachining
3. Experimental Results
   - Laser Damage Studies
   - Temperature Measurements
     - Raman Thermometry
     - Variation of Peak Temperature with Power
4. Optical and Thermal Simulations
   - Absorptance
5. Conclusions

MEMS Products



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

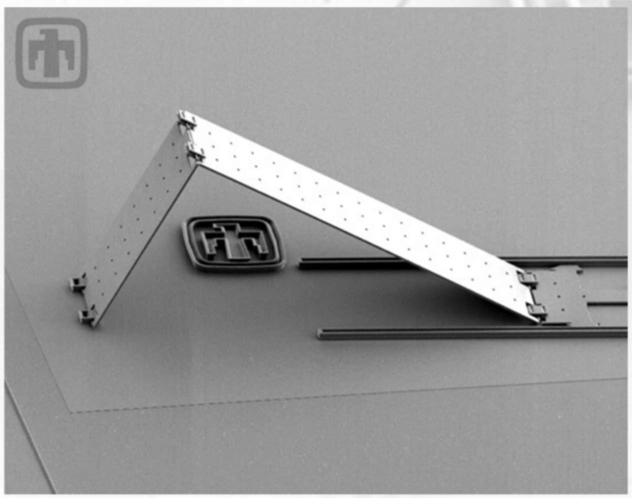




Accelerometer
Analog Devices

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
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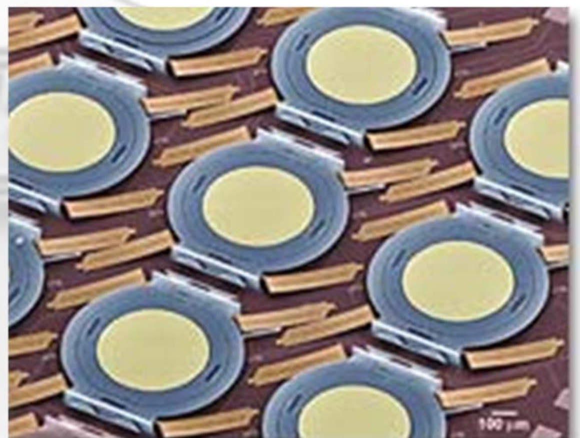

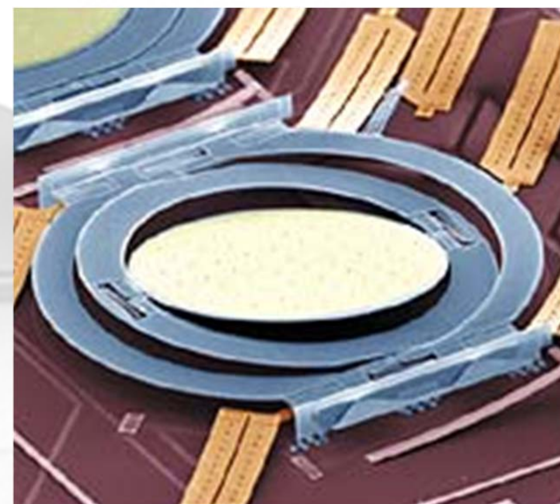

Optical Cross Connect
WaveStar™ Lambda Router, Lucent Technologies array of micromirrors route information to and from any of 256 input/output optical fibers

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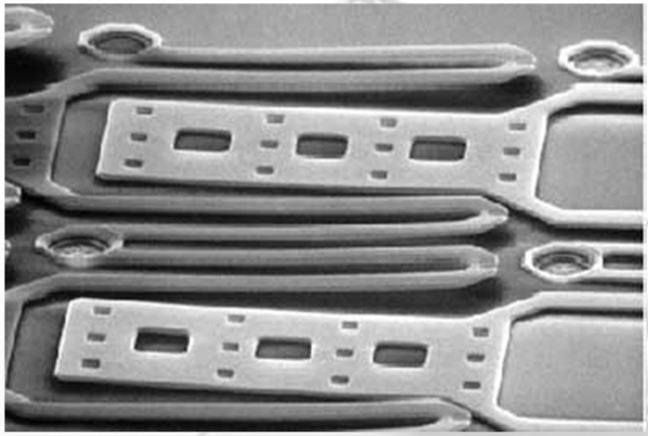
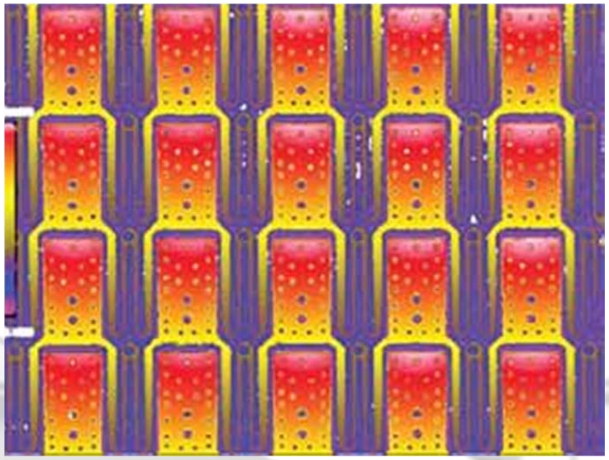
MEMS Based IR Imaging



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.

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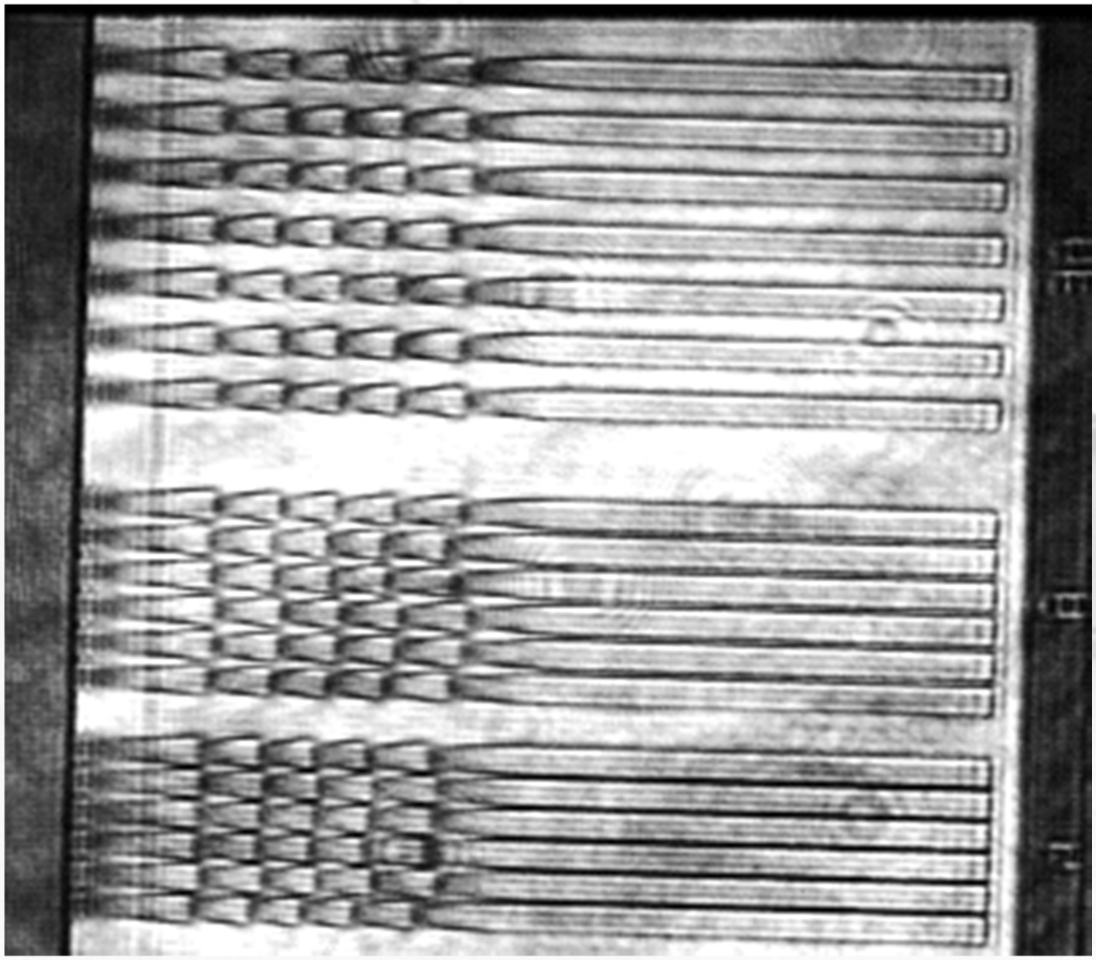
Laser Processing of MEMS Parts: Example Laser Repair of Adhered Cantilevers



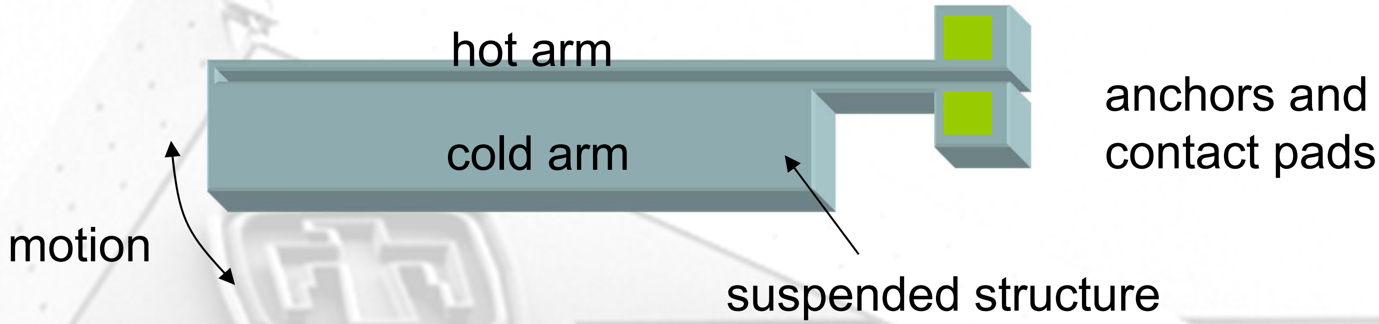
— 100 μm

500 fps
polysilicon
L = 1000 μm
w = 30 μm
t = 2.6 μm
h = 1.9 μm
Nd:YAG
532 nm
4 ns, 20 Hz
J = 25 mJ/cm^2
ΔT = 37°C

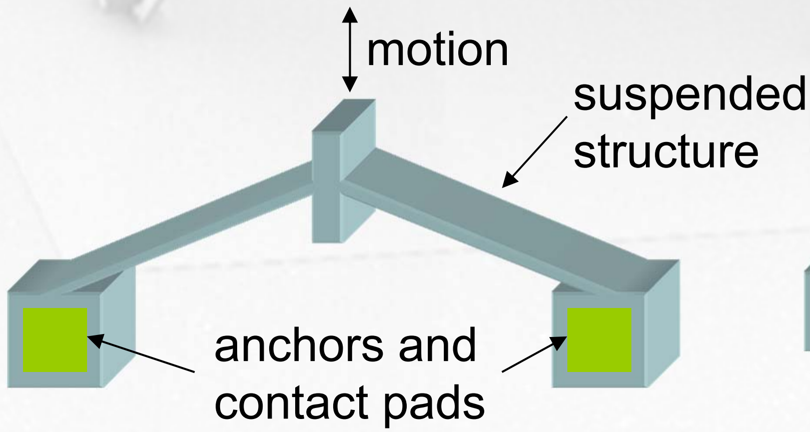
Rogers and Phinney, *Microscale Thermophysical Engineering*, **8**, pp. 43-59, 2004.

MEMS Thermal Actuators

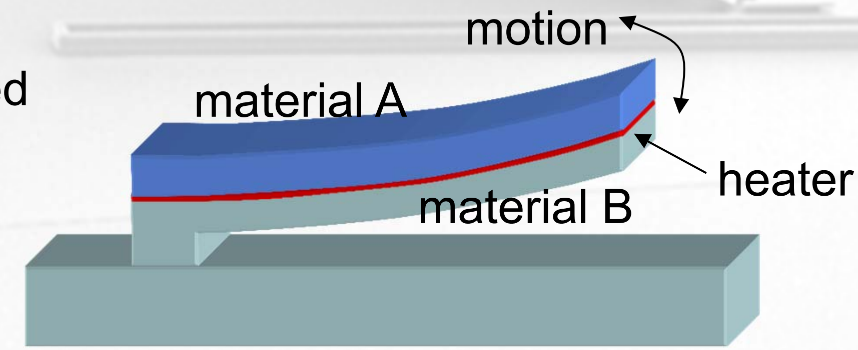
Comtois actuators, J. H. Comtois et al., *Sensors and Actuators A*, 70, pp. 23-31, 1998.



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.



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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
- Does not electrostatically attract particles
- Different actuation schemes possible, including radiation pressure, use of photostrictive materials and photothermal processes

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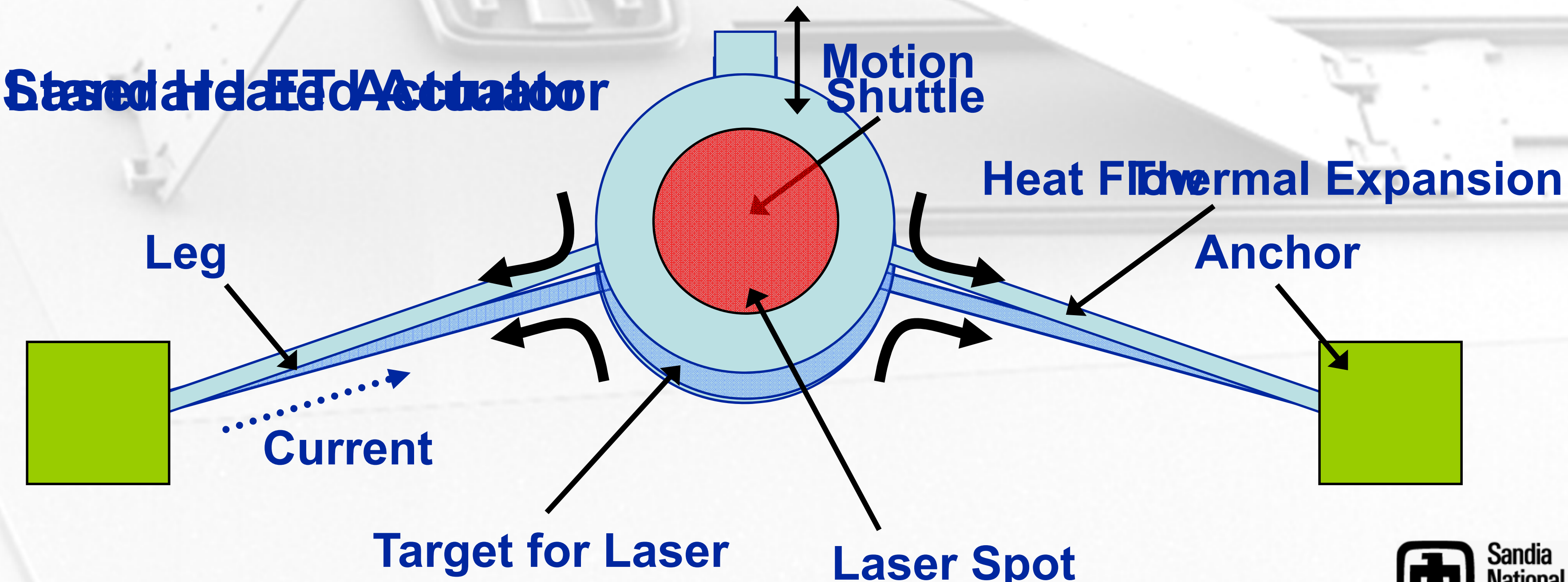
MEMS Laser Heated Bent-beam Microthermal Actuator

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



MEMS Laser Heated Flexure Microthermal Actuator

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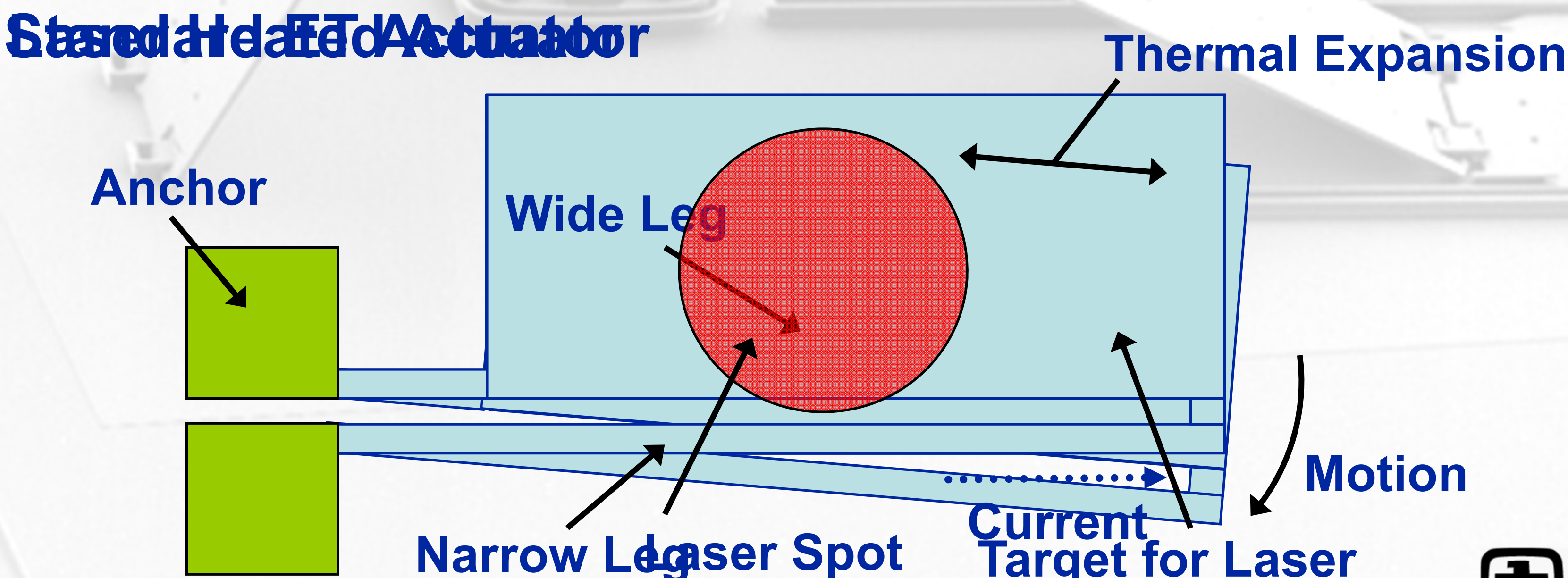
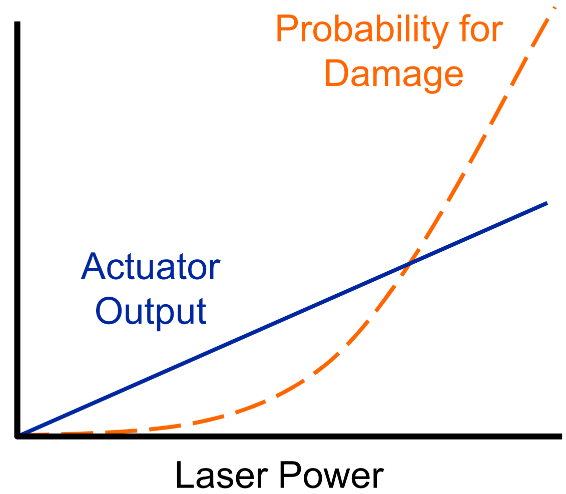
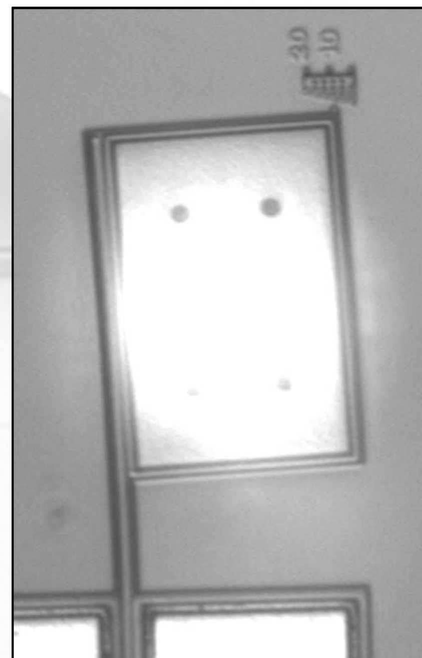


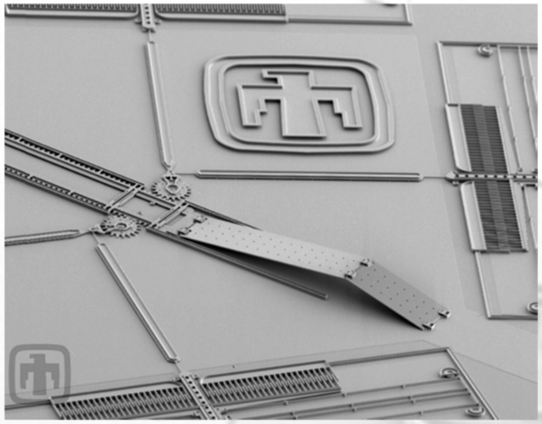
Optical Actuation

- 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.

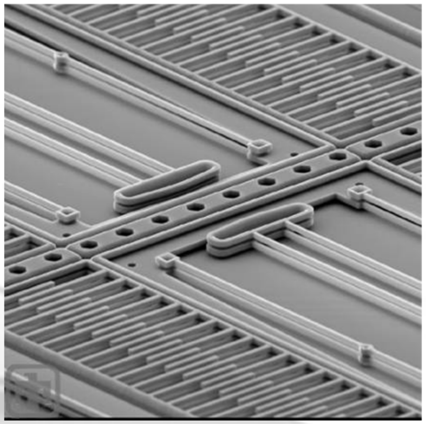




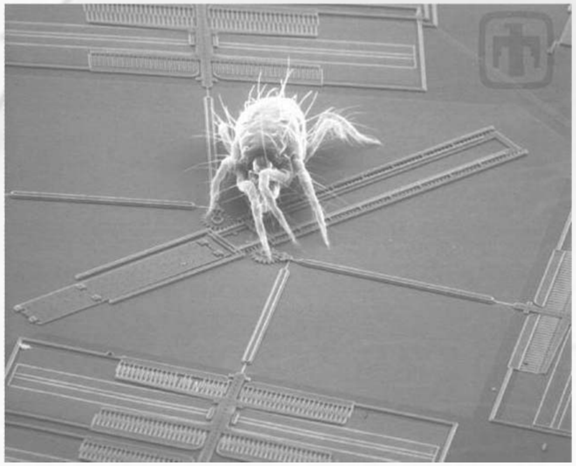
Surface Micromachined MEMS Devices



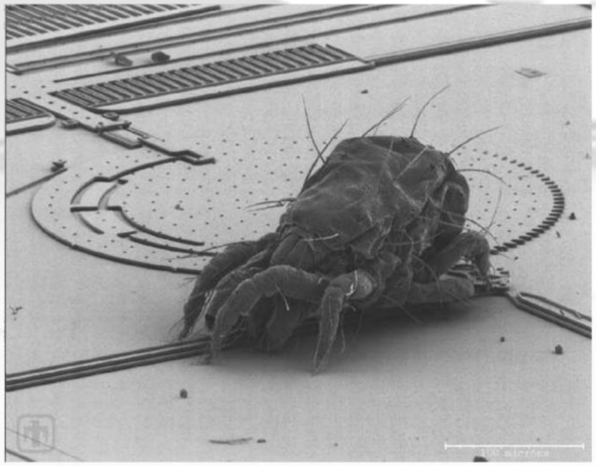
Hinged Silicon Mirror and Drive Motors



Comb
Drive
Detail



Spider Mite on a Mirror Assembly



Spider Mite on a Microlock Mechanism

http://mems.sandia.gov

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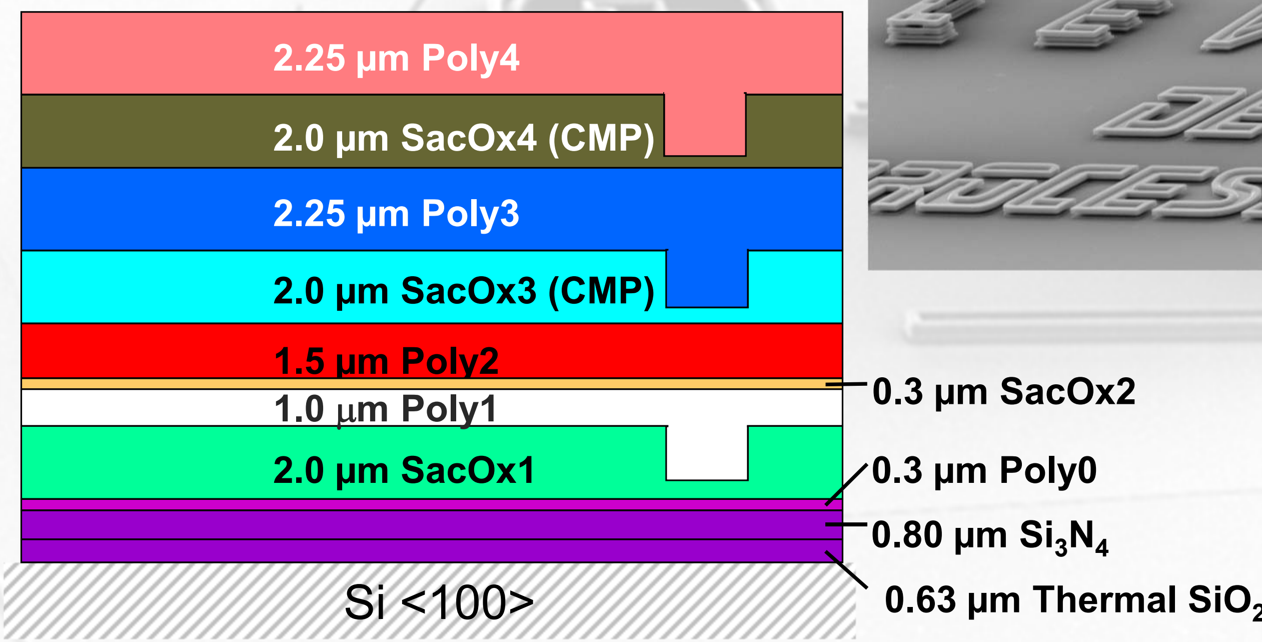
SUMMiT™ V

Sandia's Ultra-planar Multi-level MEMS Technology

SUMMiT™ Layers



All Polycrystalline Si (Poly) is doped with Phosphorus.

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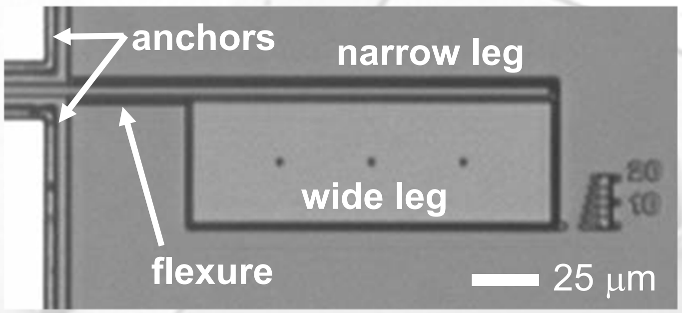
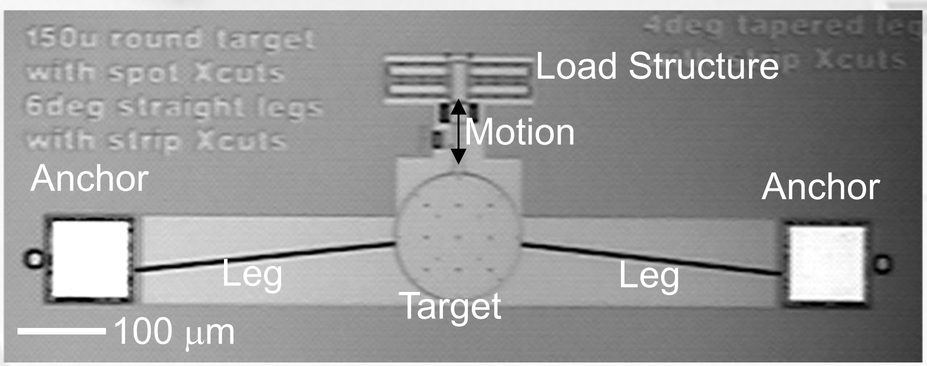
Micromachined Actuators and Structures

Laser Heated Thermal Actuators

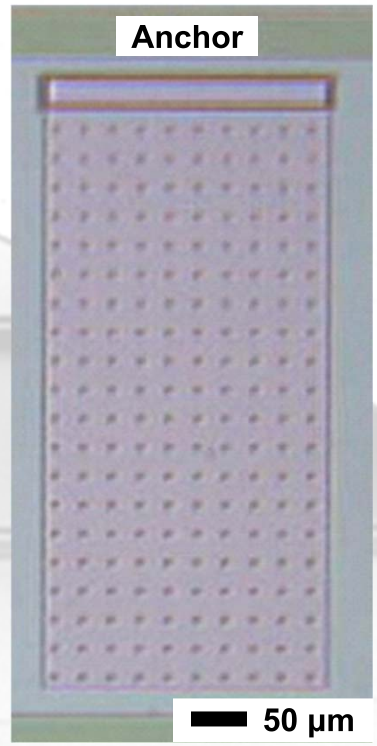


Flexure style actuator



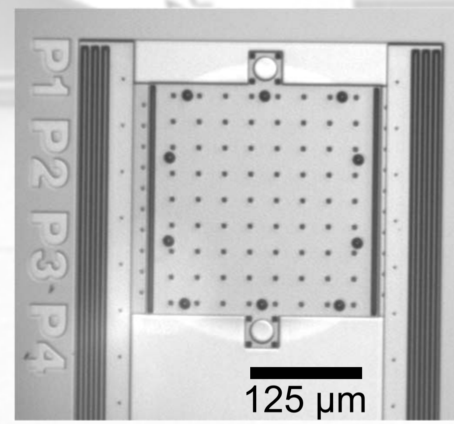
Bent-beam actuator

Test Structures



Cantilevers

Sliders



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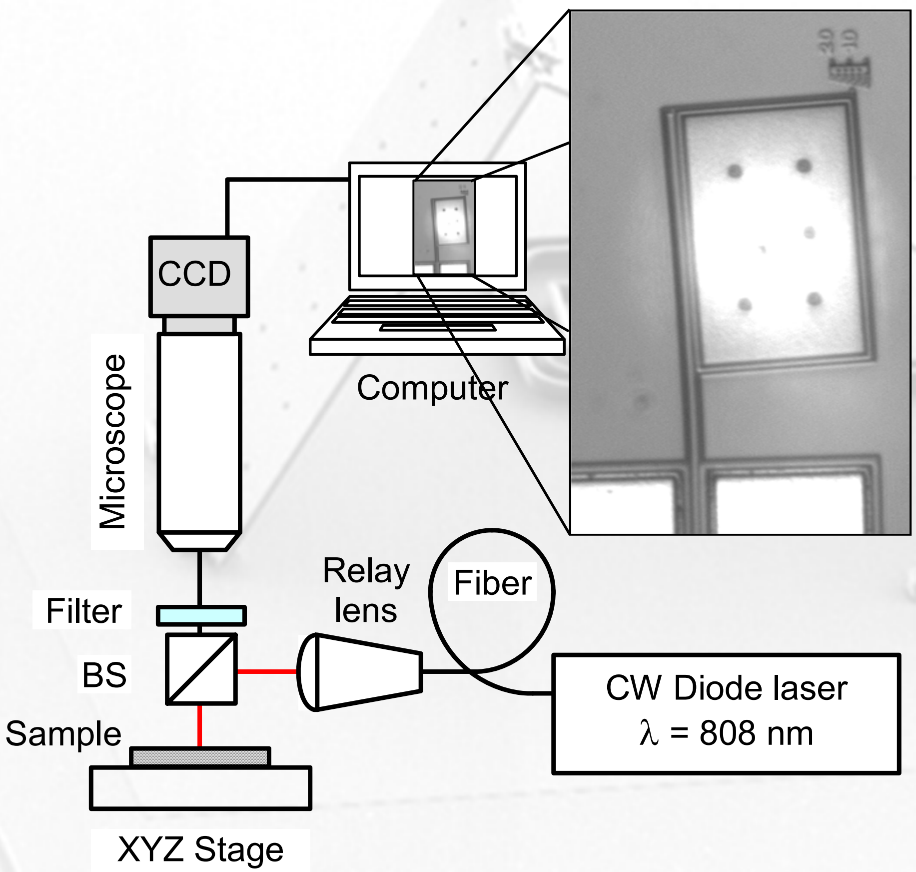
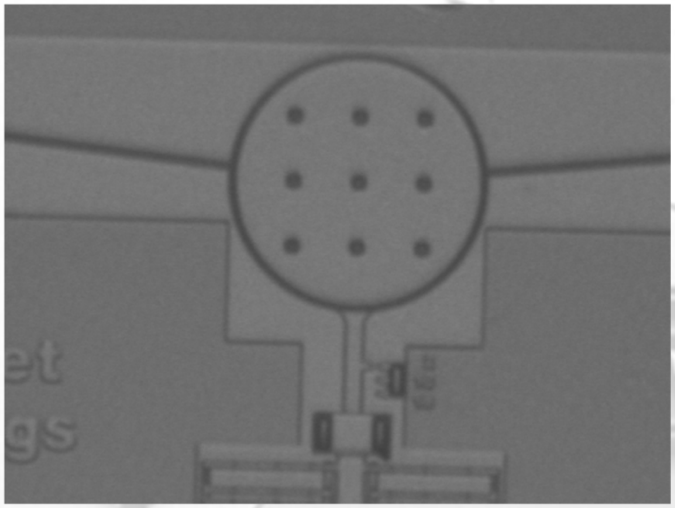
Experimental Methods



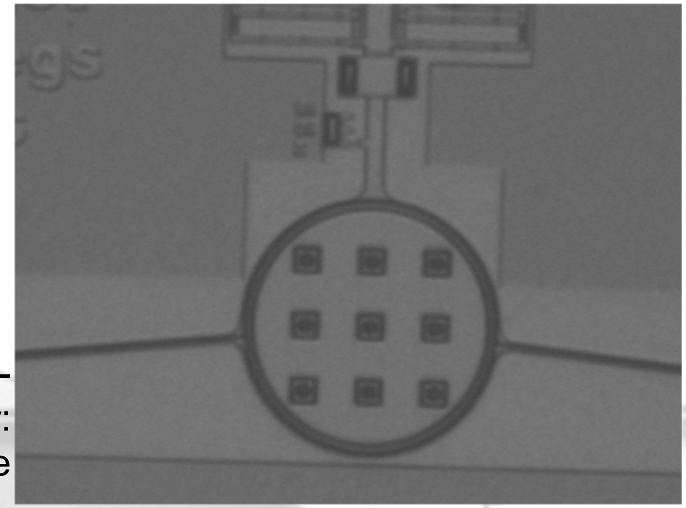
- 808 nm CW fiber coupled laser heating of MEMS
- 100 μm diameter spot on sample
- Variable laser power, up to 1 W
- Various actuator designs and MEMS structures tested
- Displacement performance and robustness evaluated through image analysis

Optically Powered Thermal Actuator Damage Characteristics

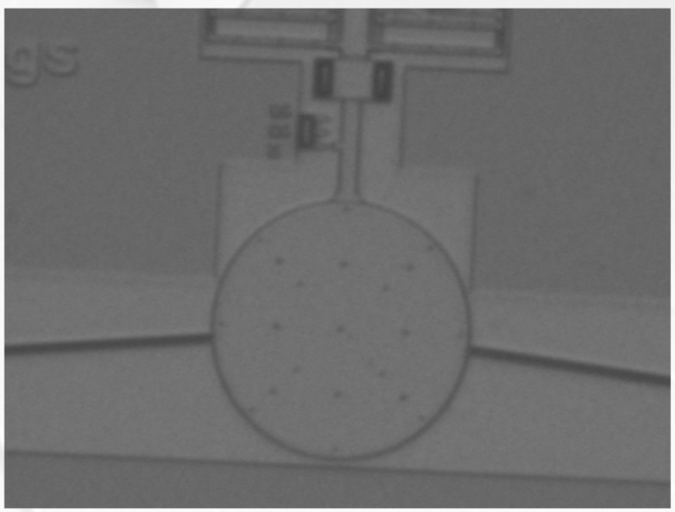


Poly3-Poly4 laminate actuator: No Damage

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

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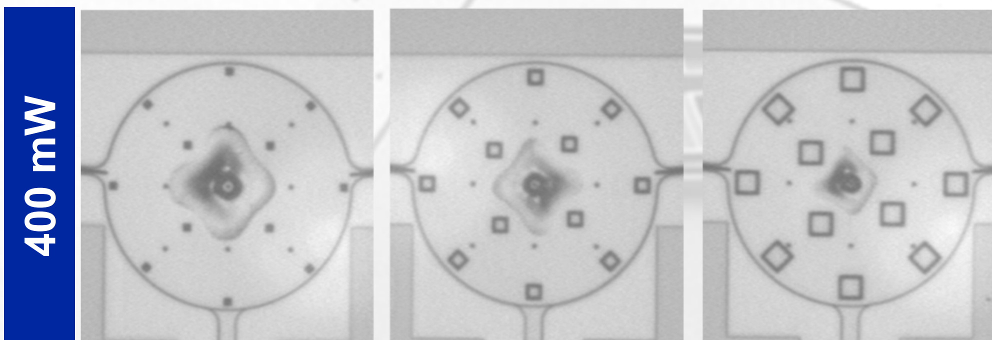
Bent-Beam Actuators

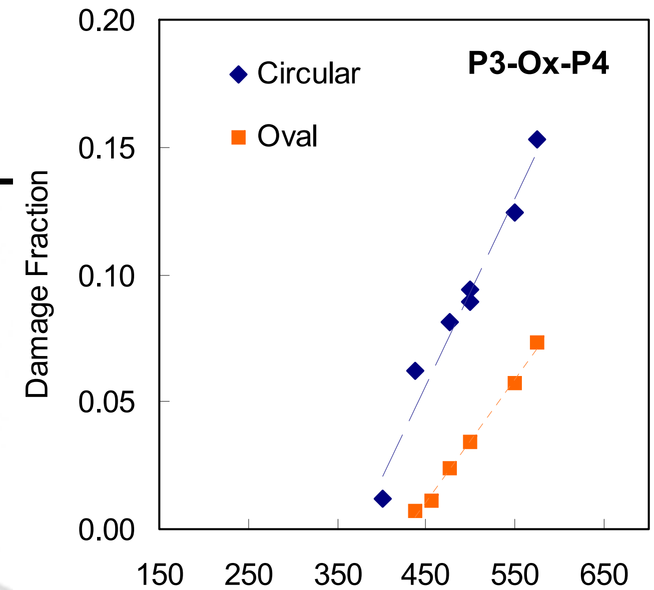
- Displacement is ~5-6 µm with minimal dependence on laser power
- Robustness to damage is key for device reliability

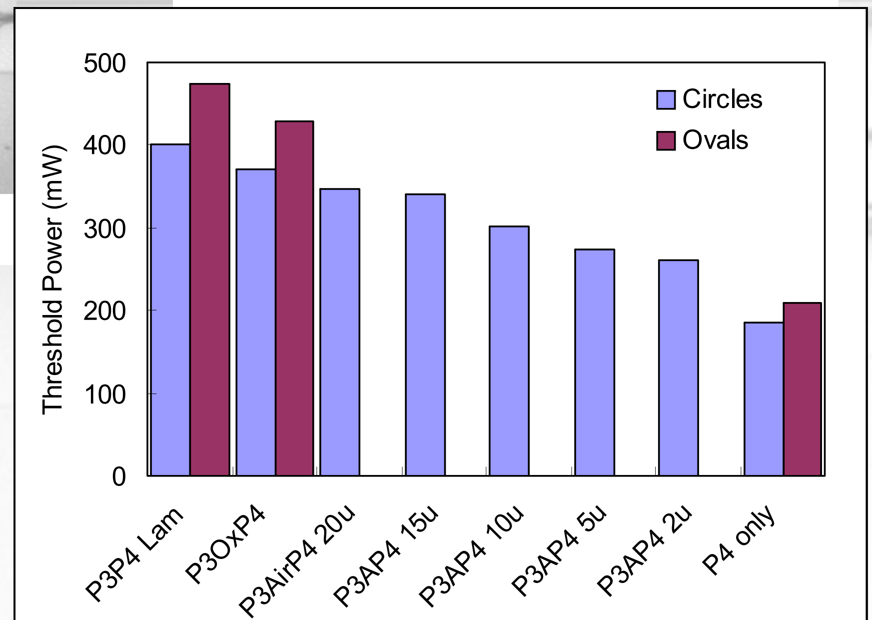


5 µm posts | 10 µm posts | 15 µm posts

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

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

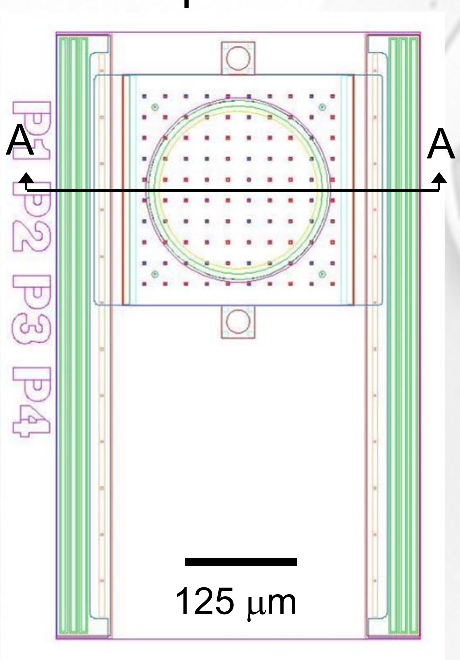




Effects of Layers and Underlying Vias

Slider Design

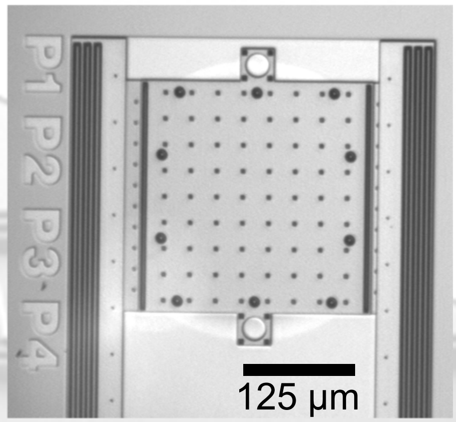
Top View



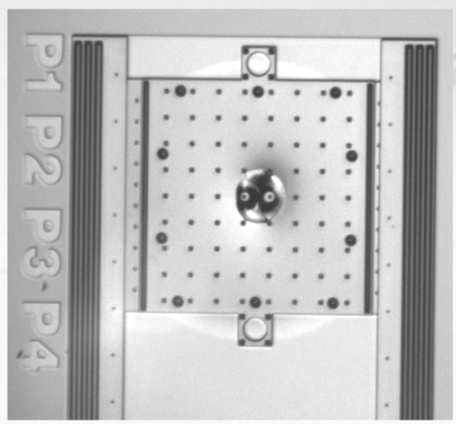
cross section A-A

substrate via (hole)

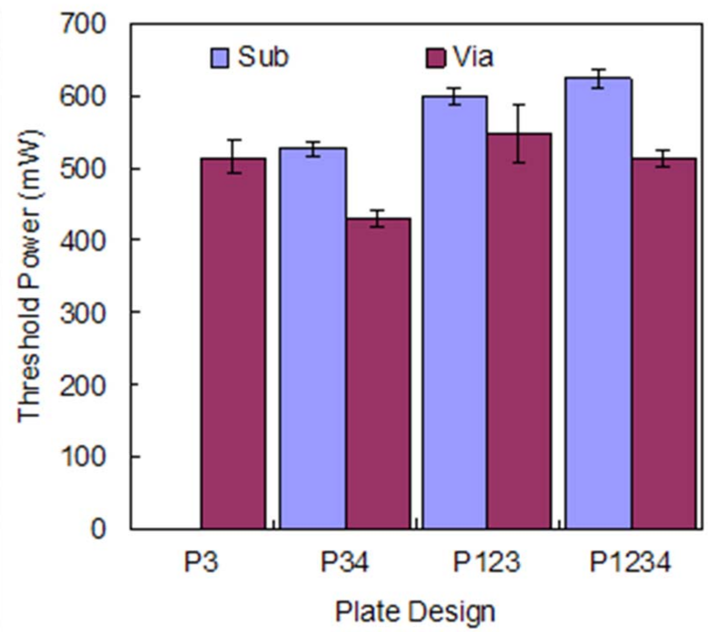
Before Laser Heating



After Laser Heating

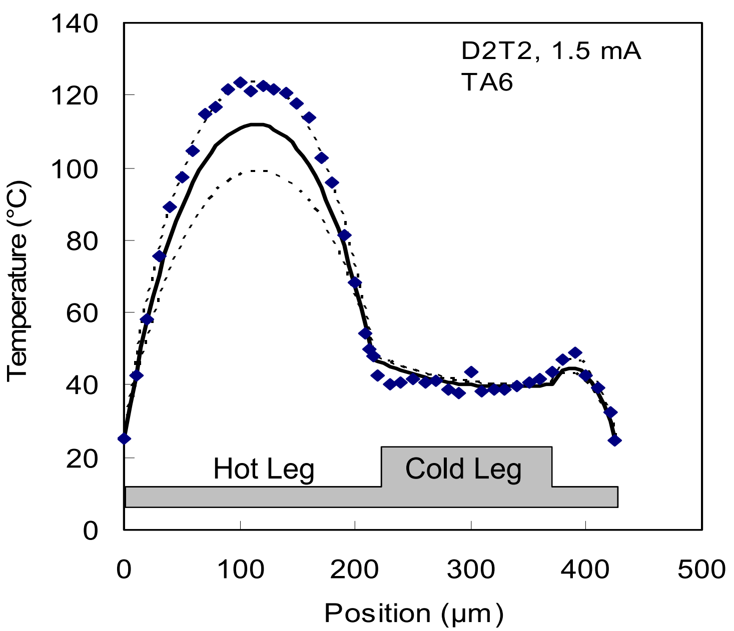


Thresholds for Damage for Polysilicon Sliders over a Substrate Via and over an Intact Substrate – 808 nm laser

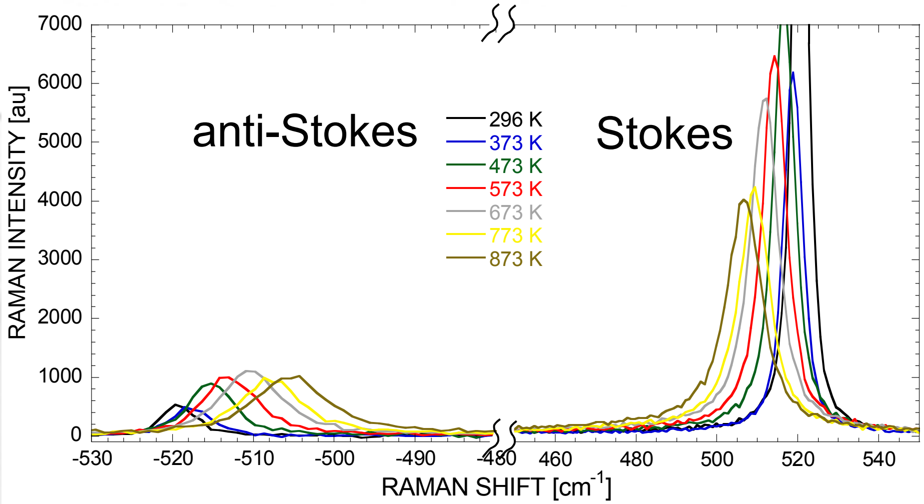


Microthermometry Using Raman Spectroscopy

Renishaw Raman Instrument



Raman Spectra from PolySi Part



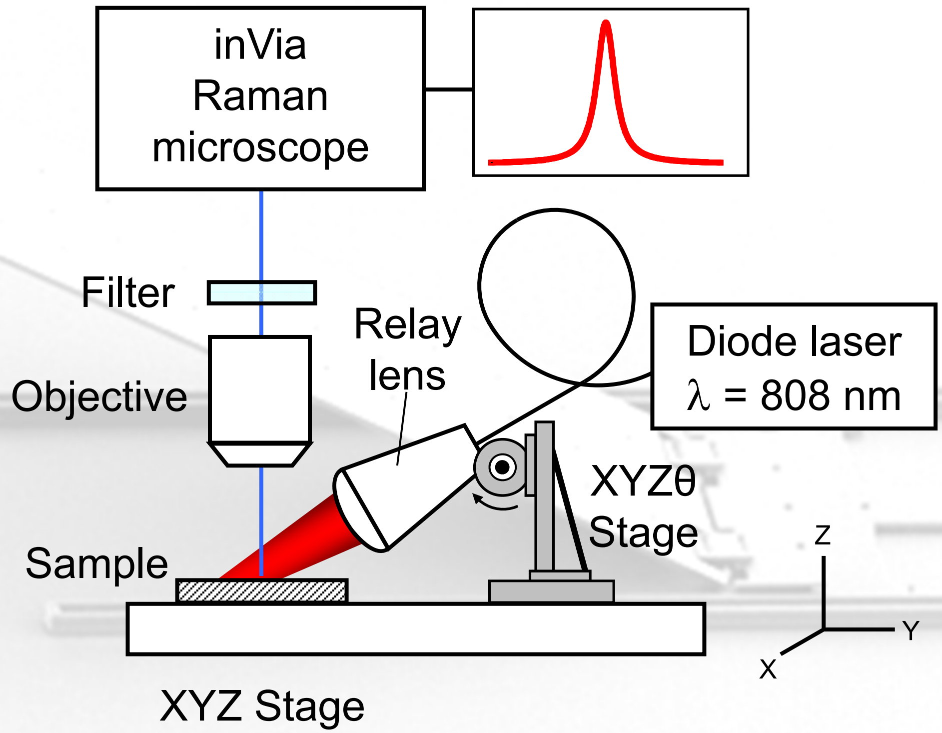
First temperature profiles for MEMS electrically heated thermal microactuators:

- Bent-beam (Kearney, Phinney, and Baker, *JMEMS*, **15**, 314-321, 2006.)
- Flexure (Serrano, Phinney, and Kearney, *JMM*, **16**, 1128-1134, 2006.)

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

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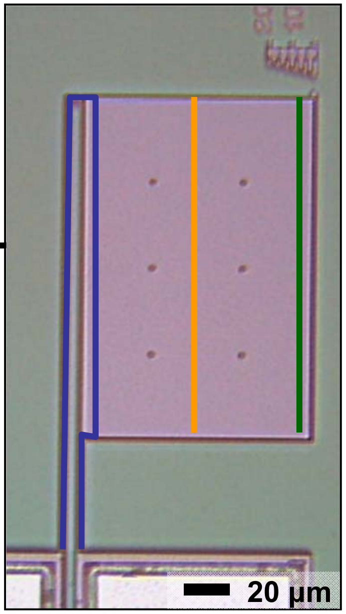
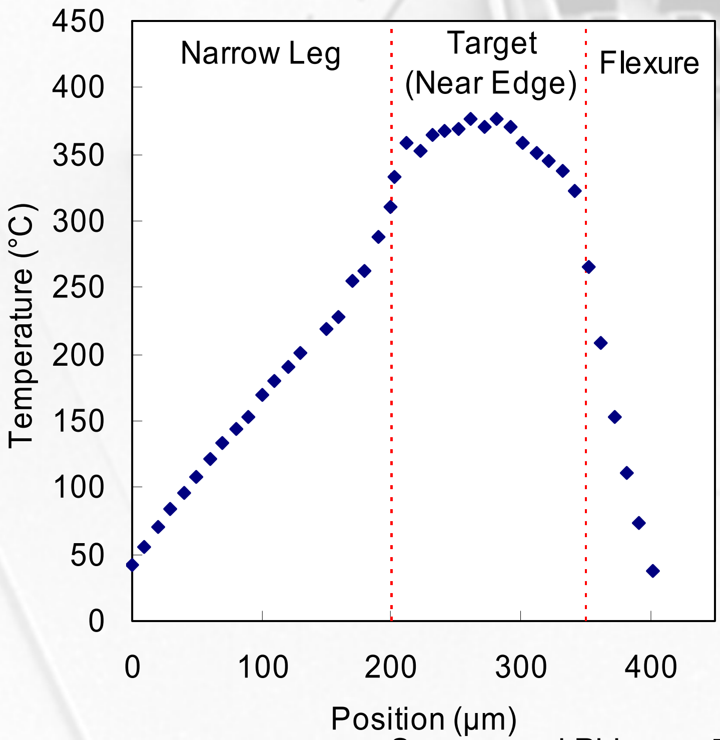
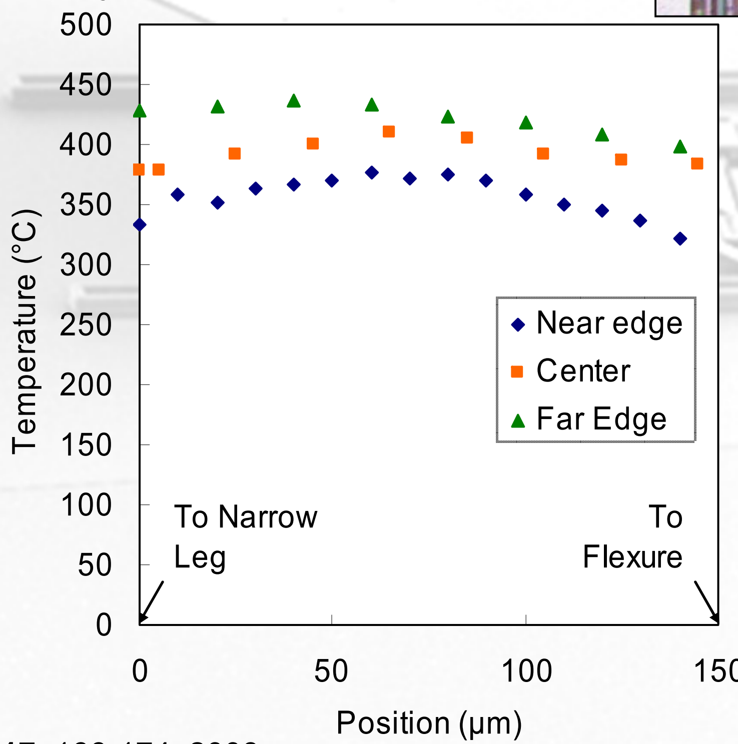
Optically-Powered Flexure Actuator

- Steady temperature increase along narrow leg
- Target temperature uniform at ~375°C up to middle, then decreases as flexure is approached for 314 mW laser
- Upper-right corner is hottest point on actuator due to device motion and longest conduction pathway







Serrano and Phinney, *JMEMS,* **17,** 166-174, 2008.

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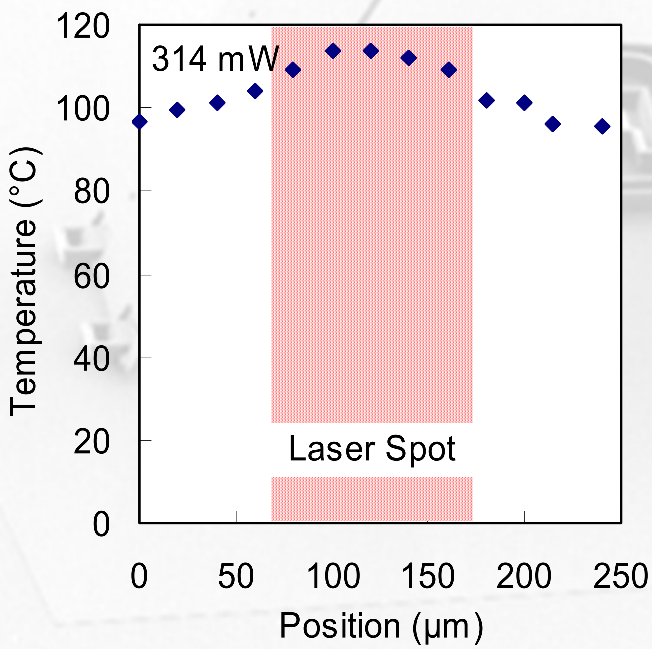
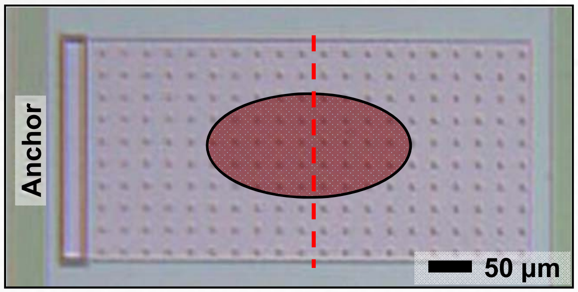
Cantilever Plate

- 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



Serrano and Phinney, *Proc. InterPACK2007*, IPACK2007-33571, 2007.
Serrano, Phinney, and Rogers, *IJHMT*, **52**, 2255-2264, 2009.

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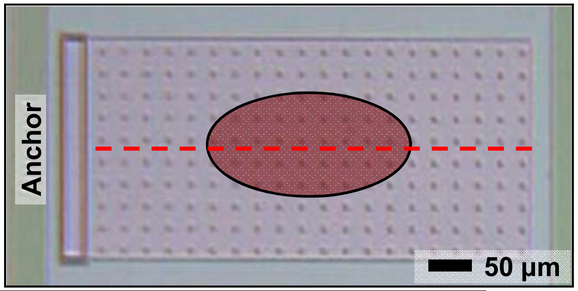
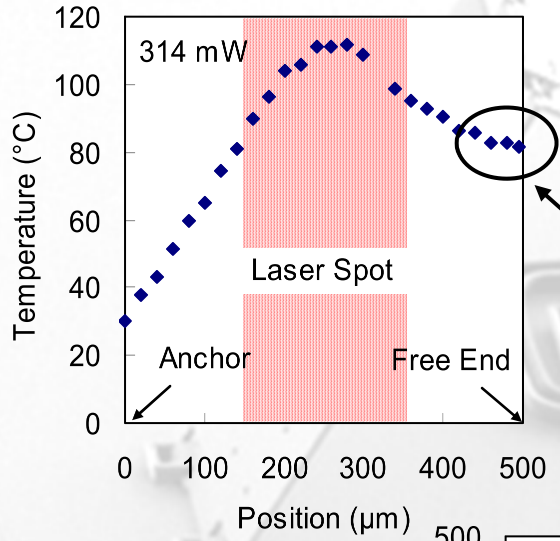
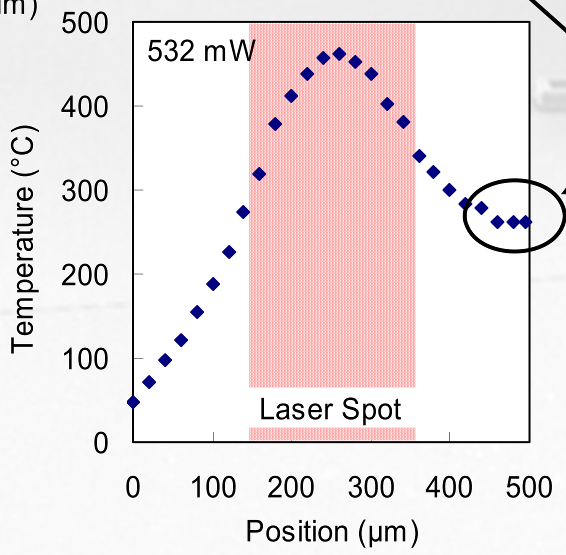
Cantilever Plate



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

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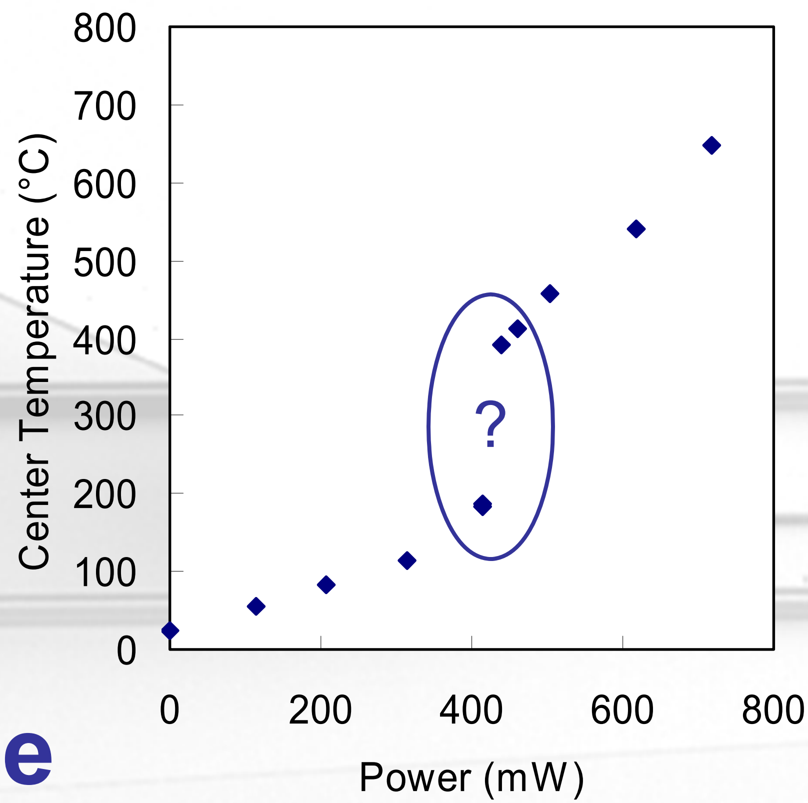
Temperature Variation with Laser Power

- 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?

Serrano and Phinney, *Proc. InterPACK2007*, IPACK2007-33571, 2007.
Serrano and Phinney, *JMEMS,* **17,** 166-174, 2008.

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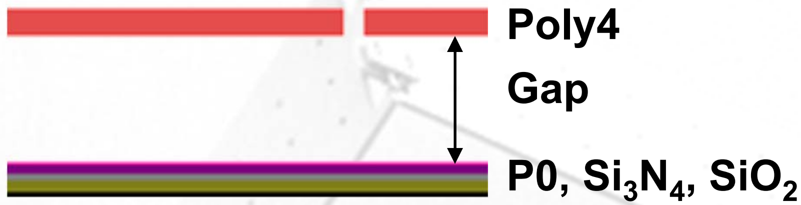
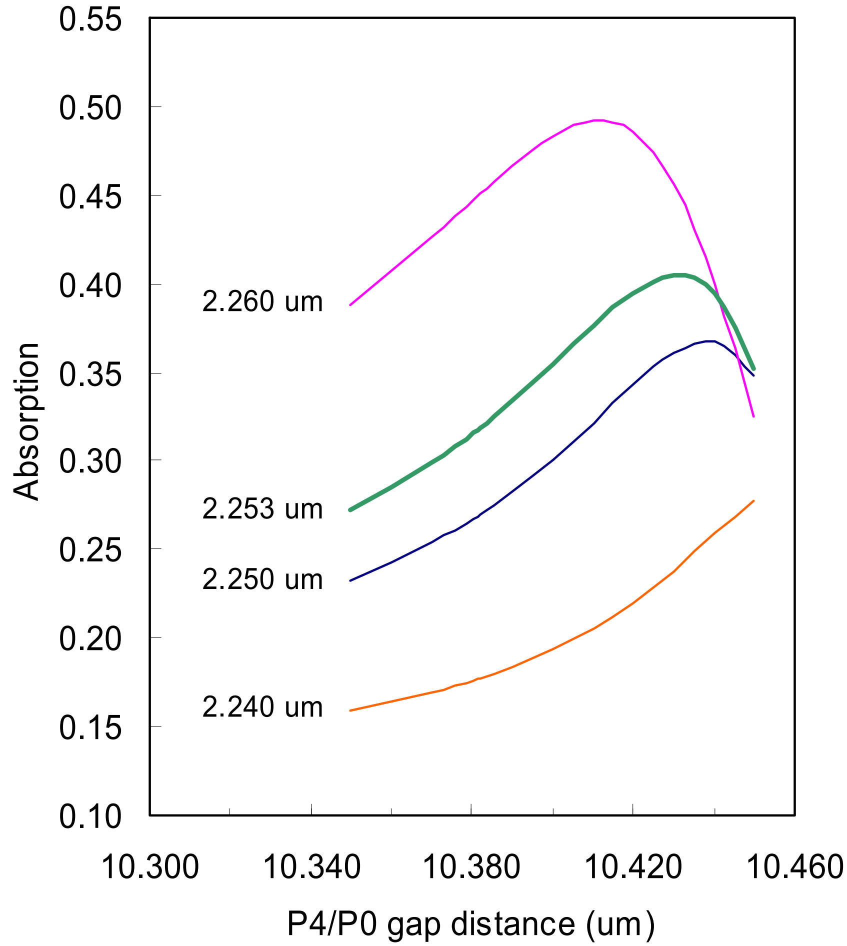
Optical Energy Absorption in MEMS: Poly4 Layer



- Thin film interference affects absorption in multi-layered PolySi MEMS that consist of semi-transparent layers with thicknesses less than penetration depth (808 nm, p.d. ~7 μm, thickness ~2 μm)
- Optical absorption, absorptance, calculated from Fresnel relations.
- Optical absorption strongly depends on film and gap thicknesses with standard processing thickness and gap variations leading to >100% change in optical energy absorption.
- Energy absorption can be affected by component deflection during operation.



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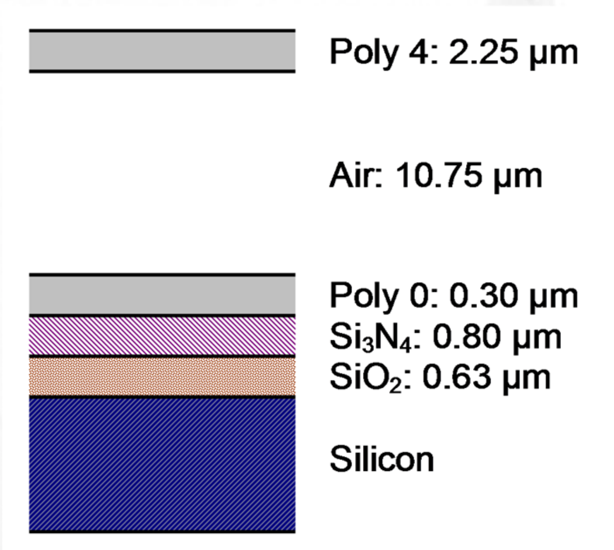
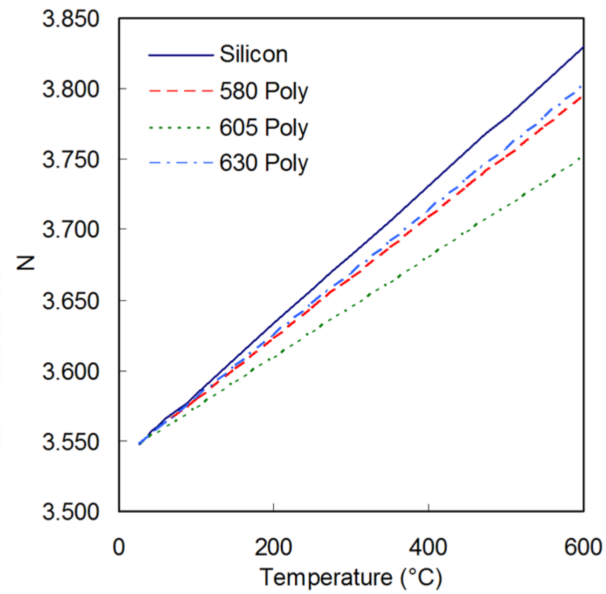
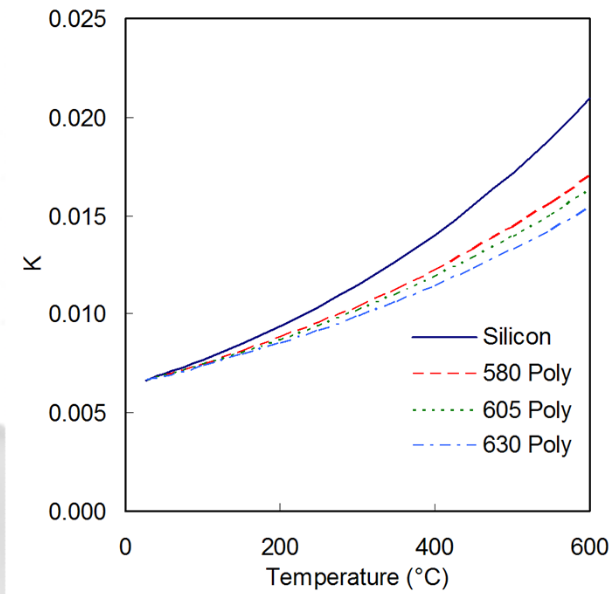
Optical Property Modeling for Cantilever Plate







- Real and imaginery refractive indices of Si and PolySi are a function of temperature
- Multiple layers considered in a modular technique adapted from the LTR method of Mazilu, Miller, and Donchev (*Applied Optics*, **40** (36), 6670-6676, 2001). This technique allows extraction of the optical properties for individual layers.

Serrano, Phinney, and Rogers, *IJHMT*, **52**, 2255-2264, 2009.

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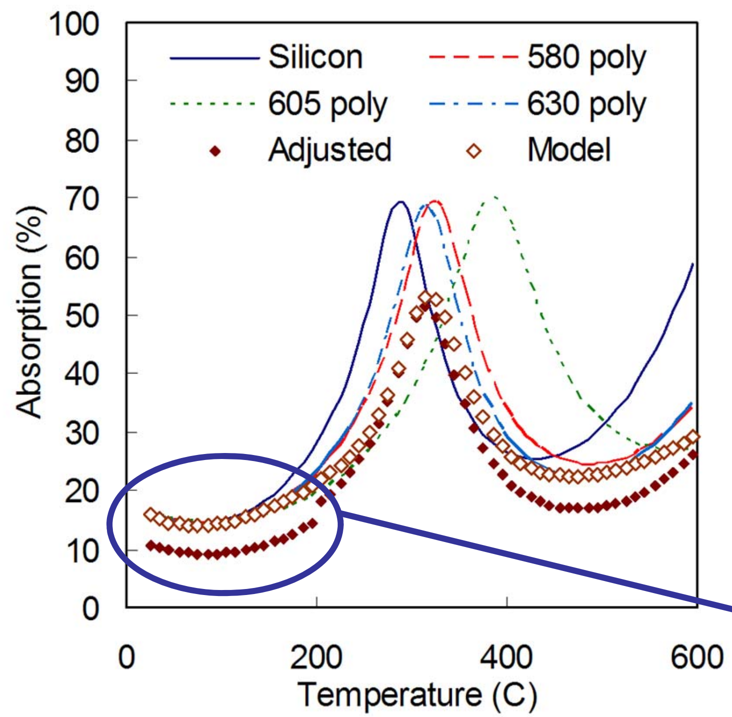
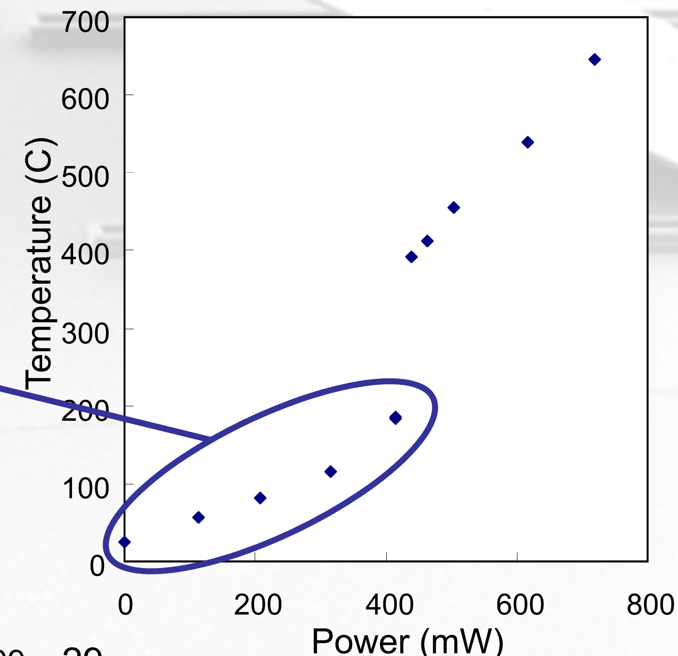
Optical-Thermal Phenomena

Small Thickness	+	T-dependant refractive index	=	T-dependant absorption



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

Flat absorption at lower T leads to initial linear temperature increase



Serrano, Phinney, and Rogers, *IJHMT*, **52**, 2255-2264, 2009.

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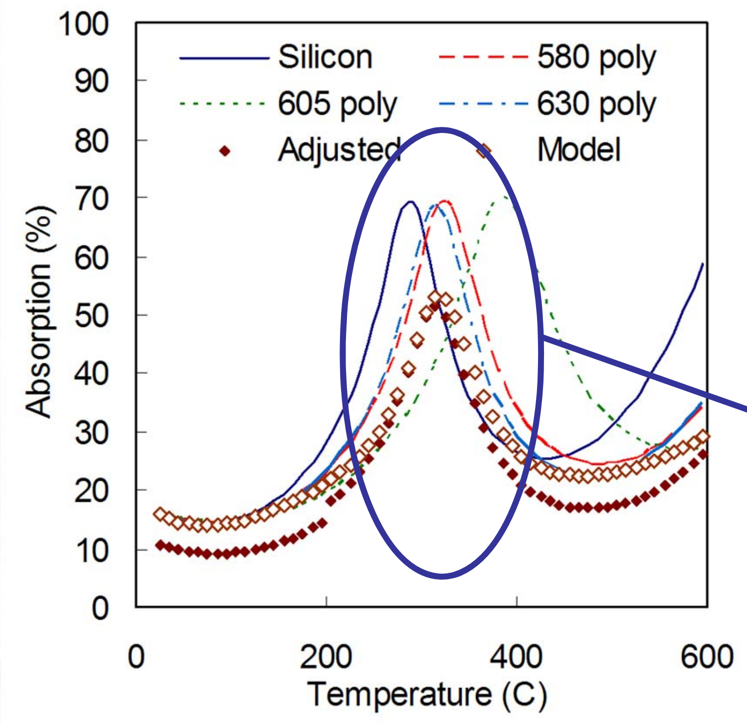
Optical-Thermal Phenomena

Small Thickness + **T-dependant refractive index** = **T-dependant absorption**

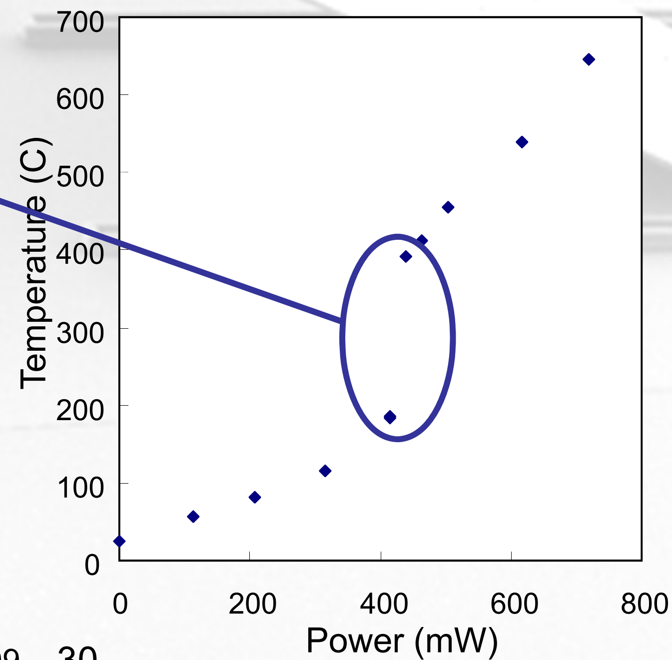


Cantilever plate: 60° incidence; 808 nm; literature temperature dependence for optical constants

Flat absorption at lower T leads to initial linear temperature increase

Absorption peak leads to "positive feedback" effect:

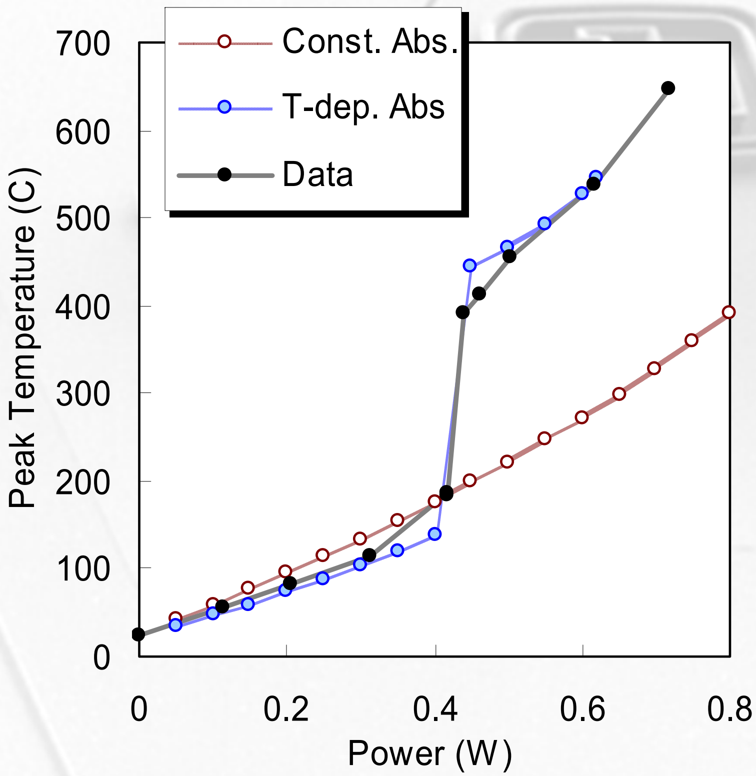
forbidden T's



Serrano, Phinney, and Rogers, *IJHMT*, **52**, 2255-2264, 2009.

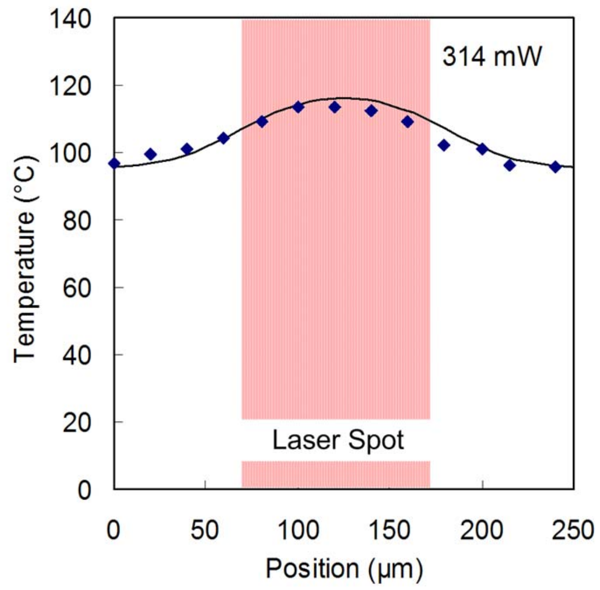
Simulating Optical-Thermal Phenomena

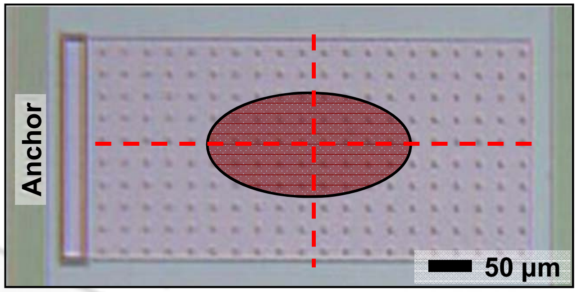
- Coupled optical-thermal phenomena must be considered for accurate device modeling
- Requires knowledge of *n*(T) and *k*(T)

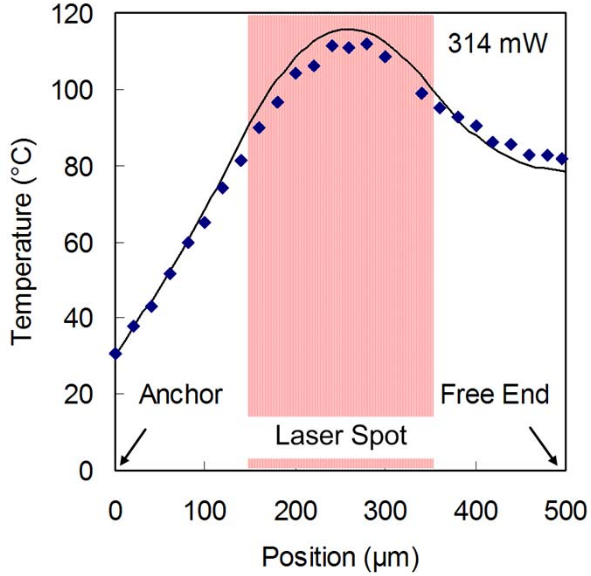


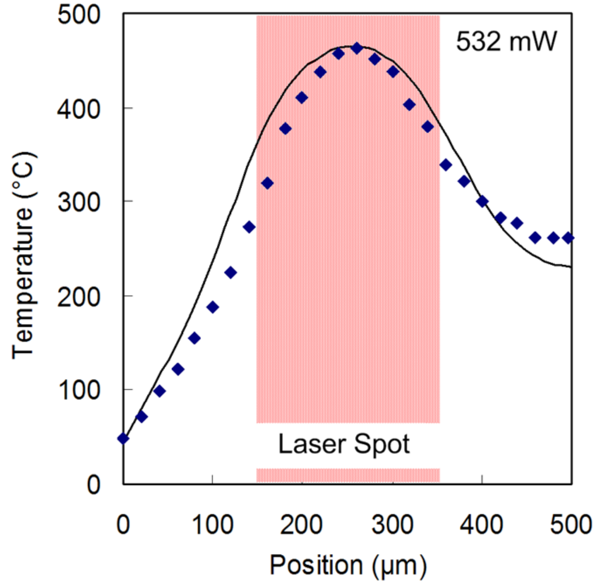
- With fixed absorption, model fails to reproduce temperature jump and under-predicts peak temperature at higher powers
- Including optical effects into thermal model improves model results and also predicts temperature jump

Comparison of Experiments and Simulations for Laser-Heated Cantilever









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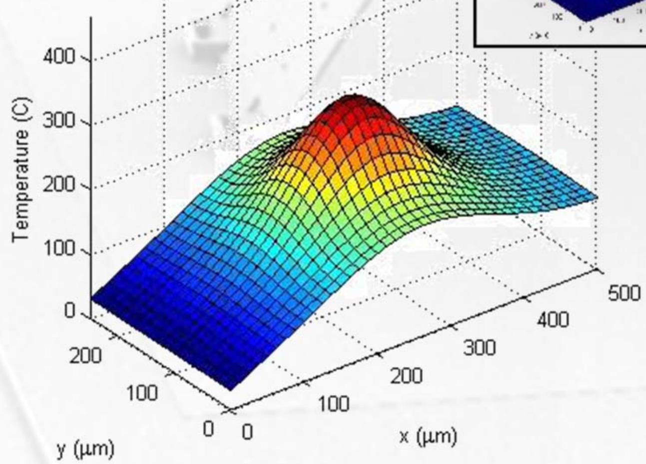
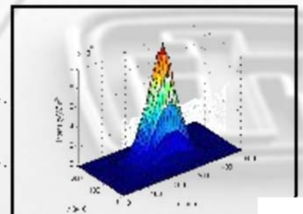
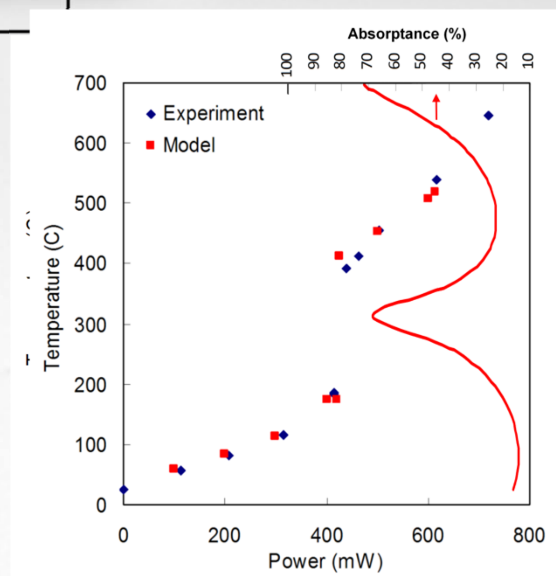
Simulating Optical-Thermal Phenomena

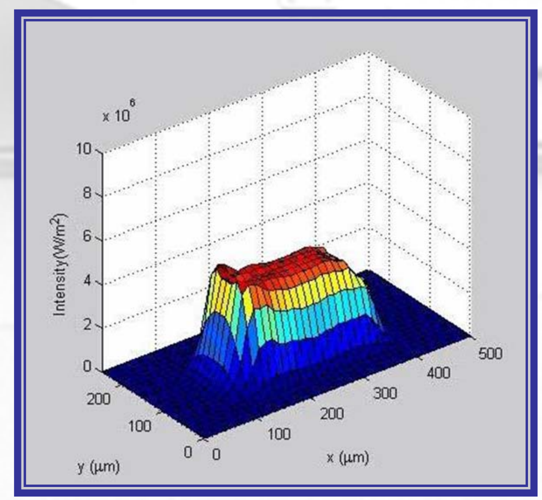
- Coupled optical-thermal phenomena must be considered for accurate device modeling
- With temperature-dependant absorption in model, temperature jump is also predicted





- Non-uniform absorption across surface drives system towards equilibrium much faster than without





Serrano, Phinney, and Rogers, *IJHMT*, **52**, 2255-2264, 2009.

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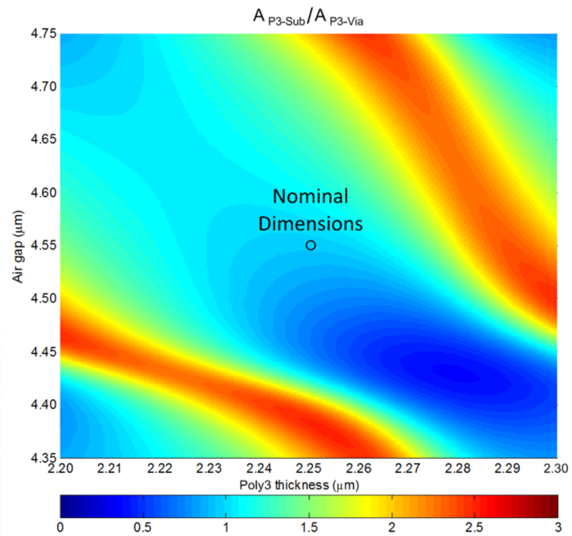
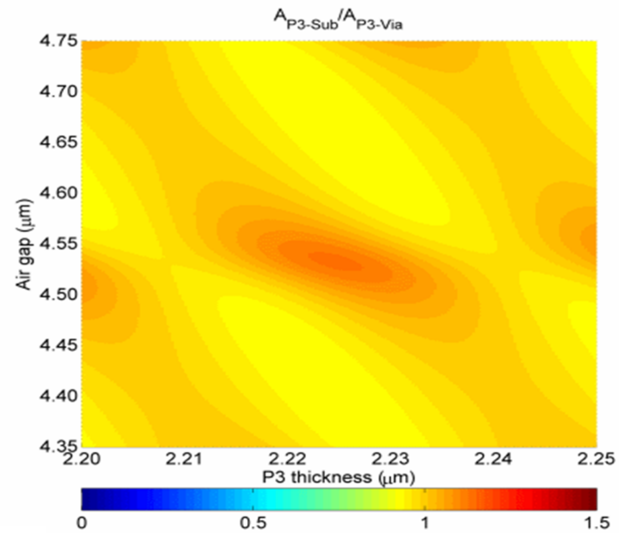
Effects of Laser Wavelength

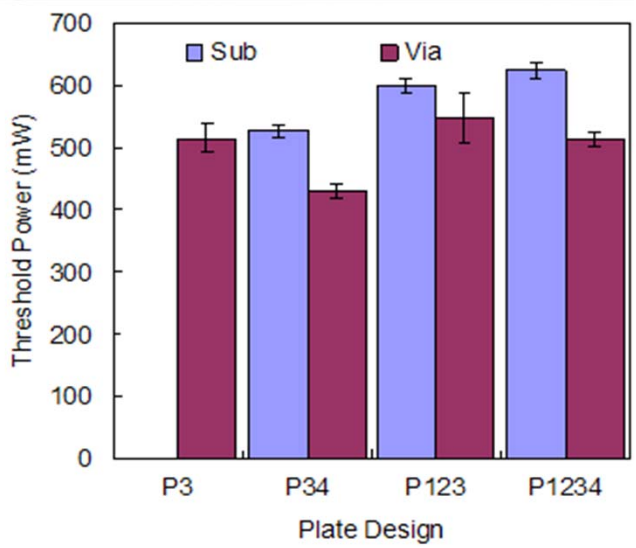
Maps of the ratio of the absorptance of a single layer PolySi slider irradiated over a substrate to the absorptance of one irradiated over a via for different gap heights and PolySi thicknesses. The experimentally determined thresholds for laser power for the two wavelengths are also shown.

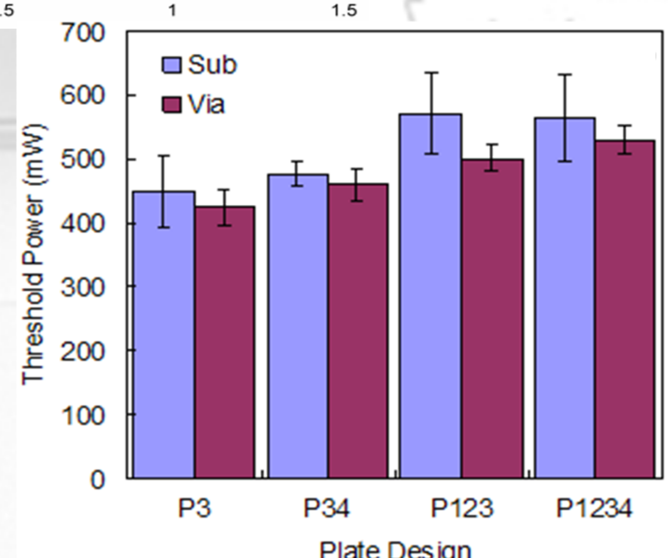




532 nm

808 nm

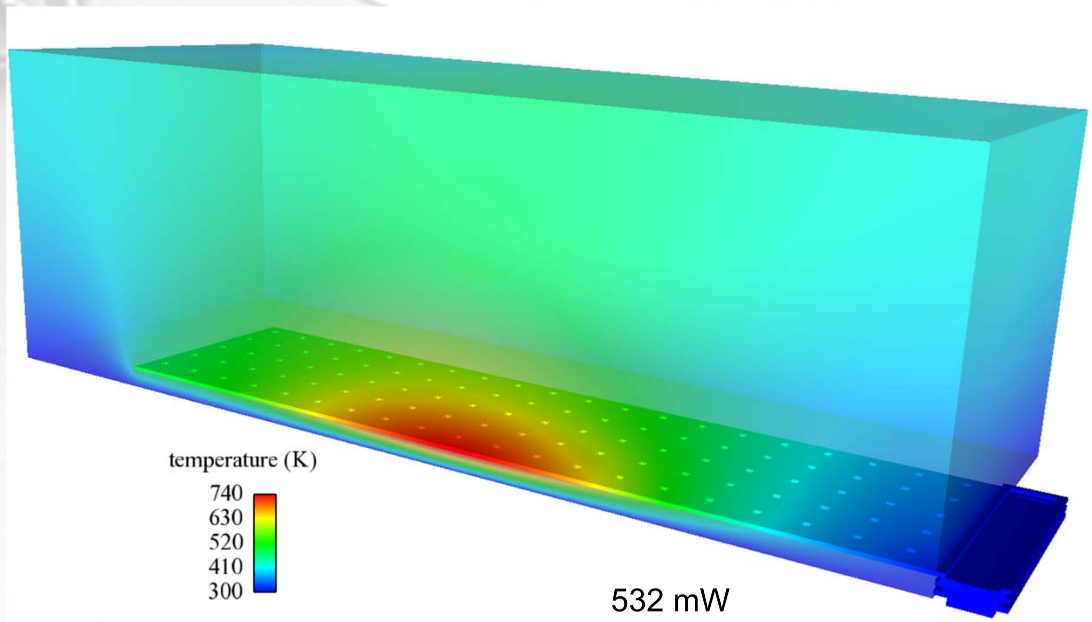




Serrano and Phinney, and Rogers, *J. of Micro/Nanolithography, MEMS, and NEMS*, **8**, Paper No. 043030, 1-7, 2009.

Benefits of Large-Scale Models

- **Increasing complexity of model reduces number of adjustable parameters**
  - **model air → eliminate convection coefficient**
  - **model bondpad → eliminate fixed end temperature**
- **Effect of other parameters can be investigated**
  - **gap**
  - **thermal conductivity**
  - **release holes**



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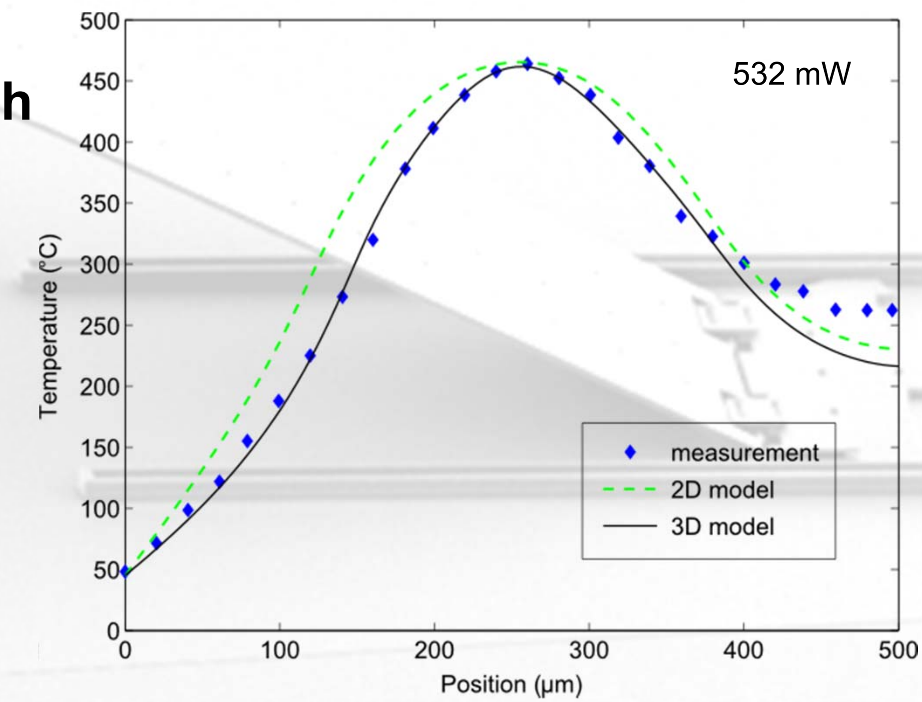
2D – 3D Comparison

- **3D simulation performed with remaining parameters fixed**
- **Generally improved agreement**
  - **except at free end**



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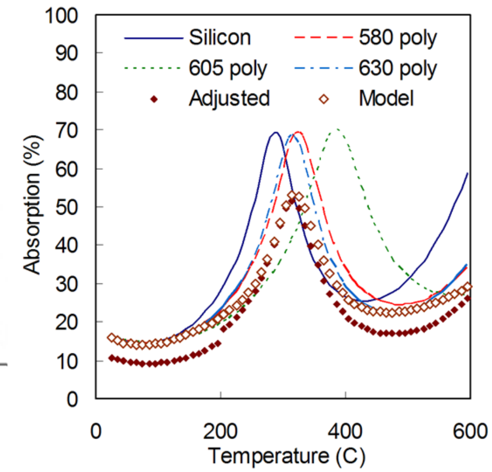
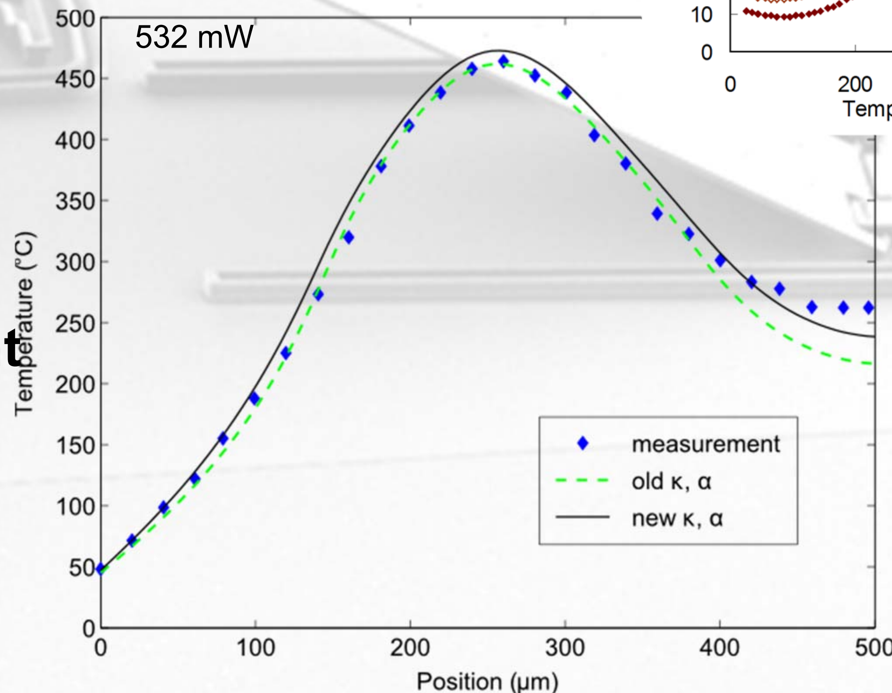
Effect of Changing Models

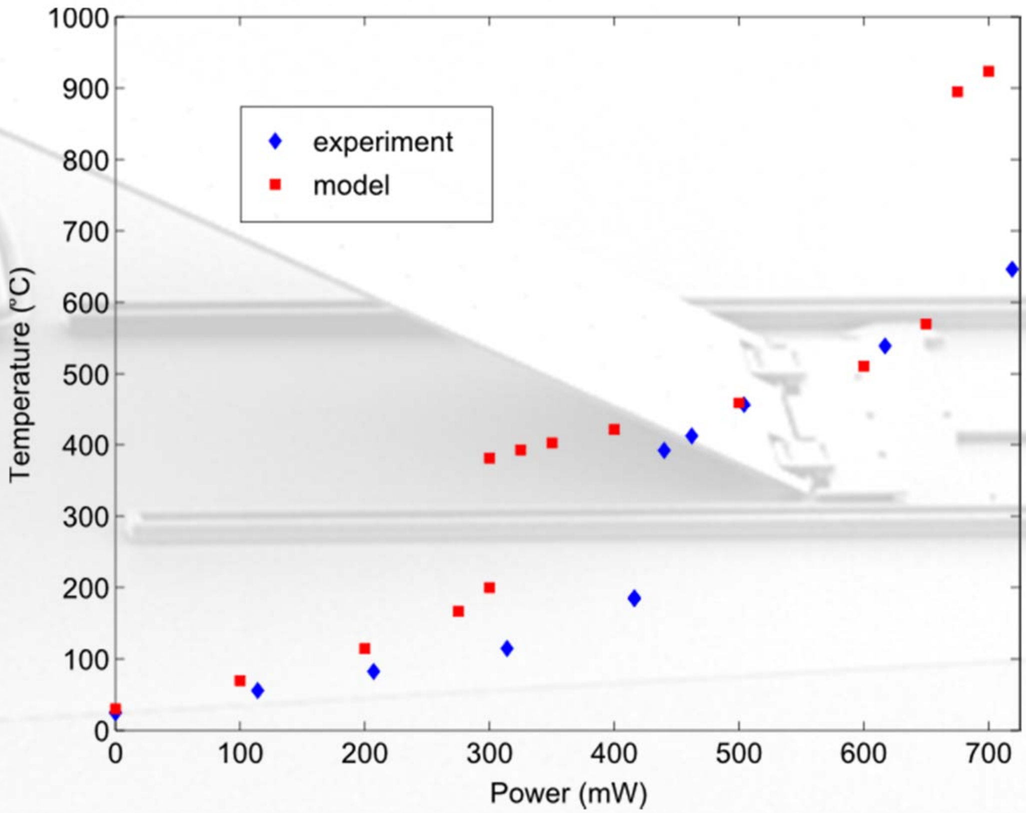
- Absorptance
  - "Model" case more comparable to measurements than "Adjusted" case
- Thermal conductivity model
  - avoids extrapolation above 300 ºC
  - fits previous work on SUMMiT structure
- No adjustable parameters
- Still reasonable agreement
  - overpredict max T





Strong Effect on Temperature Jump

- First temperature jump occurs ~100mW early
- Predicted slope too high before jump and too low after it
- Need measured absorption data
- Need better geometric information
- Must evaluate possibility of structural deformation



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Summary and Conclusions

- A complete understanding of optical and thermal phenomena in microsystems is necessary to improve the design, operation, and reliability of MEMS devices exposed to laser heating.
- Complementary experiments and simulations advance the understanding of the physical phenomena.
- Laser damage was characterized for thermal microactuator designs and test structures. Target composition, layers, and underlying substrate have significant impacts on damage due to laser heating since they affect the absorption and distribution of energy within the target.
- Raman thermometry was used to make high spatial resolution temperature measurements on laser heated MEMS and revealed a temperature increase of 200 C for 20 mW laser power increase.
- Simulations revealed the importance of the temperature dependence of the refractive index to the performance of laser heated MEMS when optical interference is present.

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Future Directions

- Improved property and geometry data are being collected and incorporated into the simulations. Temperature dependent properties are especially important for accurate simulations.
- Robust design and a priori predictive simulation of optically heated MEMS at laser wavelengths for which interference occurs is extremely challenging. Reducing interference effects by using coatings or alternate laser wavelengths can make the problem more tractable.
- Continued synergistic experimental and simulation research efforts will lead to improved understanding of the physical phenomena during laser heating of microsystems.