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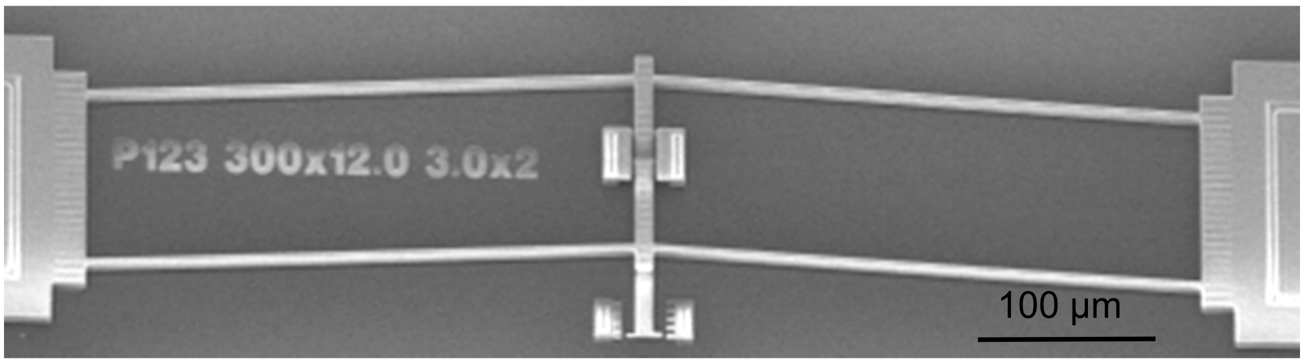

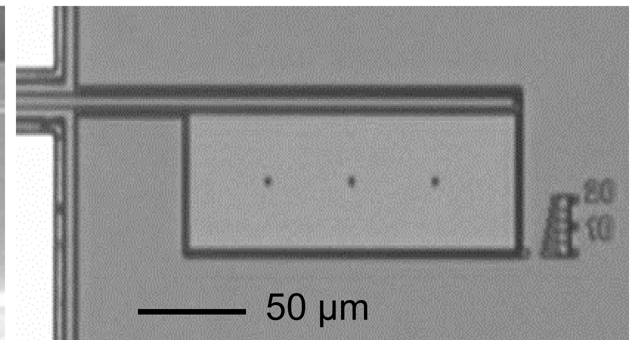

Thermal Microactuators

Leslie M. Phinney

Sandia National Laboratories, Albuquerque, New Mexico

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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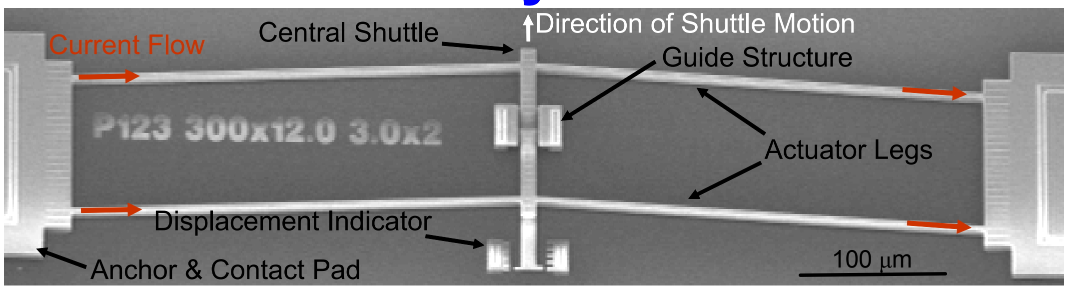
Ed Piekos, Justin Serrano, John Torczynski
MESA Fab Staff

Funding and Facilities

Sandia National Laboratories, Engineering Sciences Research Foundation and Laboratory Directed Research and Development

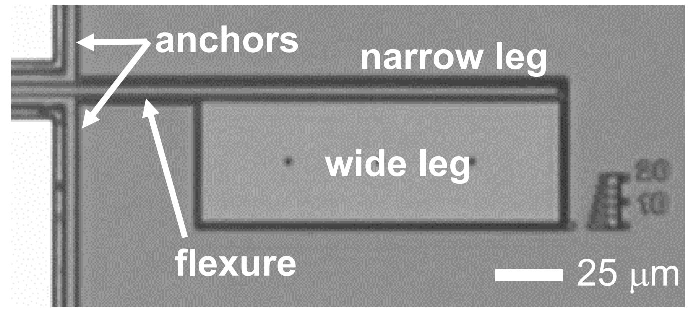
Micromachined Thermal Actuators and Test Structures

Electrically Powered

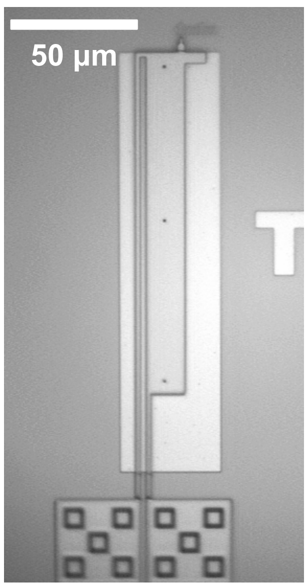


Bent-beam actuator

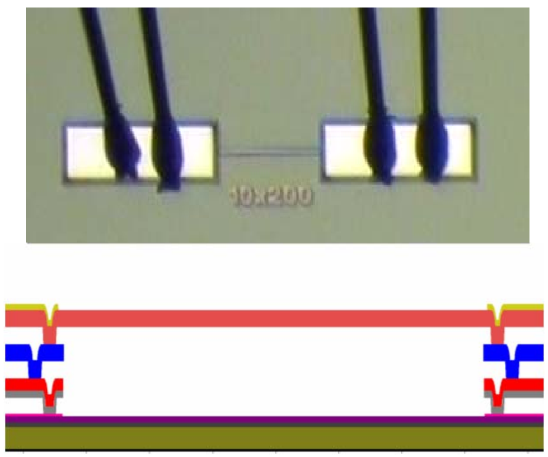
Laser Powered



Flexure actuator

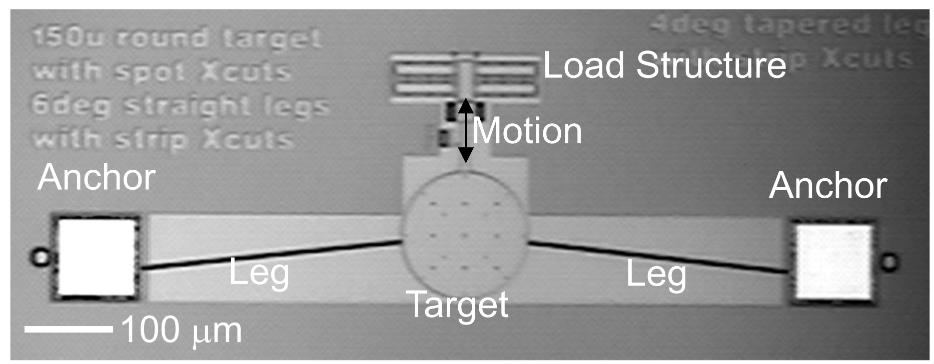


Flexure actuator



Test Structure

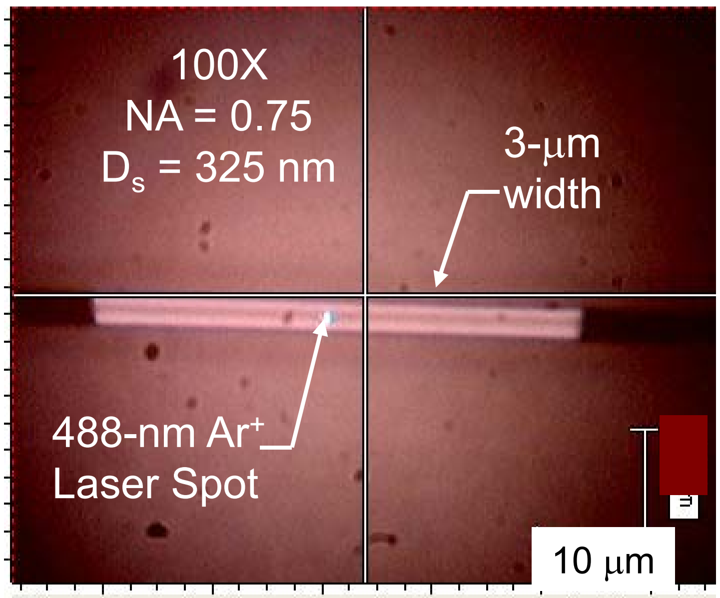
Fixed-fixed beam



Bent-beam actuator

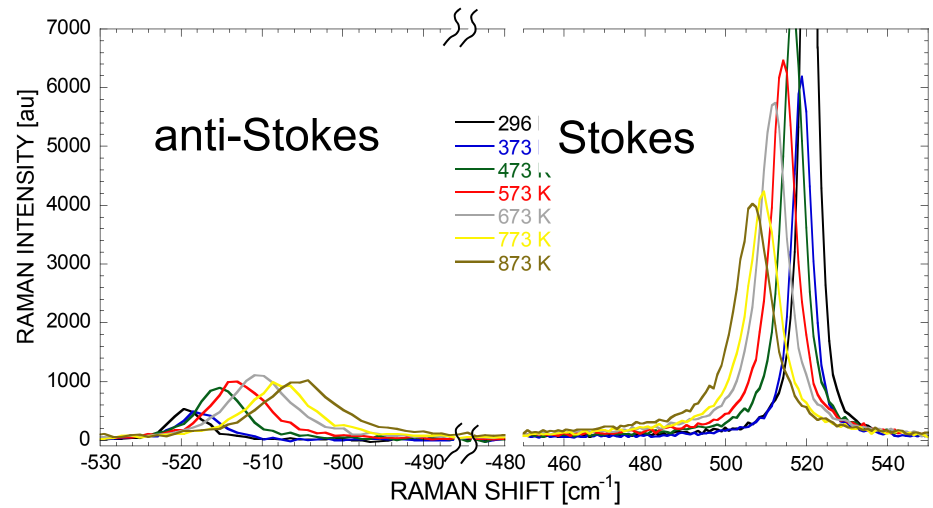
Raman Microthermometry

Renishaw Raman Instrument



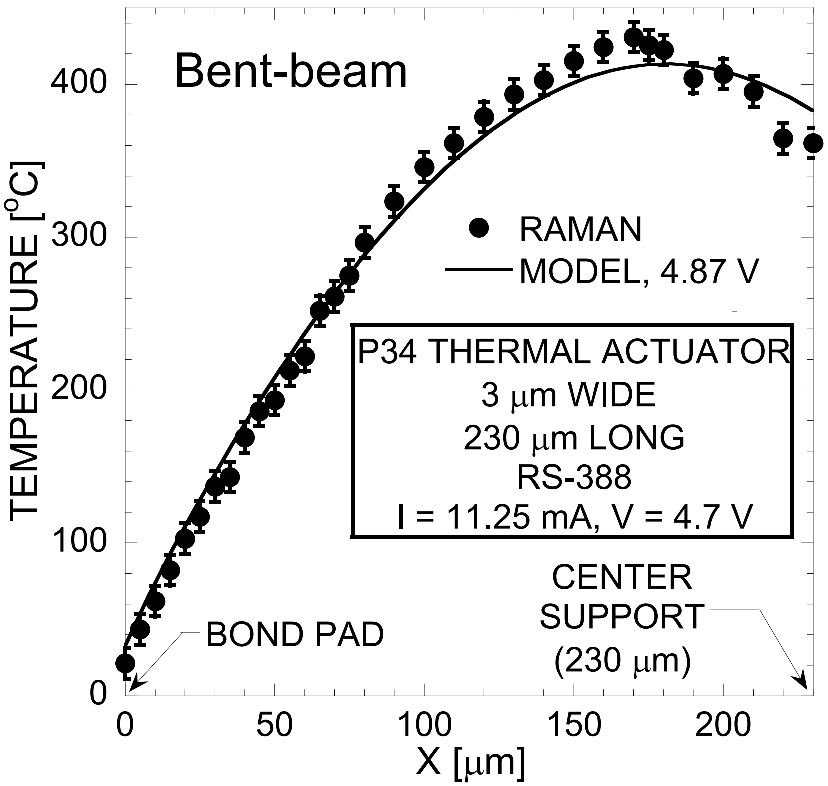
Actuator Leg Under Raman Microscope

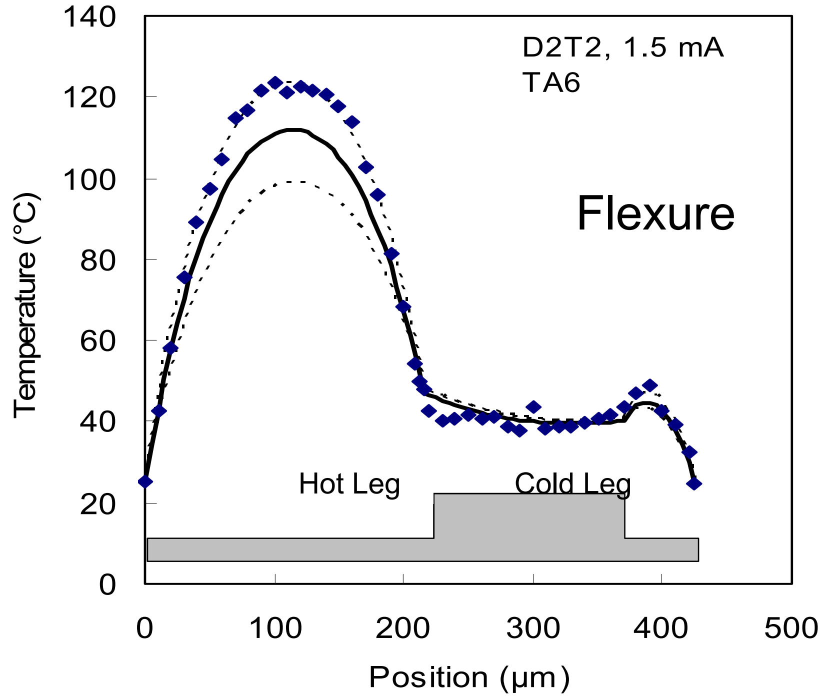
Raman Spectra from PolySi Part



- 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 -- increases with temperature as a result of increasing population of thermally excited optical phonons.
- These properties may also depend on stress and/or doping.

Raman Thermometry of Thermal Microactuators



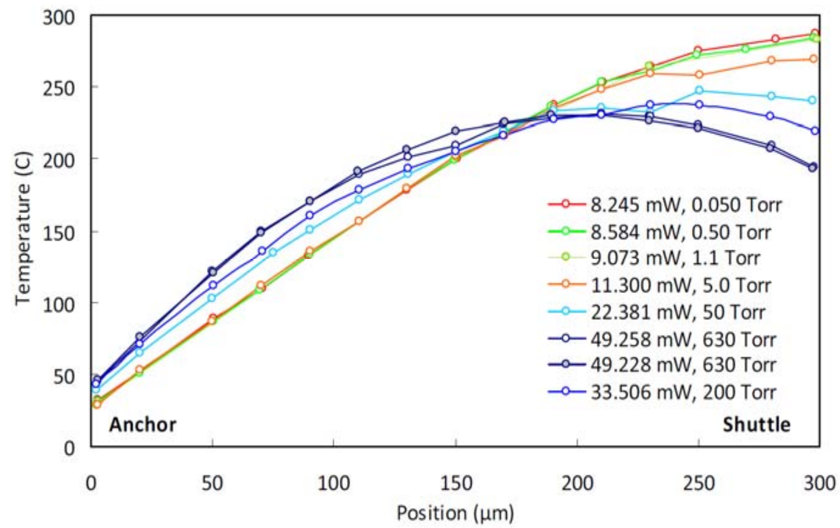


First high spatial resolution temperature profiles for MEMS electrically heated thermal microactuators:

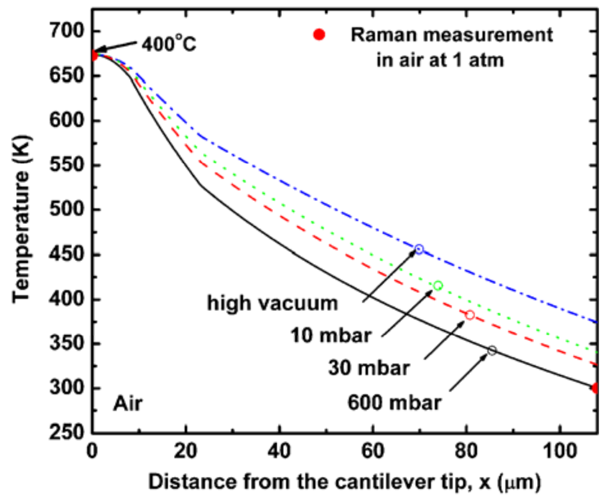
- Bent-beam (Kearney, Phinney, and Baker, *Journal of Microelectromechanical Systems*, **15**, 314-321, 2006.)
- Flexure (Serrano, Phinney, and Kearney, *Journal of Micromechanics and Microengineering*, **16**, 1128-1134, 2006.)

Low Pressure Effects on MEMS Heat Transfer

- Partial vacuum operation needed in some cases for improved sensitivity.
- Reduced pressure alters heat transfer out of heated MEMS.
- Failure to understand heat transfer leads to device failure (specs or catastrophic).



Phinney, Baker, and Serrano, "Thermal Microactuators" in Microelectromechanical Systems and Devices, I. Nazul (Ed.), InTech (2012).

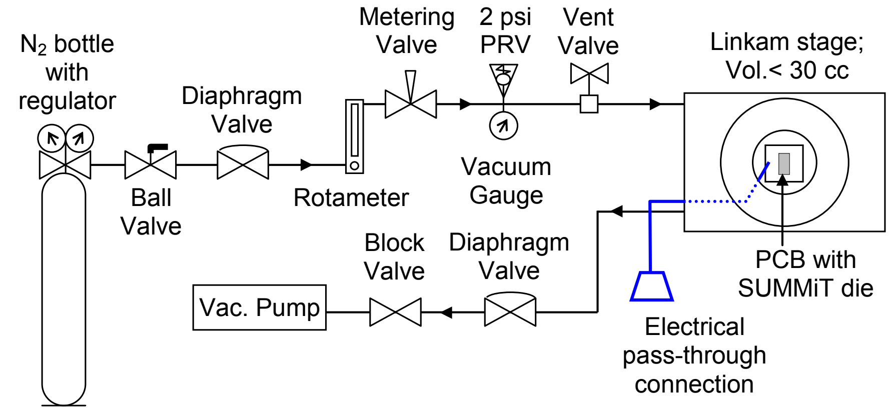


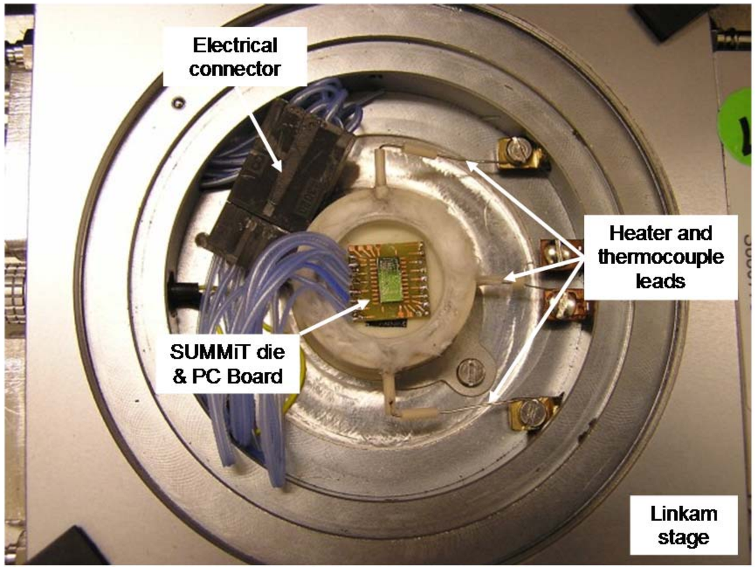
Lee, et.al., J. Appl. Phys. 101, 014906 (2007)

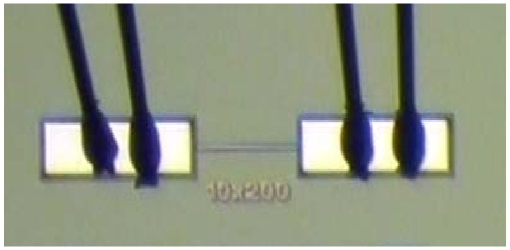
Test Structures and Environmental Control

Fixed-fixed beam samples mounted in a temperature stage with gas inlets and outlets

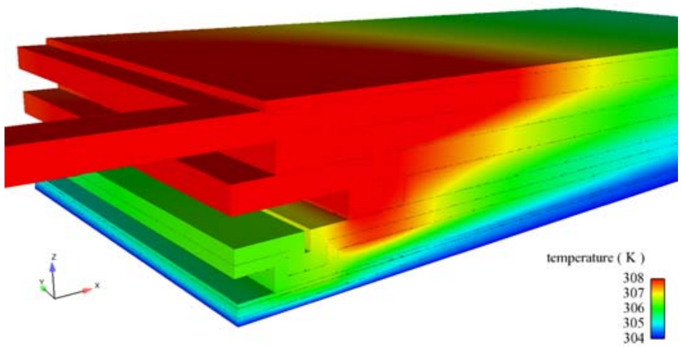
- Nitrogen pressures 0.05, 0.5, 5, 50, 625 Torr (760 Torr = 1 atm)

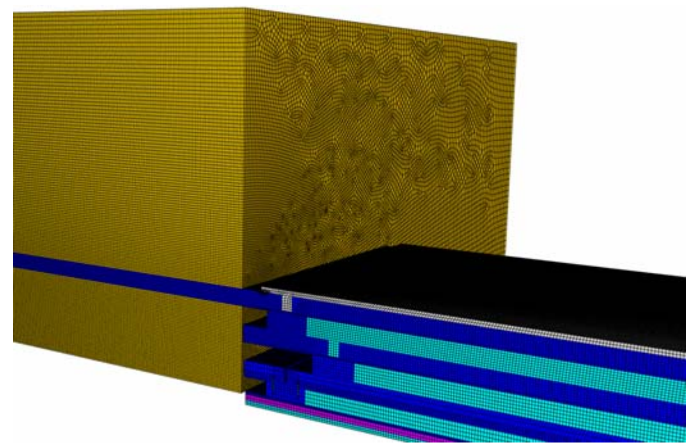


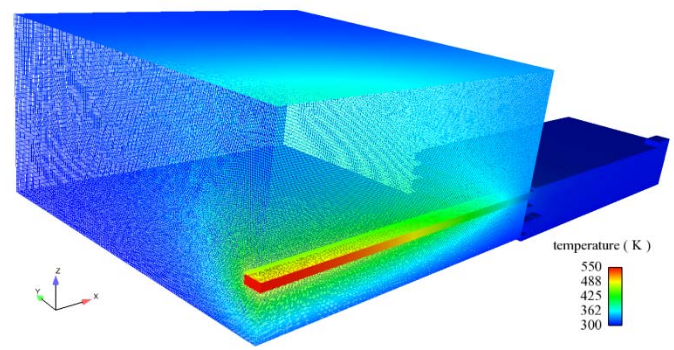




3-D Finite Element Modeling Parameters







Layer Thickness	Model Value	Other Lengths	Model Value
Thermal Oxide	0.630 µm	Beam length (short)	200.00 µm
Silicon Nitride	0.800 µm	Beam length (long)	400.00 µm
Poly0	0.300 µm	Beam width (both)	9.65 µm
SacOx1	2.000 µm	Bond pad *x* width	100.00 µm
Poly12	2.260 µm	Bond pad *y* width	41.00 µm
SacOx3	2.461 µm	Gas domain *y* width	100.00 µm
Poly3	2.320 µm	Gas domain *z* height	50.00 µm
SacOx4	2.461 µm		
Poly4	2.330 µm		
Metal	0.700 µm		

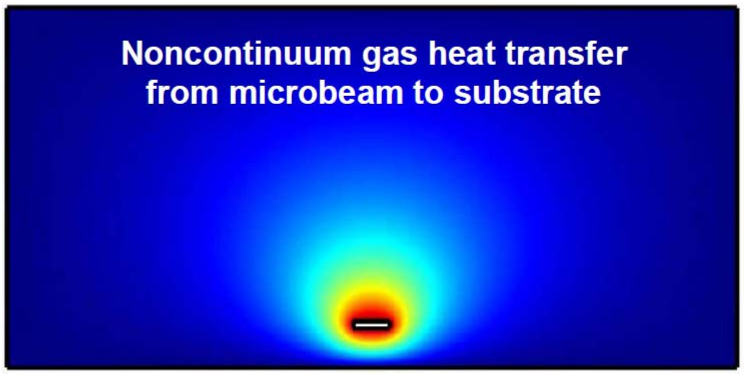
Gas, solid, electrical: 1-35, 0.2-15, 0.07-4 million elements

Thunderbird cluster: 100 processors, 0.1-6 hours per run

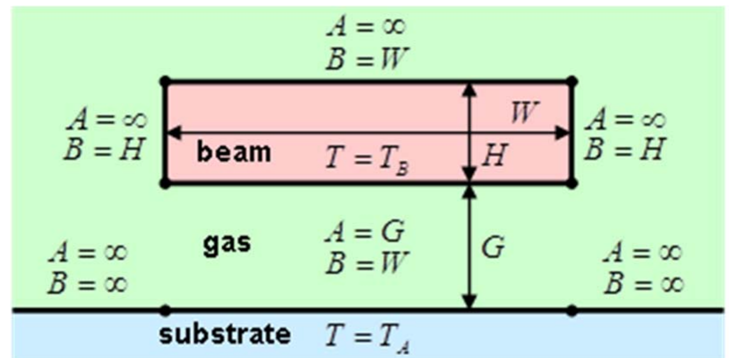
Phinney, Serrano, Piekos, Torczynski, Gallis, and Gorby, 2010, *Journal of Heat Transfer*, **132**, Article No. 072402.

Rarefied Gas Modeling

- Discrete Simulation Monte Carlo (DSMC) used to estimate heat transfer coefficient to gas for Si surface in N_2 for different pressures and accommodation coefficients



Torczynski, et. a., Sandia Report, SAND2008-5749 (2008)

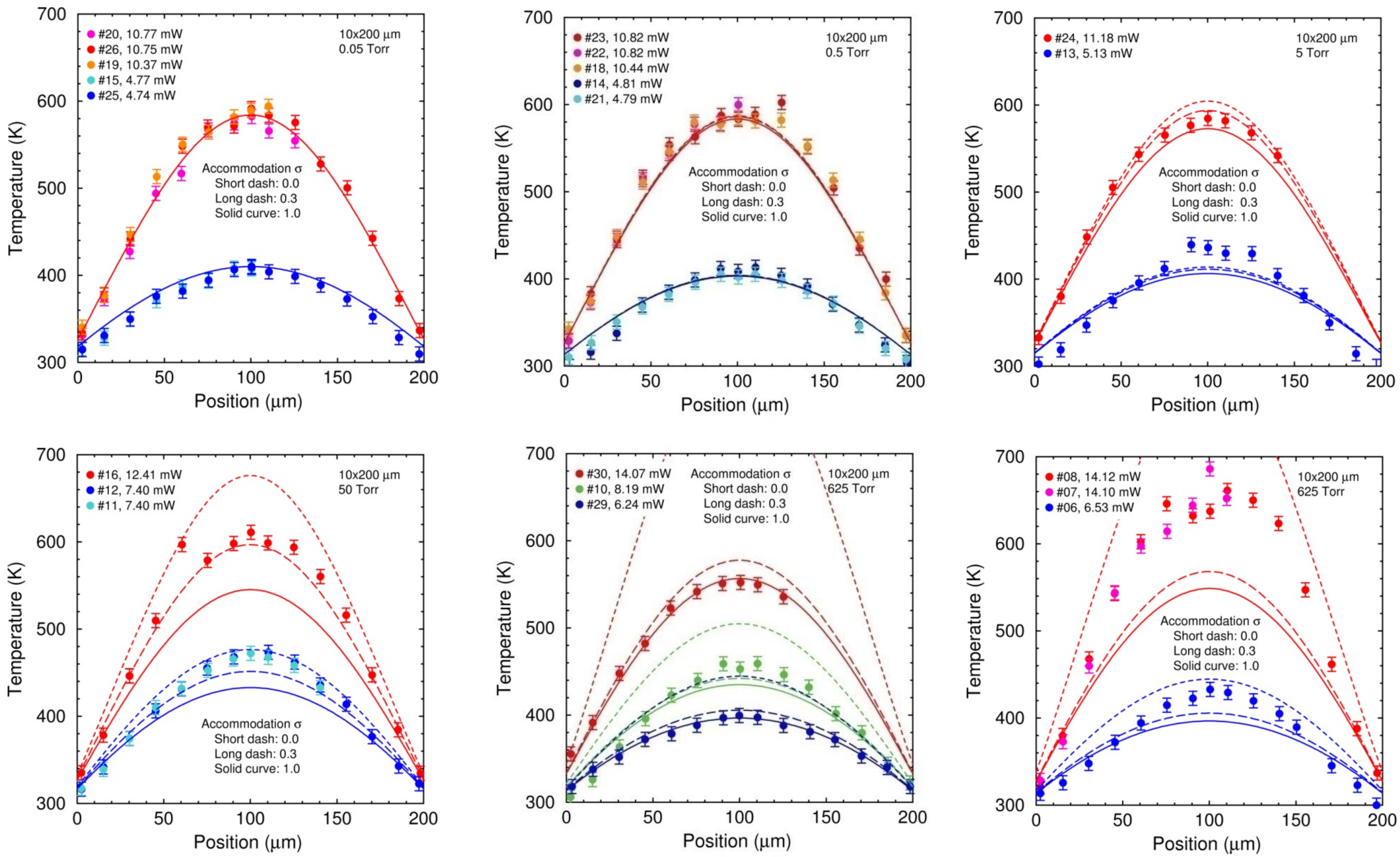


$$h = \left(1 + \frac{\zeta}{4}\right)\left(\frac{\sigma}{S_1 S_2}\right)\left(\frac{p\bar{c}}{T}\right)$$

Effective heat transfer coefficient parameterized in terms of pressure, temperature, geometry, and species

- Accommodation coefficient, σ , used as a variable parameter to consider in comparing to measurements

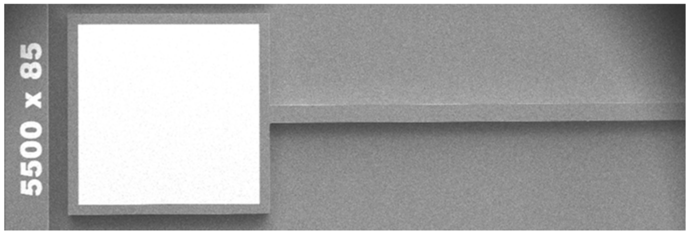
Temperature Profiles for 200 μm Beams

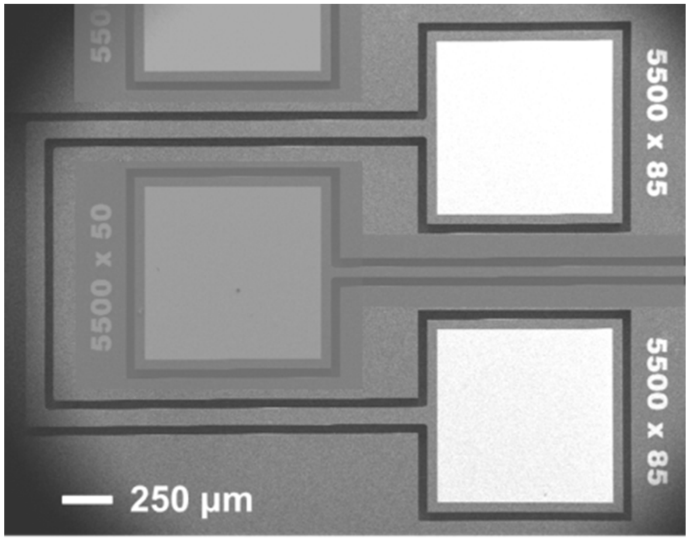


Phinney, Serrano, Piekos, Torczynski, Gallis, and Gorby, 2010, *Journal of Heat Transfer*, **132**, Article No. 072402.

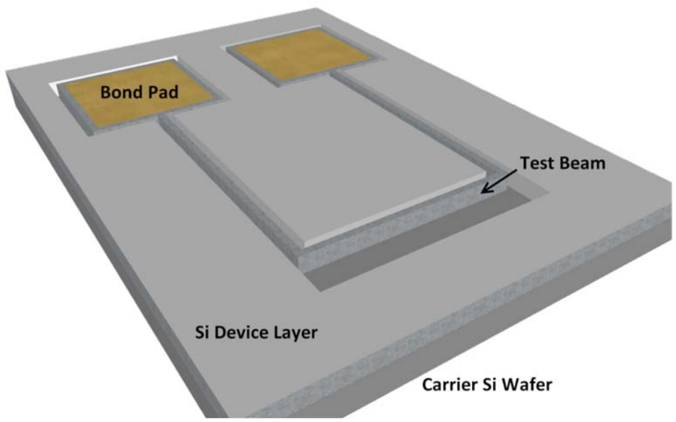
SOI Devices

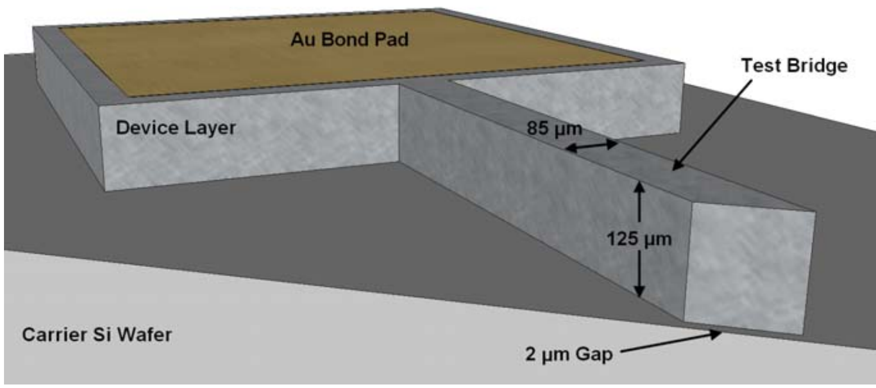
- Advantage: larger structures; single crystal Si; well known
- Only 2 μm over substrate; non-continuum effects still present
- Low-resistivity, boron-doped ($4x10^{19}$ cm^{-3}) Silicon-on-Insulator (SOI)
- Different geometries designed for thermometry
  - Fixed-fixed beam – constrained; compressively stressed when heated and prone to buckling; simple geometry
  - U-shaped beam – unconstrained; no buckling
  - 5500 μm_L x 85 μm_W x 125 μm_H





Device operation & testing

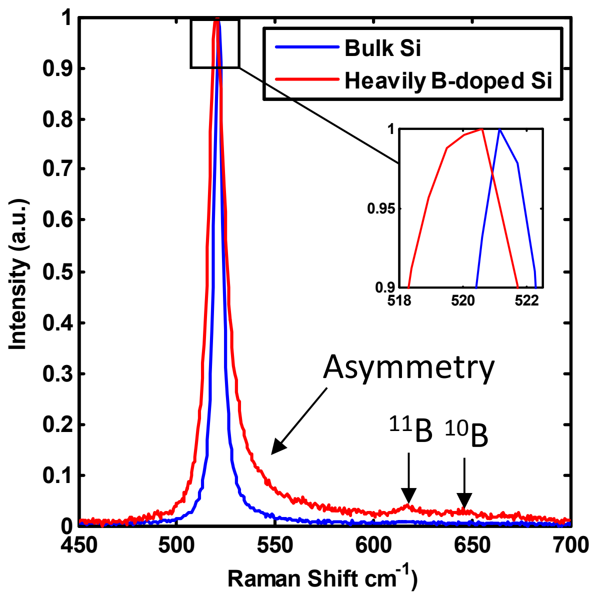




- Device operated in pressure controlled chamber; N_2 gas
- Electrical current flowing through device induces Joule heating.
- Two power dissipation conditions considered—high & low—targeting similar average temperatures across pressure range.
- Raman used to measure temperature along beam.

SOI Raman Calibration

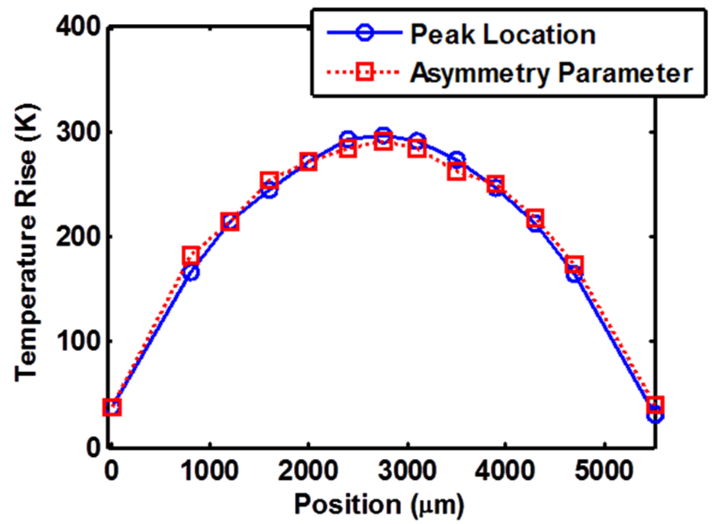
- Heavily B-doped Si device layer leads to Raman-active interband transitions resulting in asymmetric line shape



$$I = A\frac{(1+q\varepsilon)^2}{1+\varepsilon^2}$$

$$\varepsilon = \frac{\omega - \Omega}{\Gamma}$$

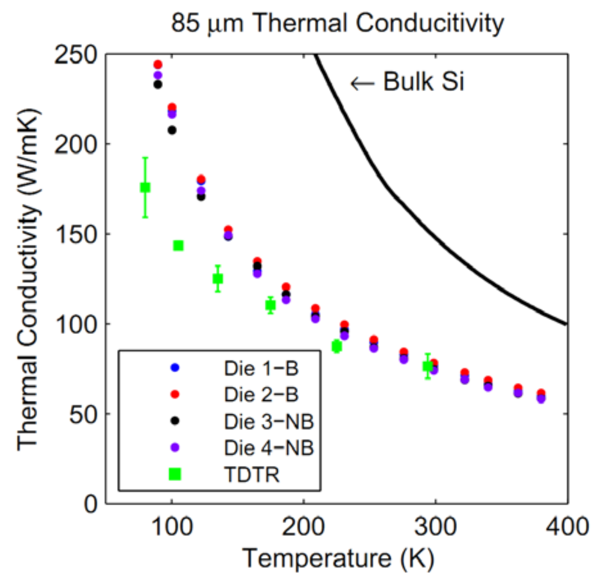
- Peak position: temperature & stress sensitive
- Line width: stress insensitive; weak temperature sensitivity
- Peak asymmetry: temperature sensitive and stress insensitive
- Peak asymmetry is a reliable temperature metric for devices with compressive or tensile stress

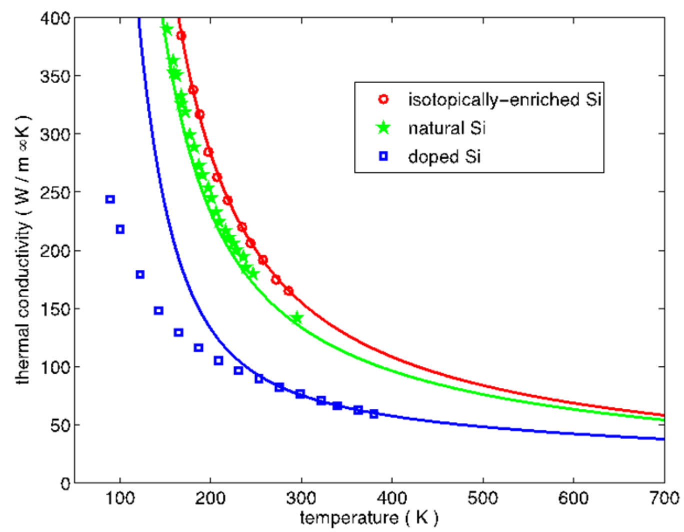


Temperature profile of U-shaped bridges measured with peak location and asymmetry parameter

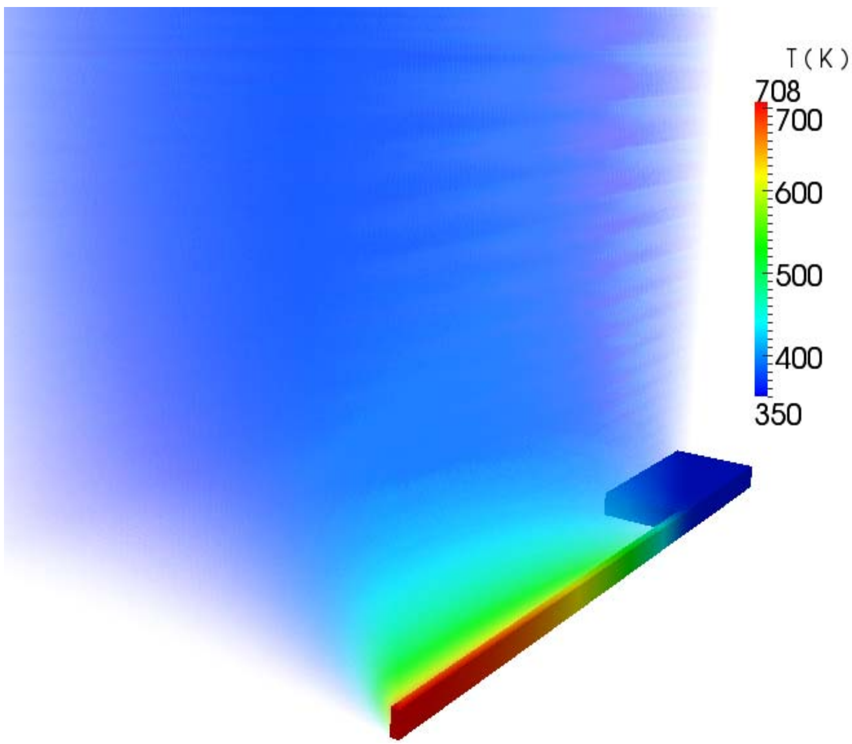
Effect of Doping on Thermal Conductivity

- Thermal conductivity and electrical resistivity of doped silicon were measured using steady-state resistivity measurement and time domain thermoreflectance (TDTR)
- Large dopant concentration increases impurity scattering; reducing thermal conductivity
- For purposes of simulations, material is modeled using a modified Holland model with an increased impurity scattering coefficient





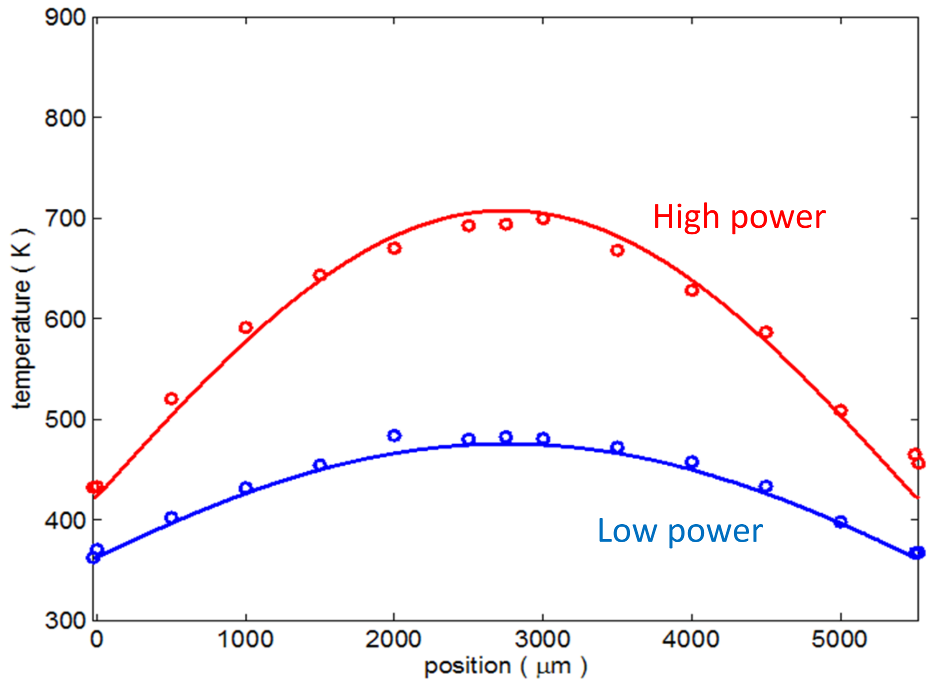
Numerical simulations



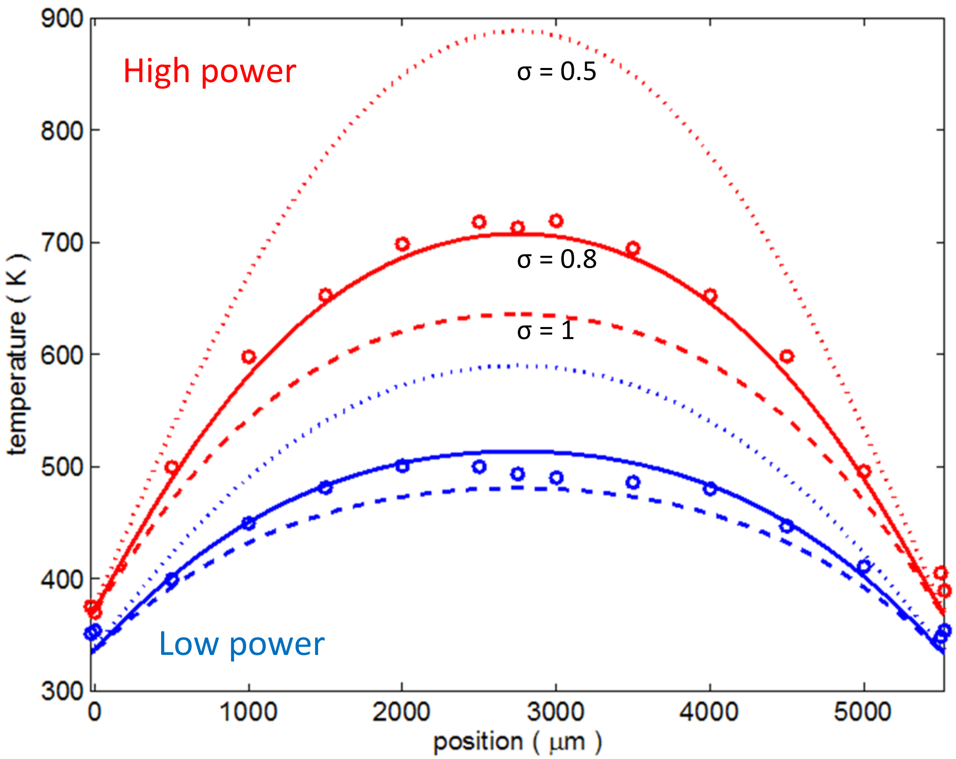
- Devices modeled using SNL's massively parallel Sierra FEA suite
- Coupled electrostatic and thermal model of device operation was loosely coupled to gas model
- Non-continuum effects of gas phase heat transport considered as a boundary condition

Vacuum (< 1 mTorr)

- Vacuum case ignores gas-phase heat transfer
- Effective gauge of solid conduction models and accuracy of thermophysical properties
- Models agree well with measurements
- Bond pad heating effects observed by measurements replicated by models

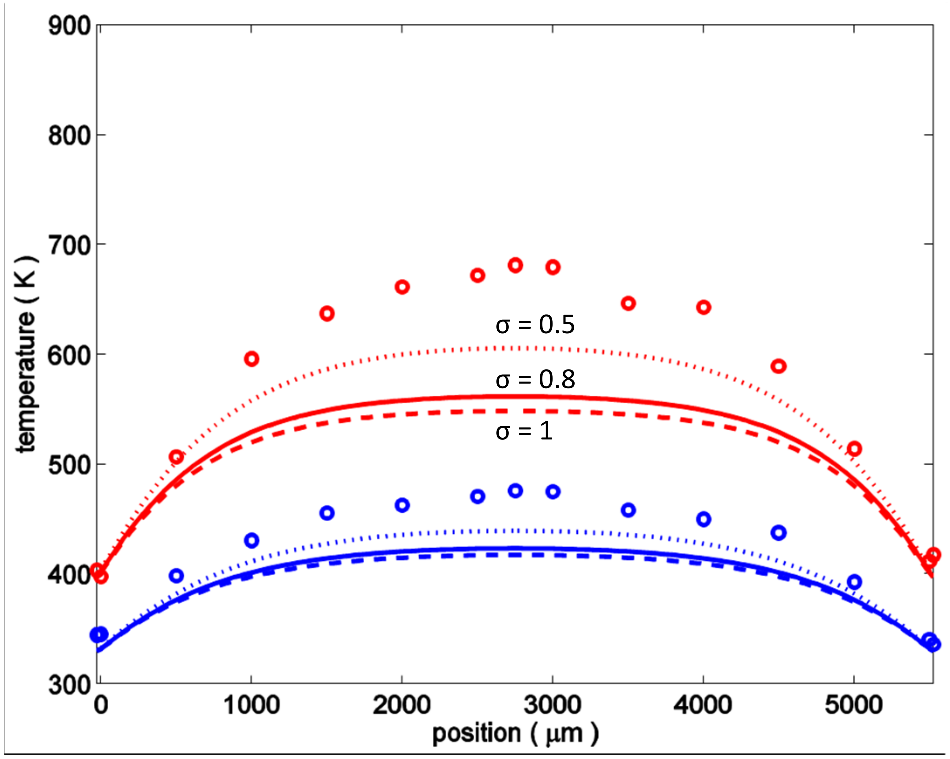


Low Pressure (~50 Torr)



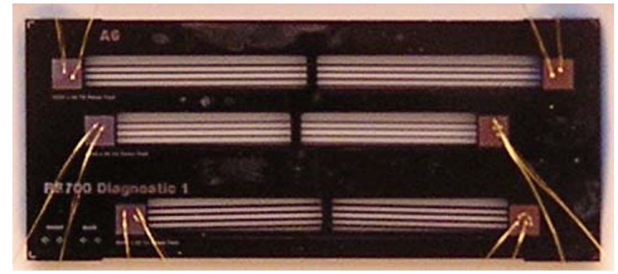
- Low pressure exhibits non-continuum effect due to small dimensions and large MFP
- FEA model with non-continuum heat transfer effects agrees very well with measurements for σ = 0.8
- Value is in agreement for Trott et al.'s result for silicon surface in nitrogen (σ = 0.82; *Trott et al., Rev. Sci. Instr, 82, 035120 (2011)*)

Atmospheric Pressure (~650 Torr)

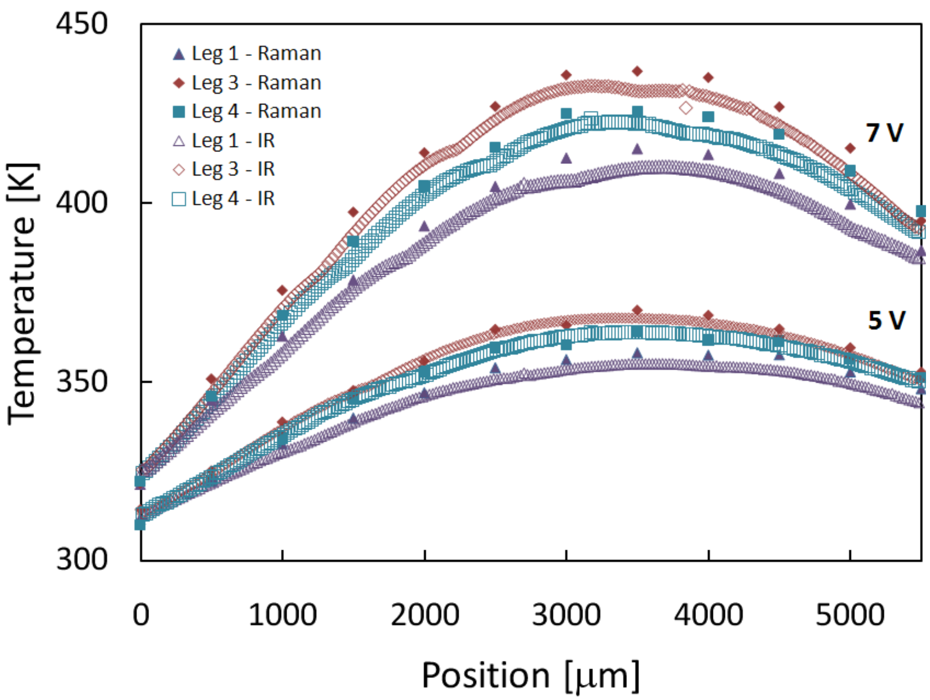


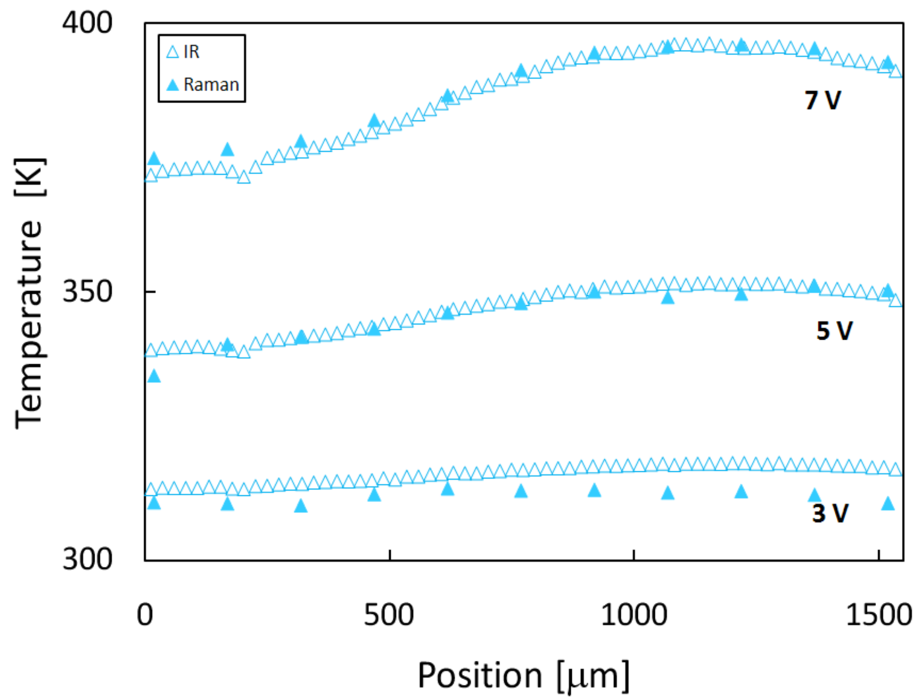
- High pressure increases discrepancies with model for all cases at reasonable accommodation coefficient (i.e., 0.5-1.0)
- Possible source of error in the DSMC calculations used in estimating gas-phase heat loss and non-continuum boundary conditions

Raman and IR Comparison



Temperature Profiles along Thermal Microactuator Legs using Raman and IR Thermometry





Temperature Profiles along the Thermal Microactuator Shuttle using Raman and IR Thermometry

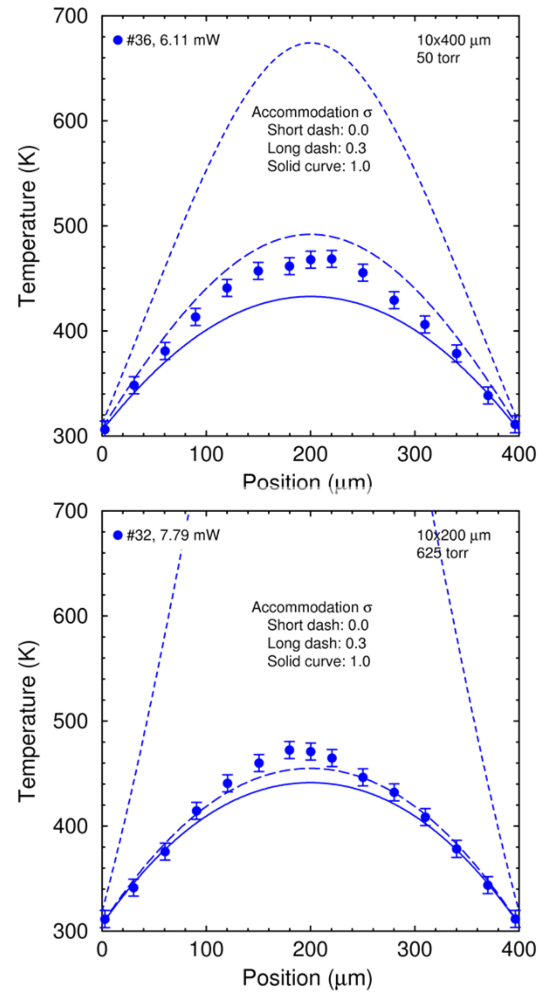
Conclusions

- Raman thermometry of MEMS microbridges, both polysilicon surface micromachined and SOI, under varying gas pressure environment is a useful tool for understanding gas-phase heat transfer in low pressure environments.
- Heavily boron doped silicon not only alters Raman peak but also affects thermal conductivity via increased impurity scattering.
- Non-continuum gas-phase model incorporated into FEA numerical simulations is accurate for low pressure situations.
- Higher pressure conditions reveal shortcomings in non-continuum model as experiments and simulations disagree for reasonable accommodation coefficients.
- Raman and IR temperature measurements on bent-beam SOI thermal microactuators agree qualitatively and quantitatively.

Gas Heat Transfer Validation

Sandia National Laboratories

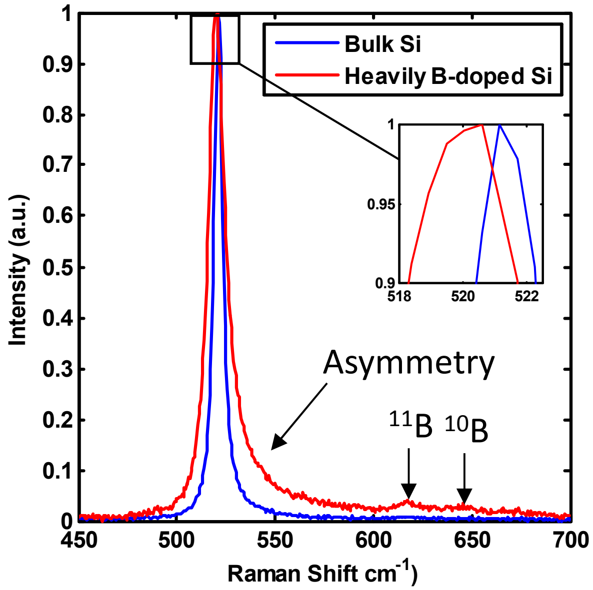
- MEMS challenge
  - Small gaps and/or low pressures ➔ non-continuum gas-phase heat transfer
  - Unknown surface accommodation coefficient
- Previous work:
  - Gallis, et al.: DSMC models of MEMS in reduced pressures used to estimate heat loss given accommodation coefficient
  - Torczynski, et al.: DSMC results rolled into FEA code. FEA models compared to temperature measurements on polySi microbridges to estimate accommodation coefficient. Discrepancies attributed to uncertainty in thermophysical properties & geometry



Phinney, et al., J. Heat Transfer 132, 072402 (2010)

SOI Raman Calibration

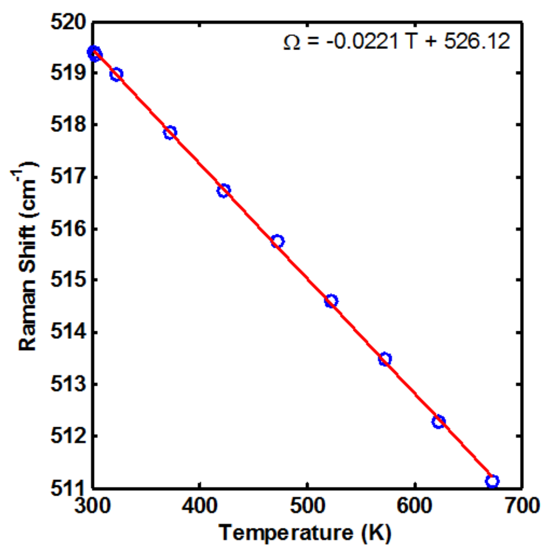
- Heavily B-doped Si device layer leads to Raman-active interband transitions resulting in asymmetric line shape

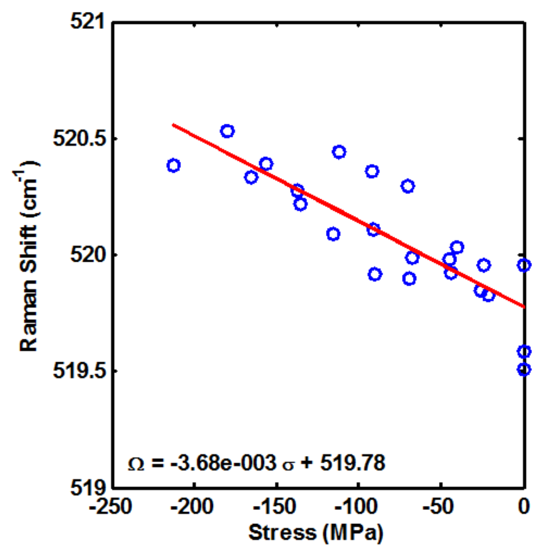


$$I = A\frac{(1+q\varepsilon)^2}{1+\varepsilon^2}$$

$$\varepsilon = \frac{\omega - \Omega}{\Gamma}$$

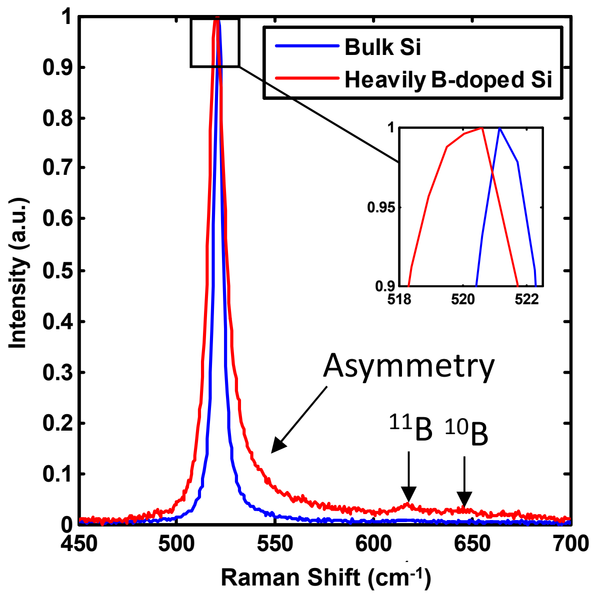
- Peak position: temperature & stress sensitive; bad for stressed samples





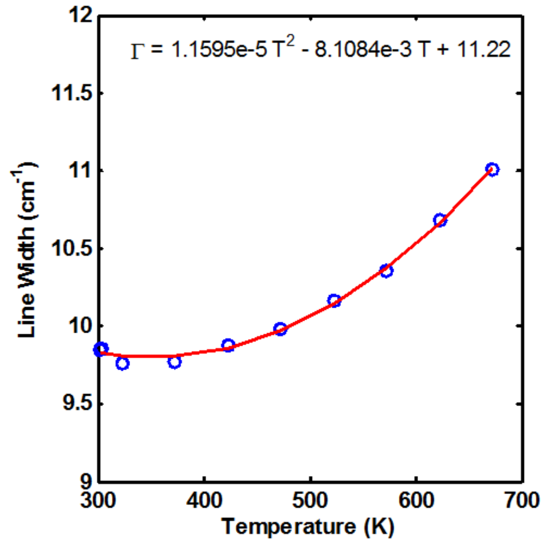
SOI Raman Calibration

- Heavily B-doped Si device layer leads to Raman-active interband transitions resulting in asymmetric line shape
  - Peak position: temperature & stress sensitive
  - Line width: stress insensitive; weak temperature sensitivity



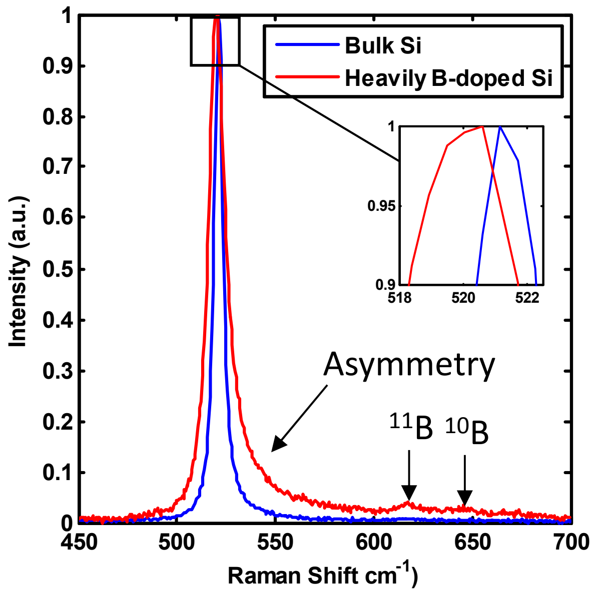
$$I = A\frac{(1+q\varepsilon)^2}{1+\varepsilon^2}$$

$$\varepsilon = \frac{\omega-\Omega}{\Gamma}$$



SOI Raman Calibration

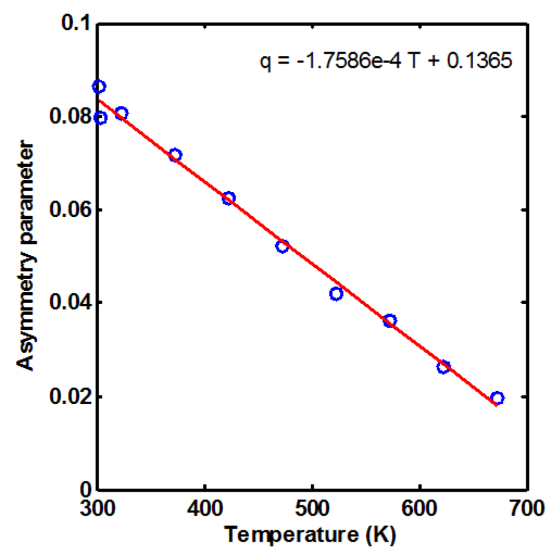
- Heavily B-doped Si device layer leads to Raman-active interband transitions resulting in asymmetric line shape



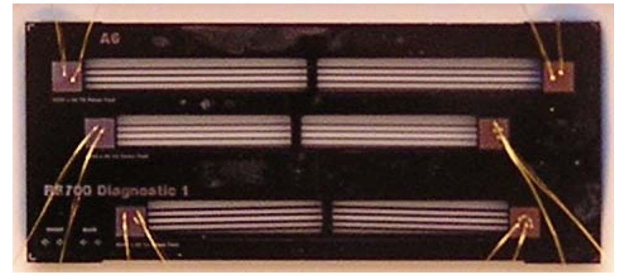
$$I = A\frac{(1+q\varepsilon)^2}{1+\varepsilon^2}$$

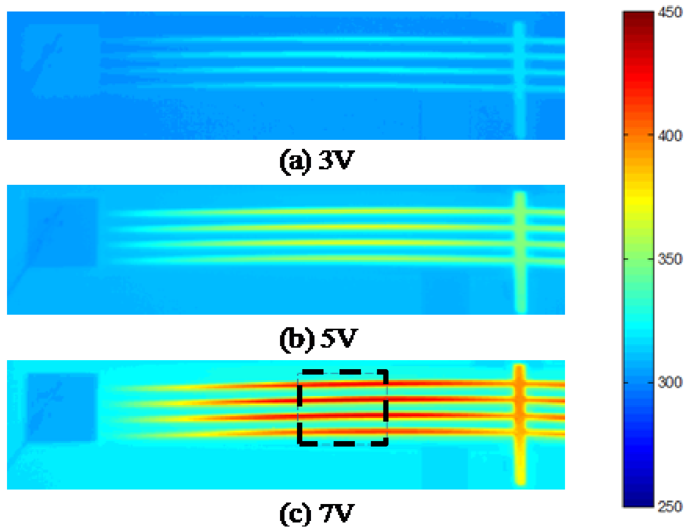
$$\varepsilon = \frac{\omega - \Omega}{\Gamma}$$

- Peak position: temperature & stress sensitive
- Line width: stress insensitive; weak temperature sensitivity
- Peak asymmetry: temperature sensitive and stress insensitive



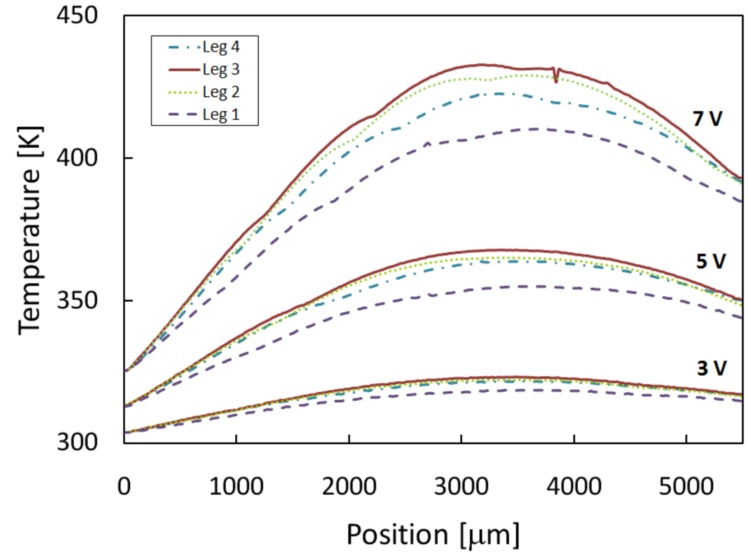
IR Measurements

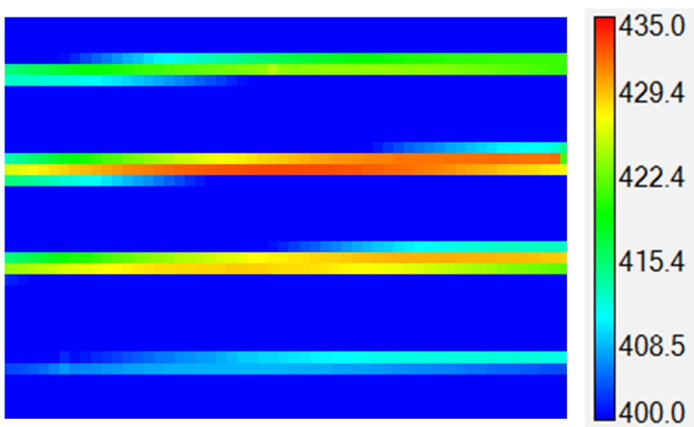




IR Thermal Images

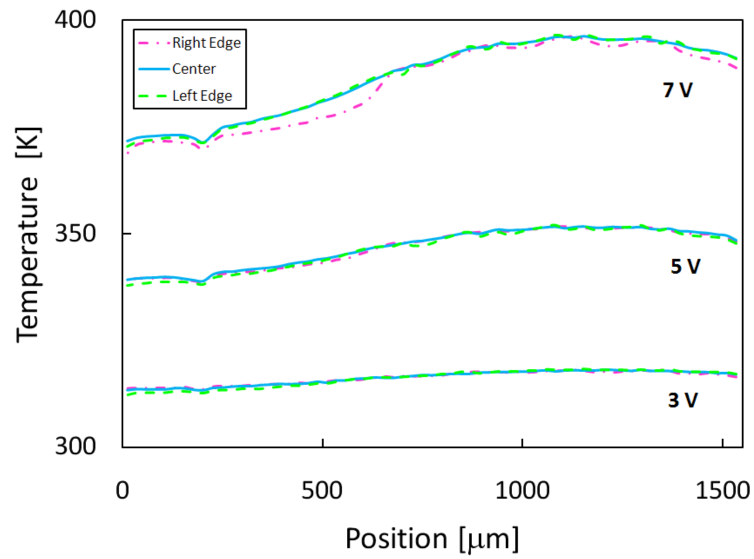
Profiles along Actuator Legs





Magnified View of Boxed Region in above 7V IR Thermal Image

Profiles along the Shuttle



Summary and Conclusions

- Raman and IR temperature measurements are reported for bent-beam SOI thermal microactuators.
- The temperatures measurements from the two techniques agree qualitatively and quantitatively with the maximum temperature at 60-65% of the distance from the anchor to the shuttle and with the inner legs achieving higher temperatures than the outer ones.
- The Raman thermometry technique is able to achieve higher spatial resolutions and can validate IR thermometry calibrations and uncertainties.
- IR thermometry produces full field images and has a faster data collection time.