The CINT Cantilever Array Discovery Platform™

SAND2007-4604C

J. P. Sullivan
Center for Integrated Nanotechnologies (CINT)
Sandia National Laboratories,
Albuquerque, NM

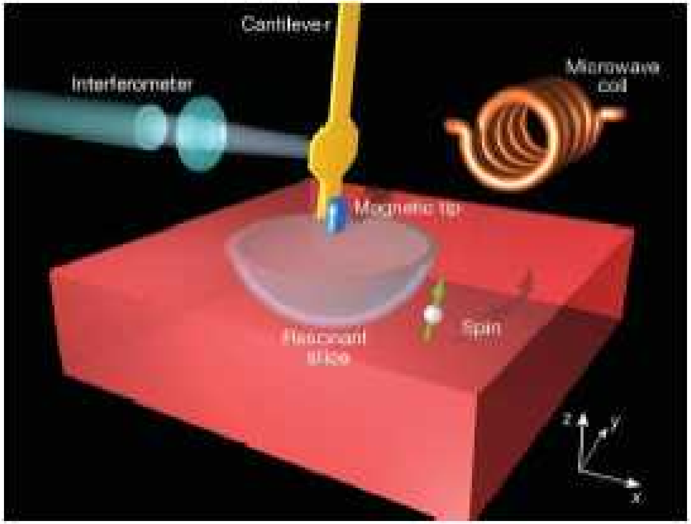
Special thanks to Mike Shaw for process engineering, David Luck for mask design, and Anton Sumali for resonance measurements (Sandia), and for design input from M. de Boer, M. Baker, G. Bogart, H. Stewart, S. Koch, D. Carr, S. Howell (SNL), A. Misra, G. Swadener, A. Migliori (Los Alamos), T. Saif (Univ. Ill.), D. Bahr (Wash. State Univ.), D. Cole and S. Kennedy (Duke Univ.) and others …

This work was supported by the Dept. of Energy Office of Basic Energy Science and by the joint Sandia-Los Alamos Center for Integrated Nanotechnologies (CINT). Sandia is a multiprogram laboratory operated by Sandia Corp., a Lockheed Martin Co., for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

May 21, 2007

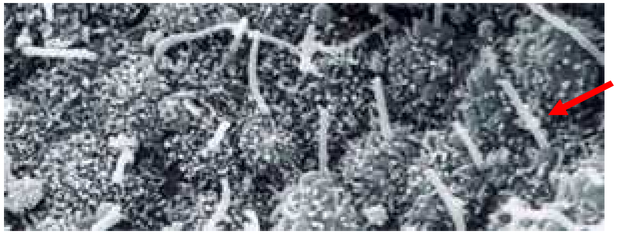
Interest in resonant mechanical systems centers around a simple idea.

Rugar, et al., Nature ***430****, '04*



SIMPLE IDEA: to make a mechanical structure that is sensitive to a small force, create a structure with a small force constant
$\Rightarrow$ a small, long and thin beam

for a cantilever, $$K = \frac{E_Y w}{4}\left(\frac{t}{L}\right)^3$$



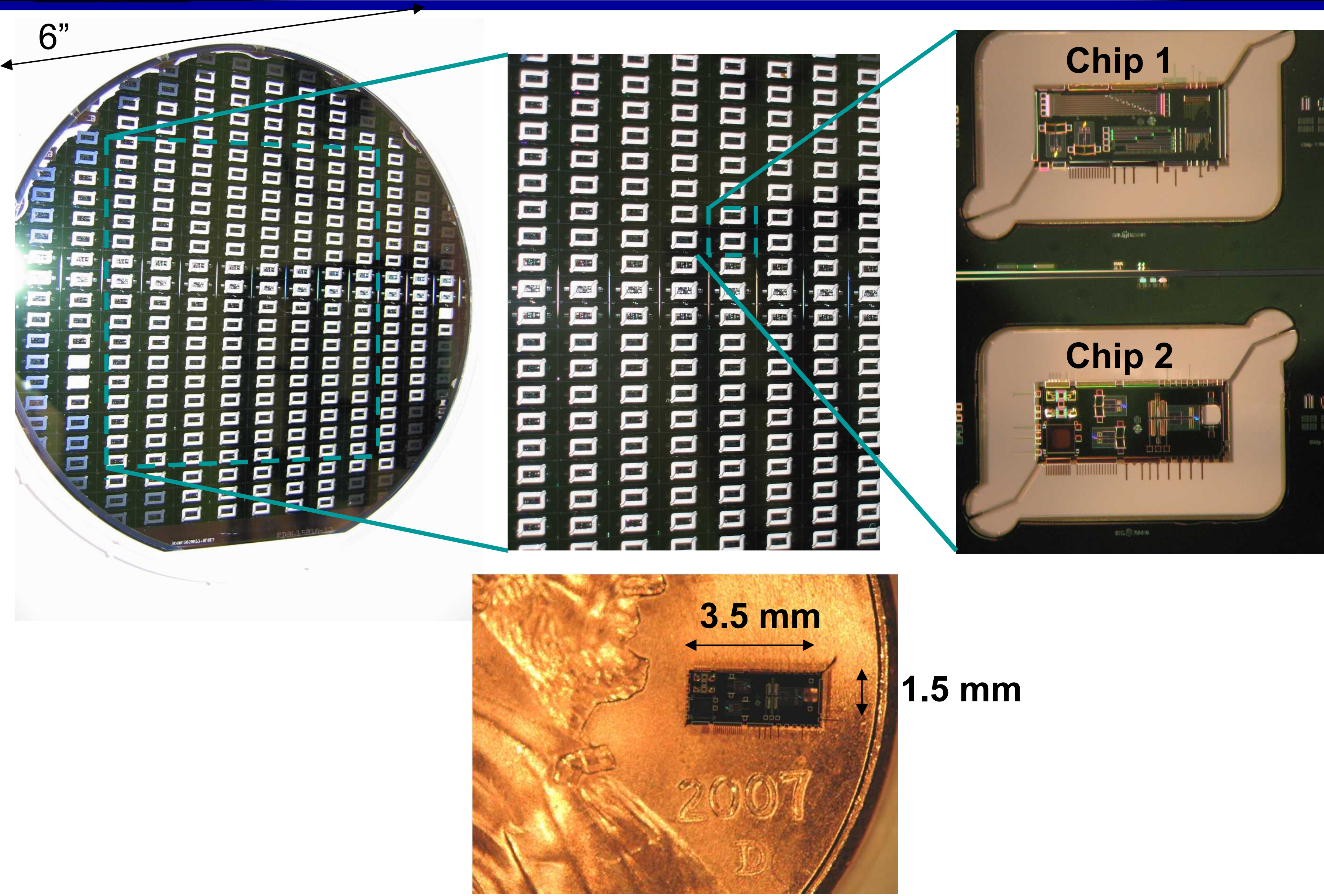
cilia on mouse embryonic cells

M. M. Stephan, The Scientist ***18****, '04*
(pic. from Marszalek & Goldstein)

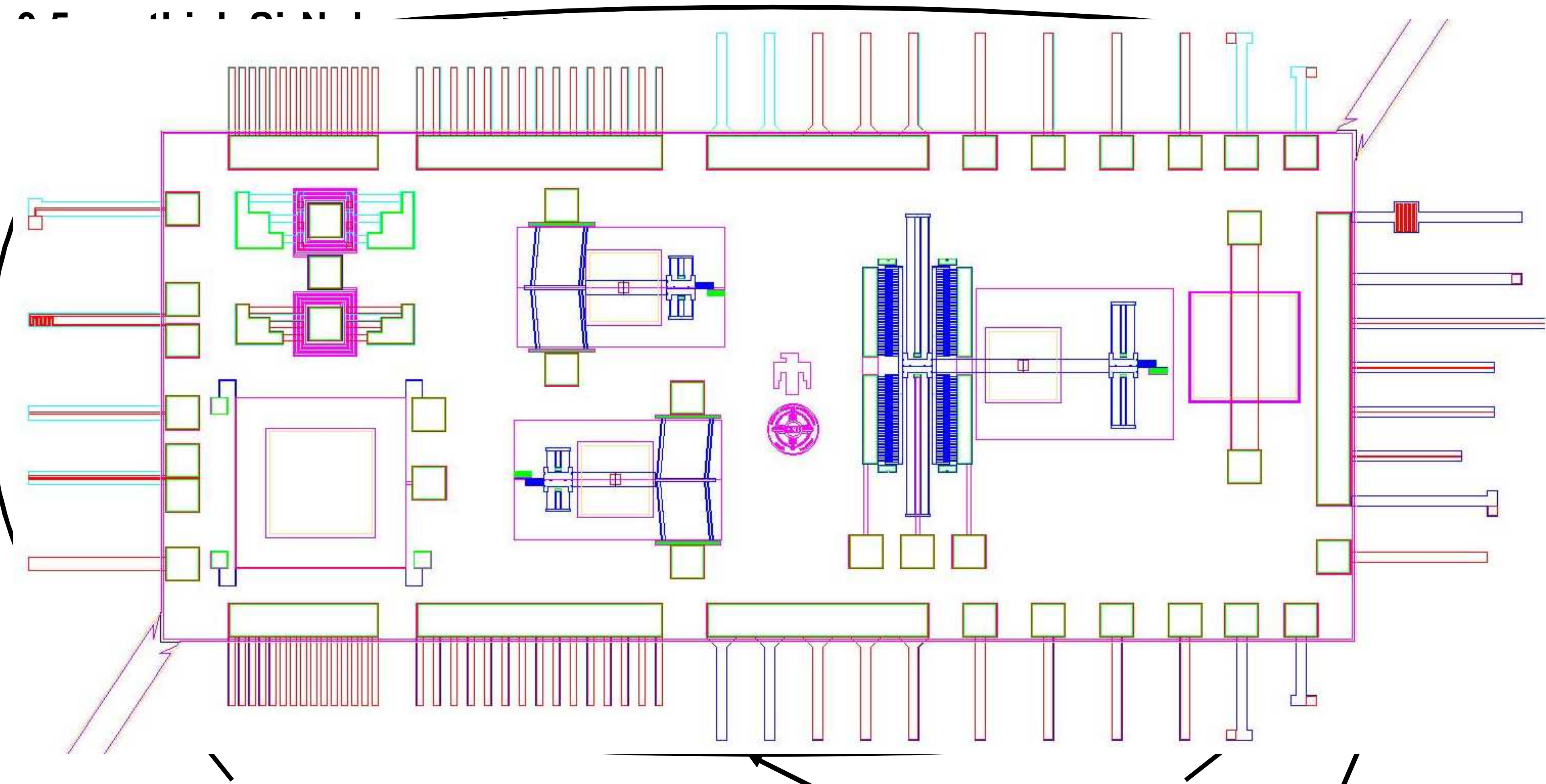
<u>Biology</u>: specialized cilia are involved in 3 of our senses

- *hearing*
- *seeing*
- *smelling*

There are *two* chips that are part of the Cantilever Array Discovery Platform™ (CADP).



Chip 1 has structures designed to test coated beams and structures.

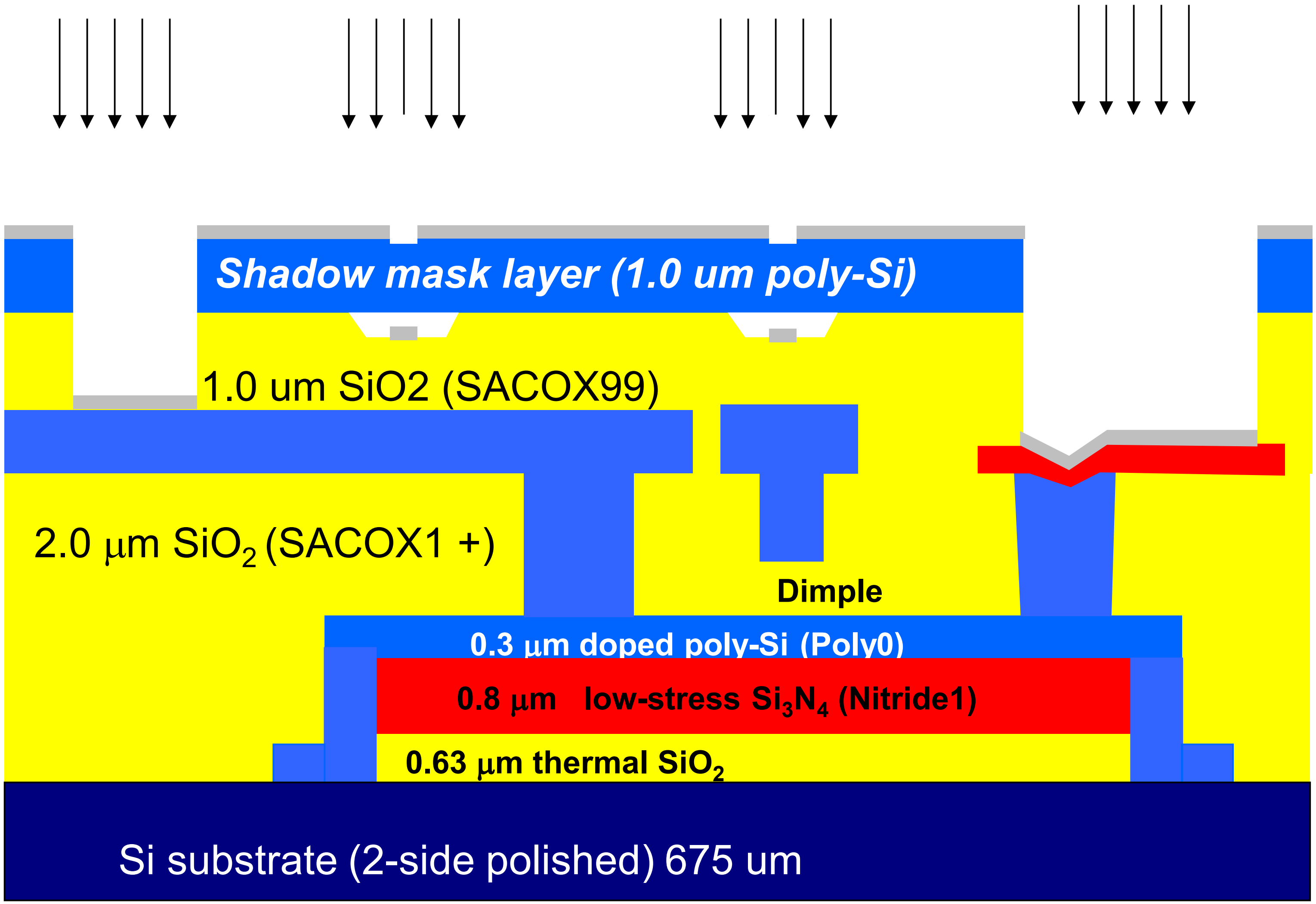


2.25 μm thick doped polycrystalline Si beams

MEMS structures, contact pads, etc.

oscillator physics

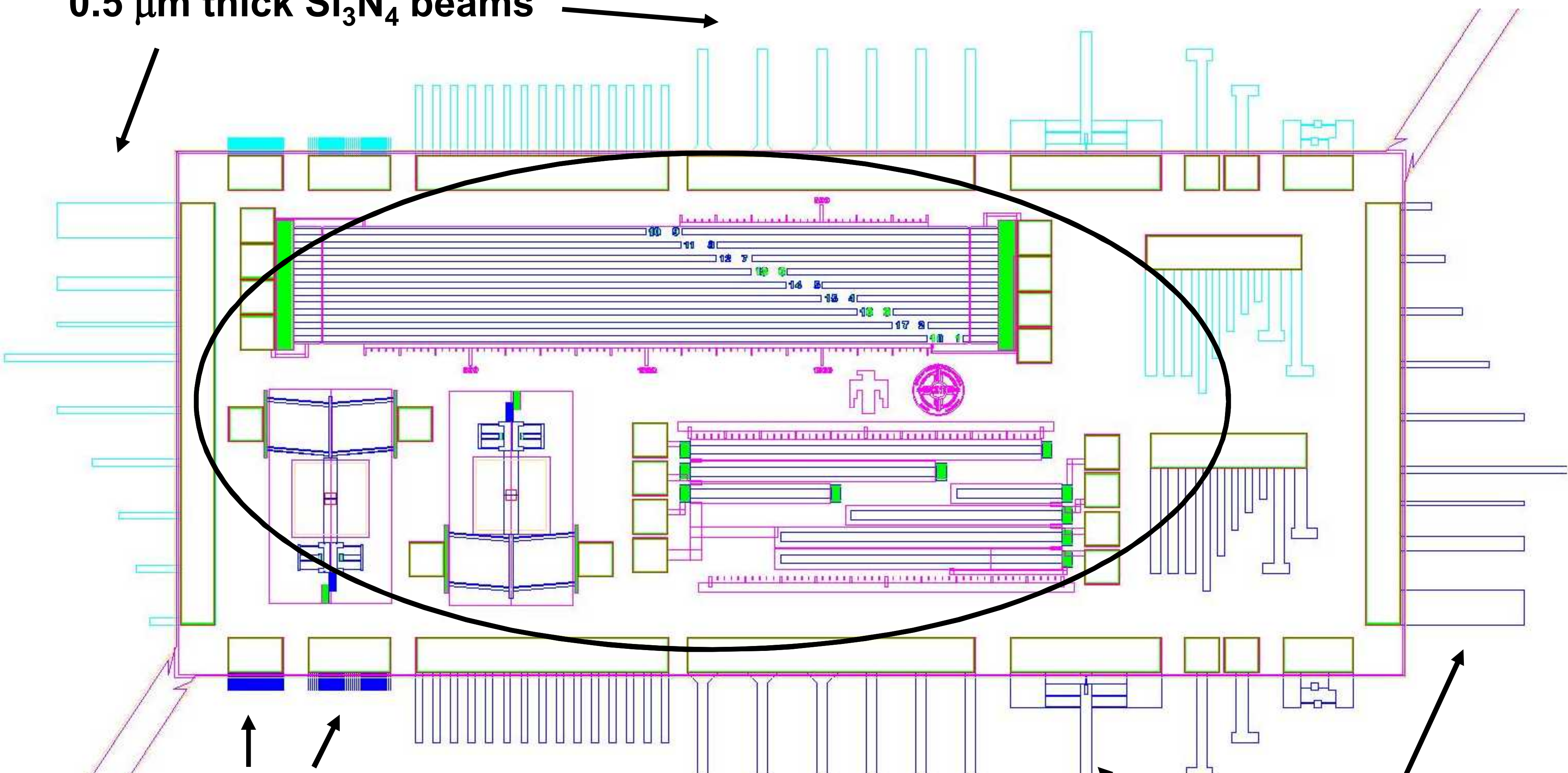
Shadow mask layer enables user-defined material on parts of chip.



Design by Mike Shaw, SNL

Chip 2 contains additional structures.

0.5 μm thick Si_3N_4 beams

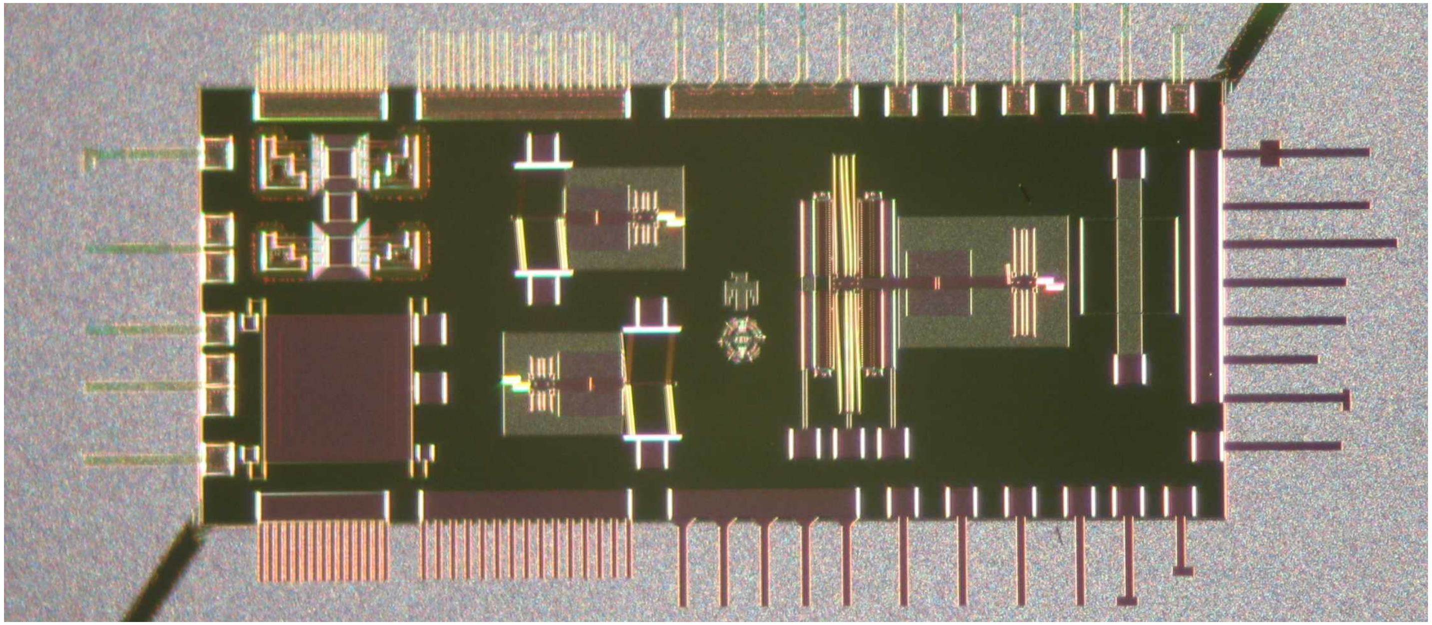


High density arrays

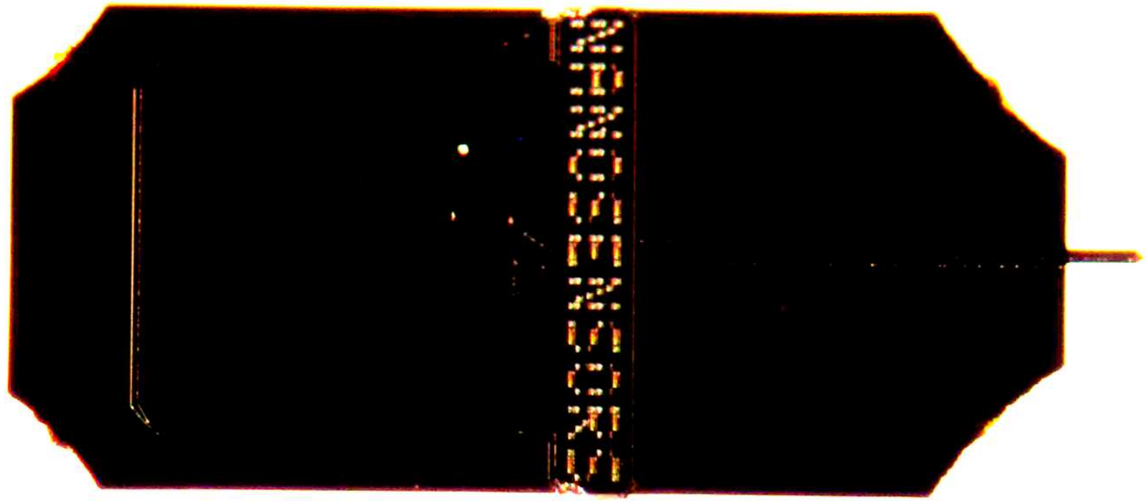
5. Electrostatically-controlled cantilever and doubly-clamped beams for surface studies (adhesion, surface tension, etc.)

2.25 μm thick polycrystalline Si beams

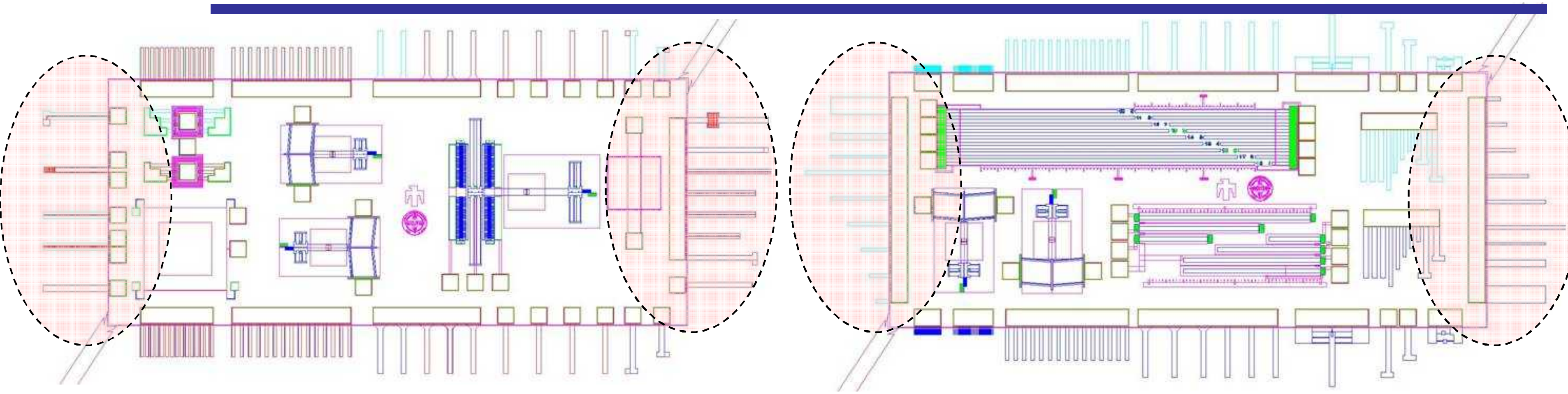
The chip dimensions are the same size as a standard AFM chip.



Standard AFM chip



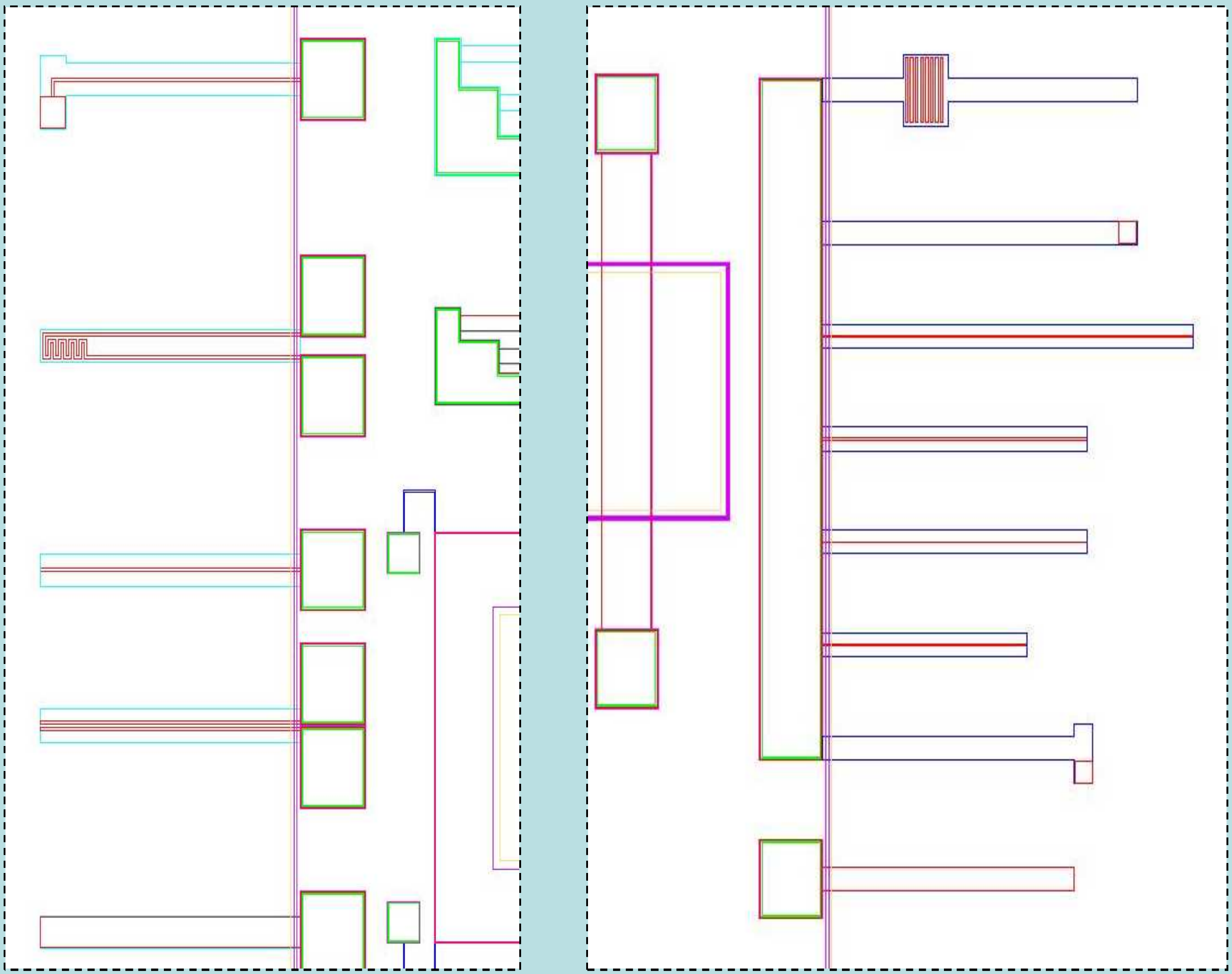
1. Isolated cantilevers (scanning probe cantilevers, other probes)



- **both poly-Si and silicon nitride beams of varying lengths (varying force constants) – user can select desired beams**
- **bimporph beams for thin film testing of user material**

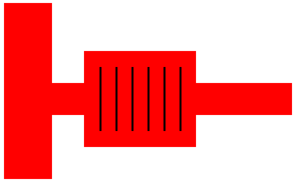
User coatings allow functional AFM tips, etc.

Chip 1

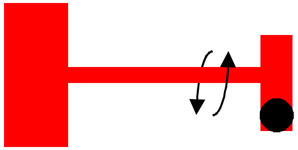


- scanning probe beams with heaters, resistance thermometers, magnetic particles, etc.

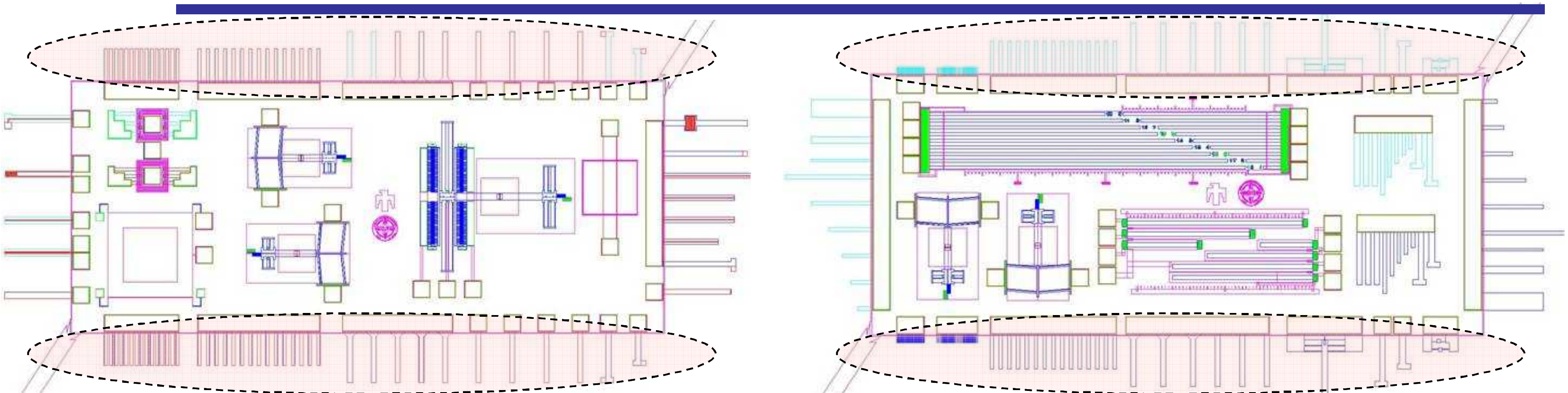
- beams with optical gratings for interferometry



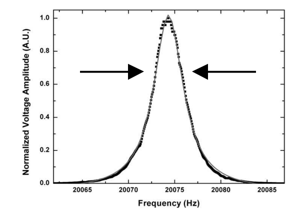
- torsional beams



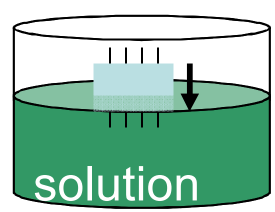
2. Cantilever arrays (coupled beams, sensor structures, etc.)

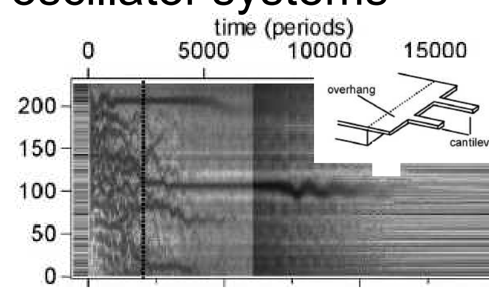


- both poly-Si and silicon nitride cantilever beam arrays
- de-coupled beams for internal dissipation studies in crystalline and amorphous materials



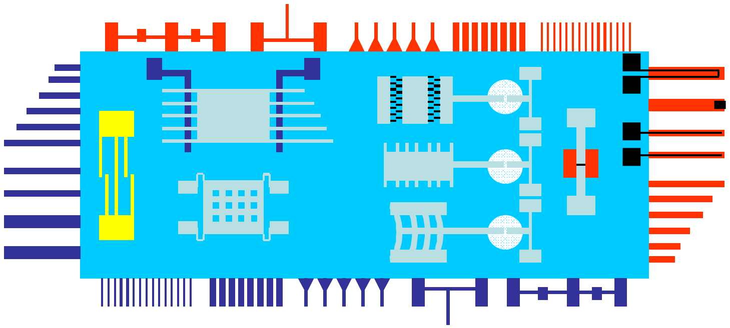
- beams with triangular bases for force-displacement testing
- beams with coupling for sensors or physics of coupled oscillator systems
- arrays for functionalization and chem/bio sensing
- torsional beam arrays
- beams w/ in-plane deflection





Sato et al., PRL 90, 044102 (2003)

Examples of mechanics studies with cantilever beams.



I. Internal dissipation

- *defect relaxation in materials*
- *use cantilever and torsional beams*

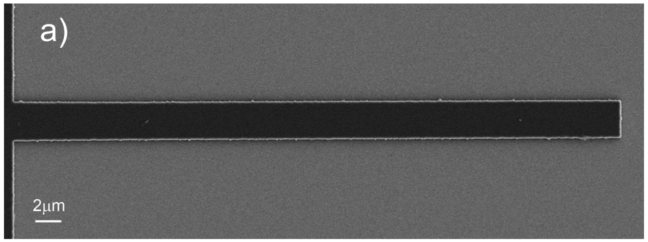
II. Cantilevers as sensors

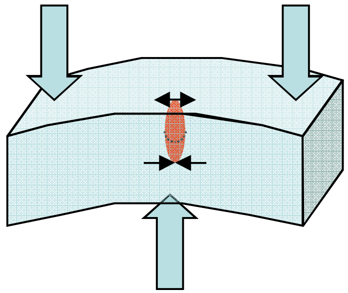
- *atmospheric corrosion sensing*

III. Coupled oscillator arrays

- *arrays with low to high degrees of coupling*

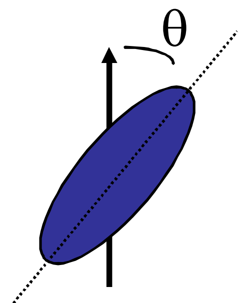
Example 1: Defect-related internal dissipation.



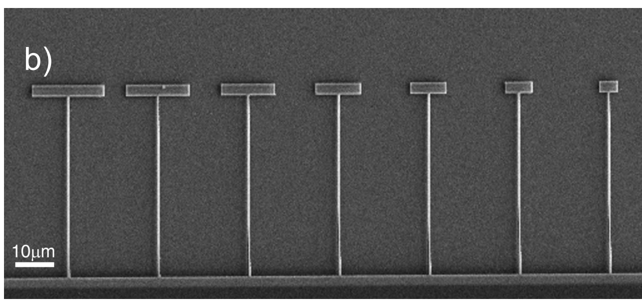


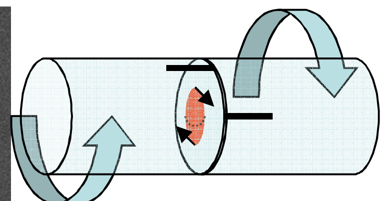
bending

How Defect Relaxation Works:



- defect relaxes to relieve stress
- defect needs to have lower symmetry than crystal system





shear

assuming the defect has a simple strain ellipsoid

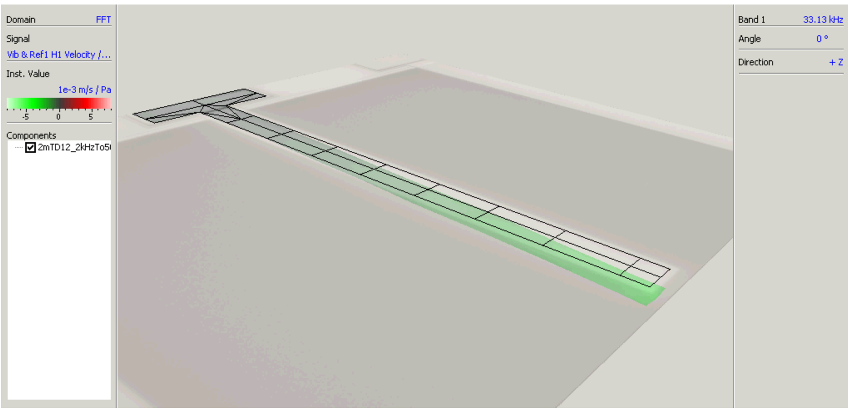
$$\tilde{\lambda} = \begin{pmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_2 \end{pmatrix}$$

(bending) $$\delta J = \delta E^{-1} \propto C_0 \left[\frac{51}{512} (\lambda_1 - \lambda_2)^2 \right]$$

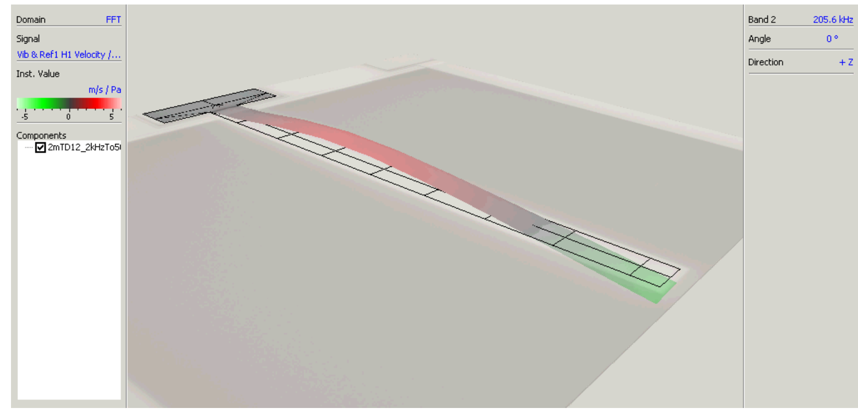
(shear) $$\delta J = \delta (2G)^{-1} \propto C_0 \left[\frac{41}{512} (\lambda_1 - \lambda_2)^2 \right]$$

Isolated beams show simple beam behavior.

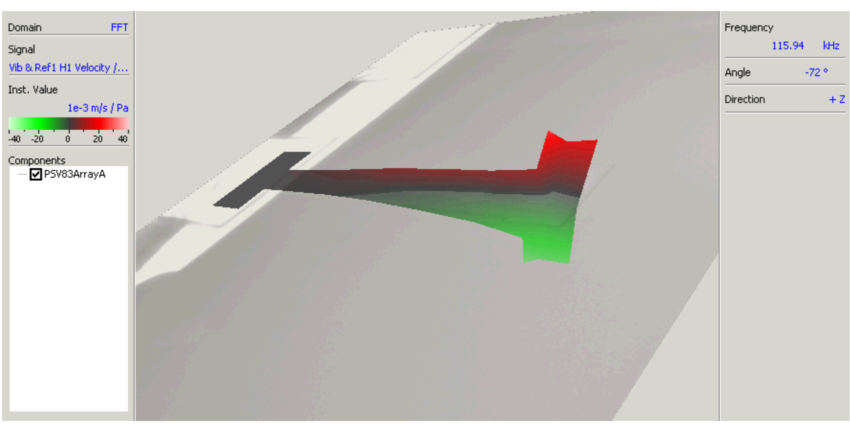
Laser Doppler Vibrometer measurements of simple beam resonance modes.



300 μm poly-Si 1st bending (33.13 KHz)



300 μm poly-Si 2nd bending (205.6 KHz)



200 μm Si_3N_4 1st torsion (115.94 KHz)

Temperature-dependent studies are used to measure defect relaxation.

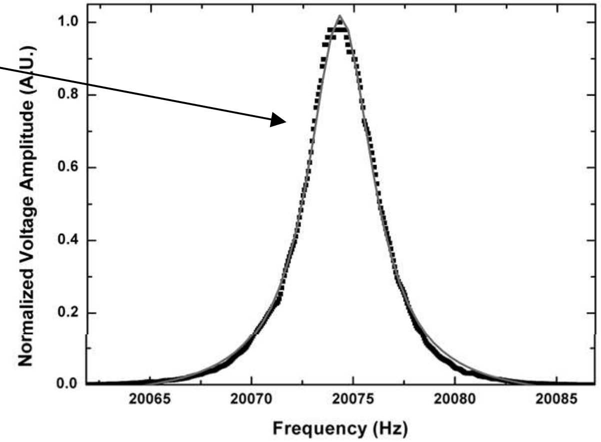
Defect relaxation is thermally activated:

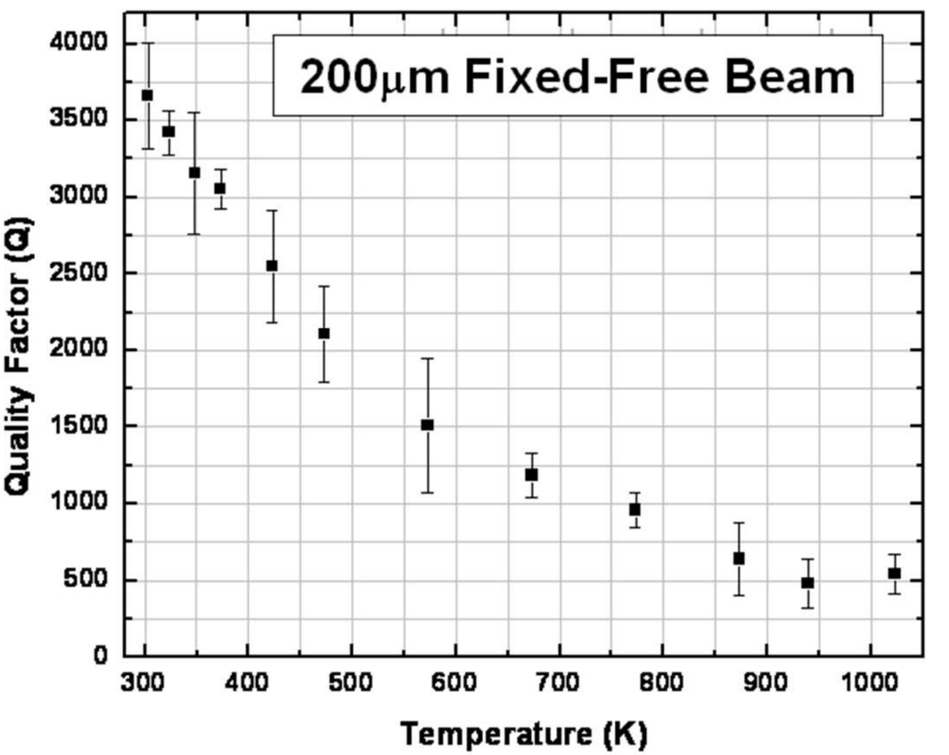
$$Q_{defect} = A\left[\frac{\omega\tau^*}{1+(\omega\tau^*)^2}\right]^{-1},$$

$$\frac{1}{\tau^*} = \frac{1}{\tau_0}\exp\left(\frac{-E_A}{k_B T}\right),$$

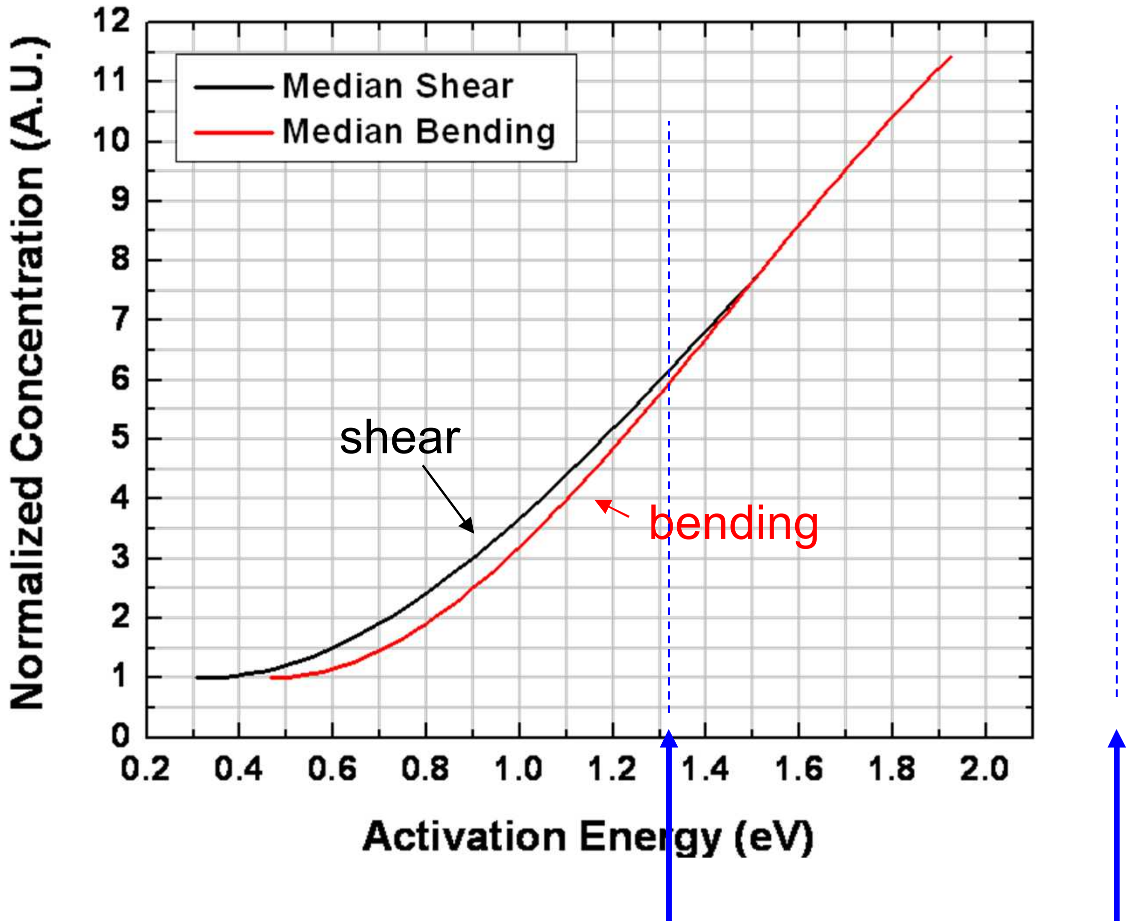
We use temperature-dependent studies of internal dissipation to measure the activation energies of the defects that give rise to mechanical dissipation.

fit to obtain Q





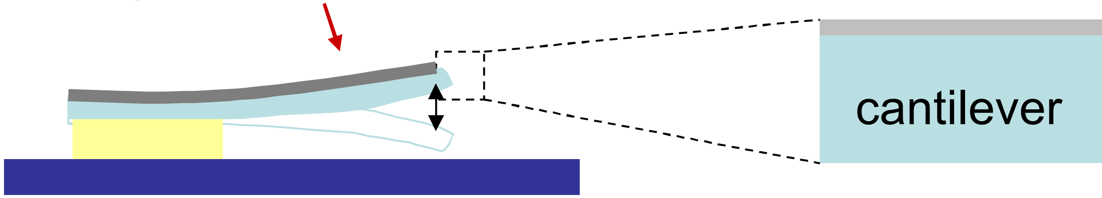
For amorphous carbon there is only a weak effect from the strain state.



Czaplewski, Sullivan, Friedmann, and Wendt, Diamond and Relat. Mater. (2006).

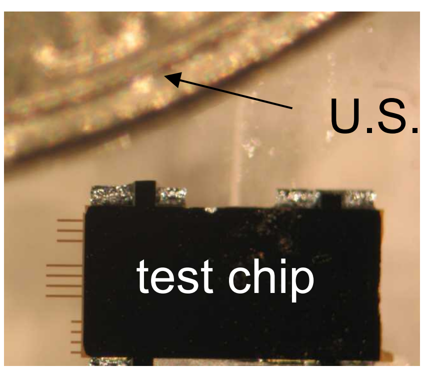
Example 2: Cantilever-based sensing.

look at shift in resonance frequency w/ corrosion

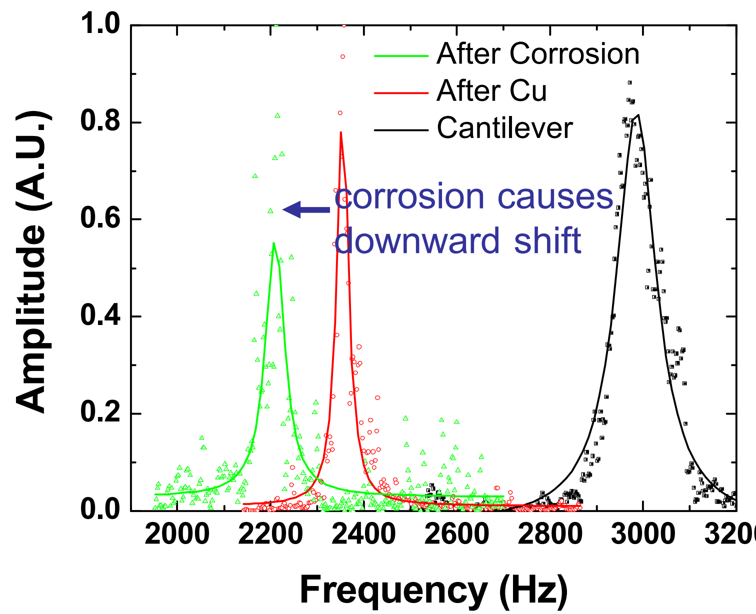


example of data from a Cu-coated cantilever before and after corrosion (<u>measured in air</u>)

test structure: Cu-coated cantilevers

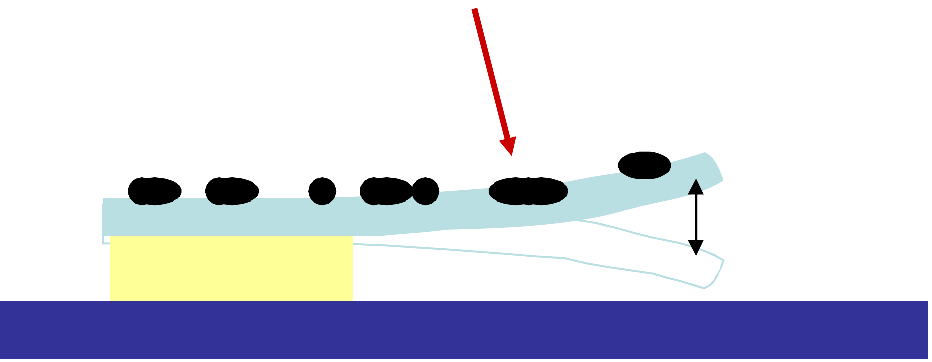


U.S. Nickel



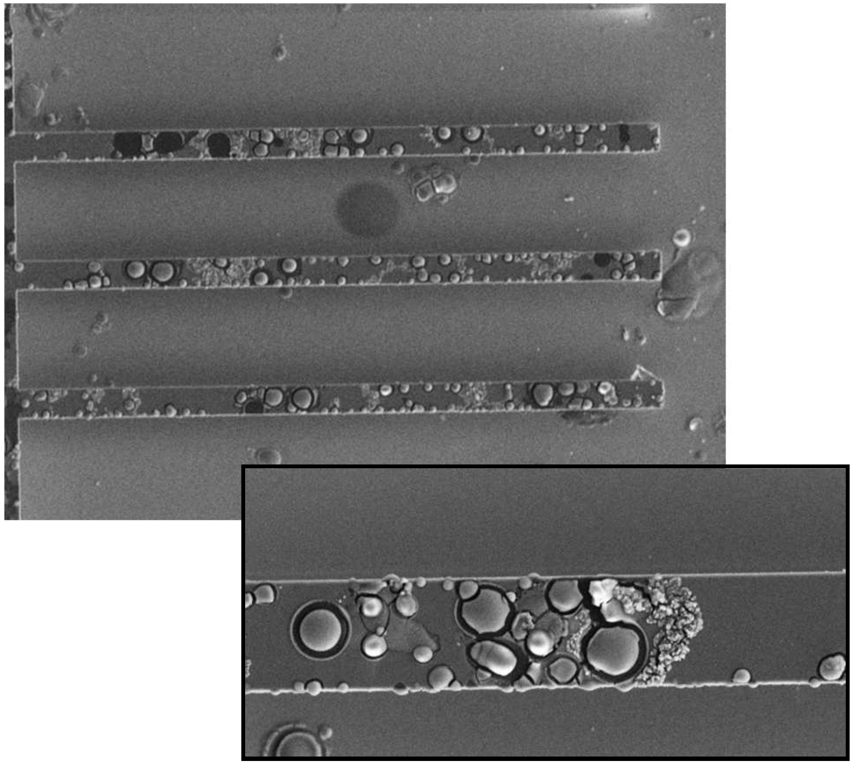
Arrays increase statistical response.

- Atmospheric corrosion of Al leads to localized corrosion sites.

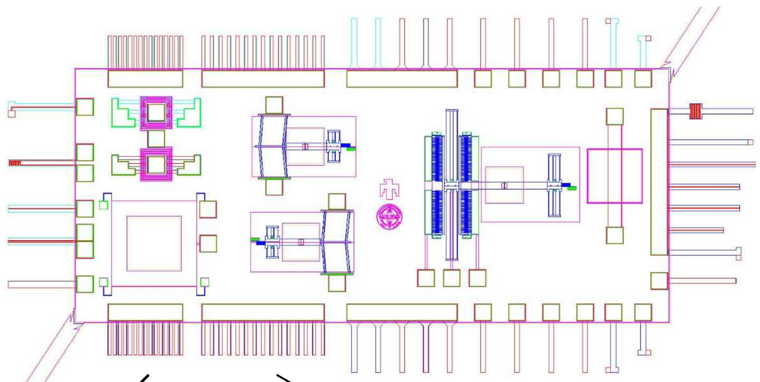


- Multiple sensors are needed to determine a statistical response.

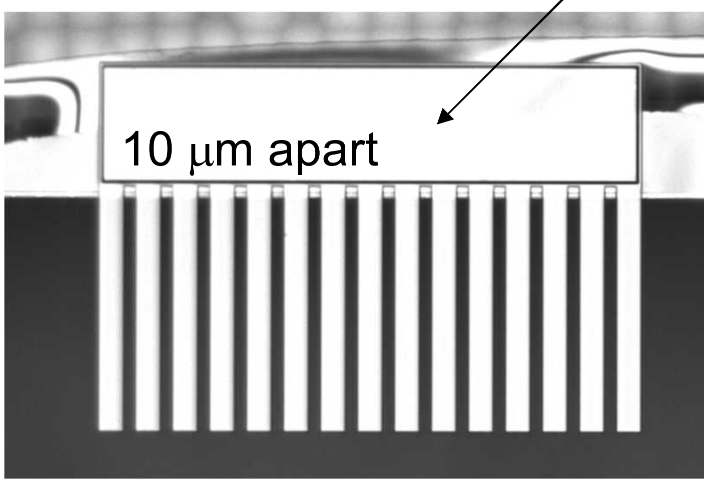
examples of Al atmospheric corrosion on Al-coated cantilevers



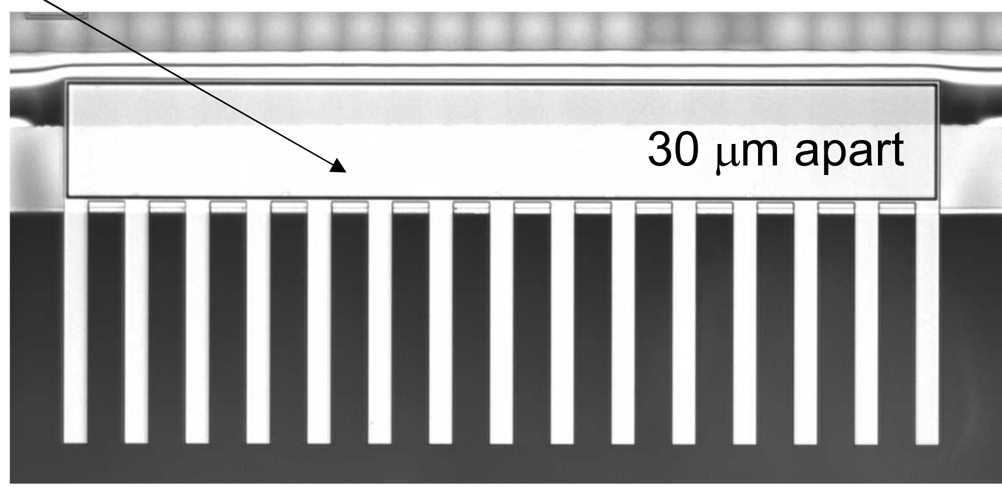
Example 3: Coupled oscillator arrays.



chip 1



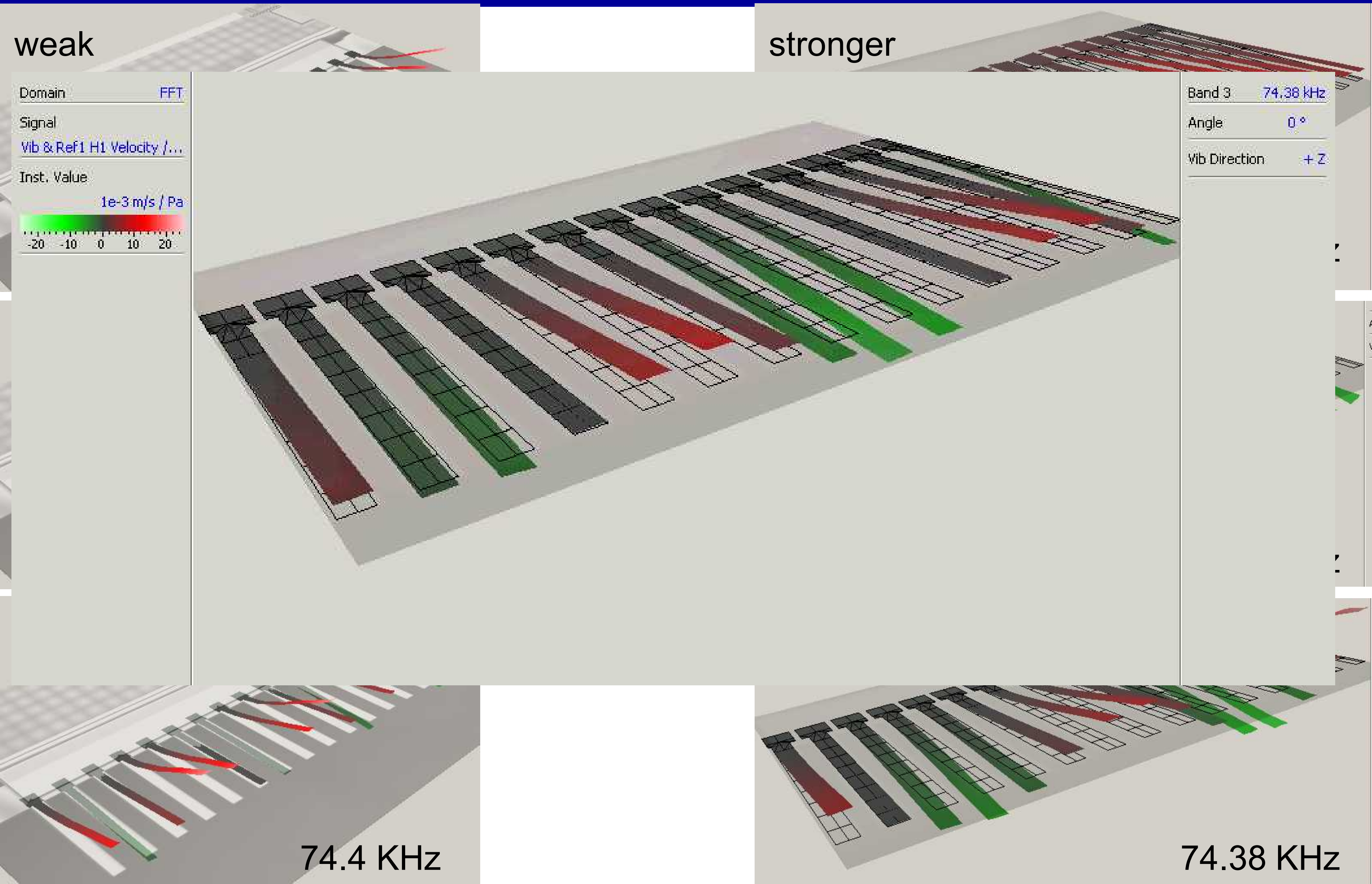
closely-coupled array



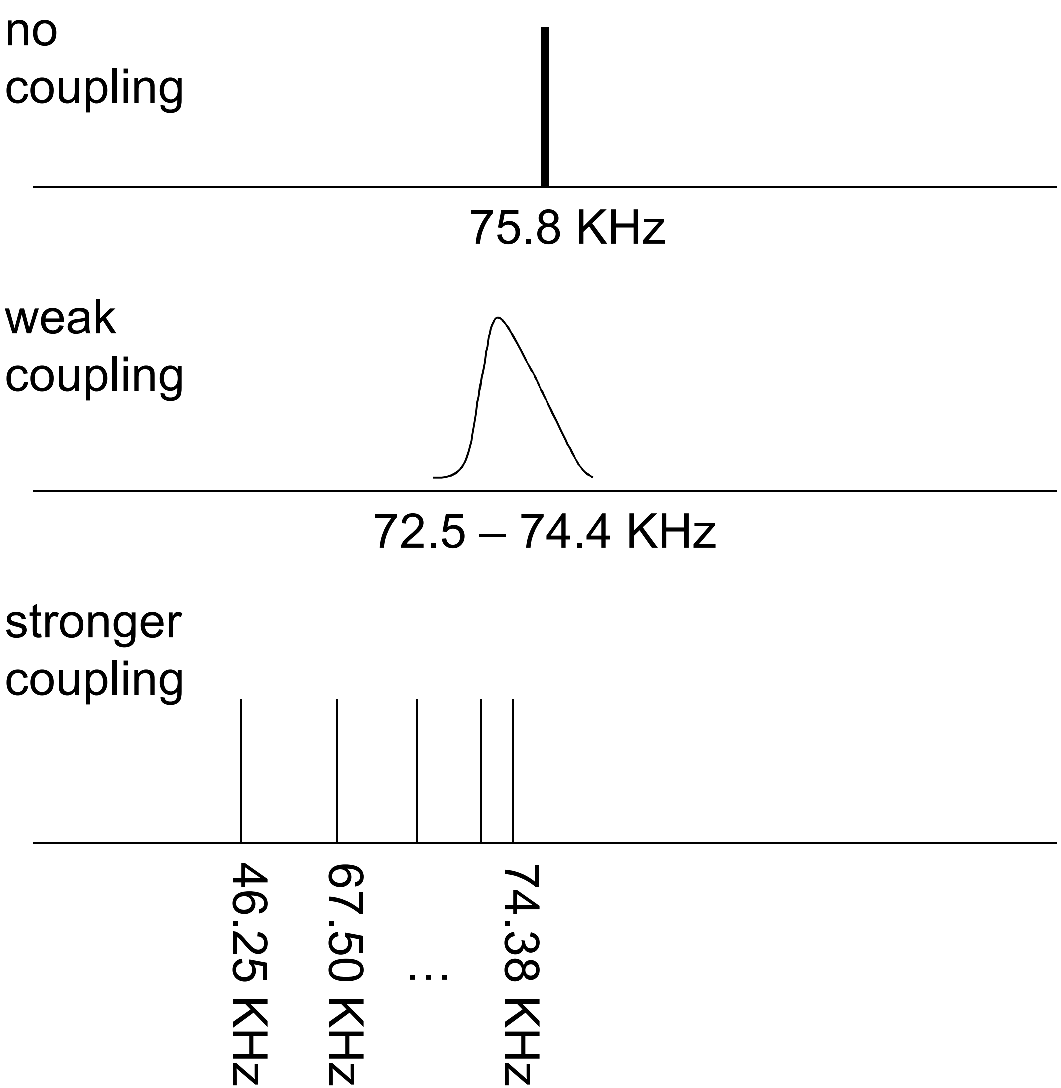
weakly-coupled array

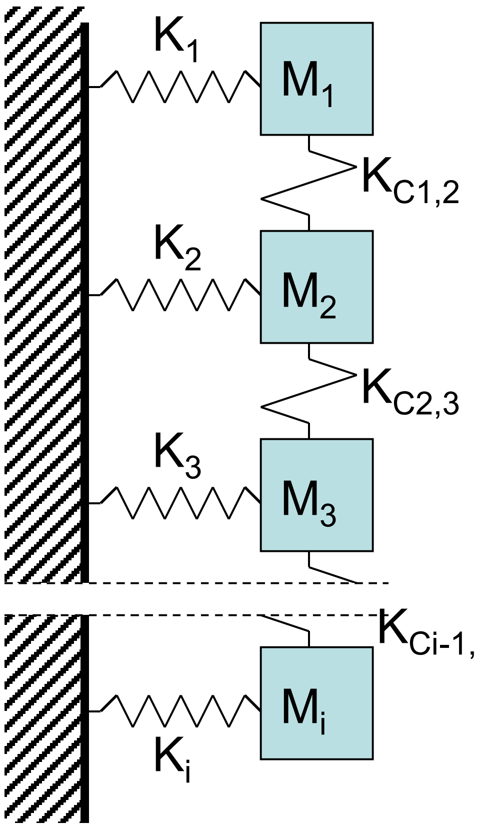
15 beams: 20 μm wide, 200 μm long

Increasing coupling breaks degeneracy of modes.



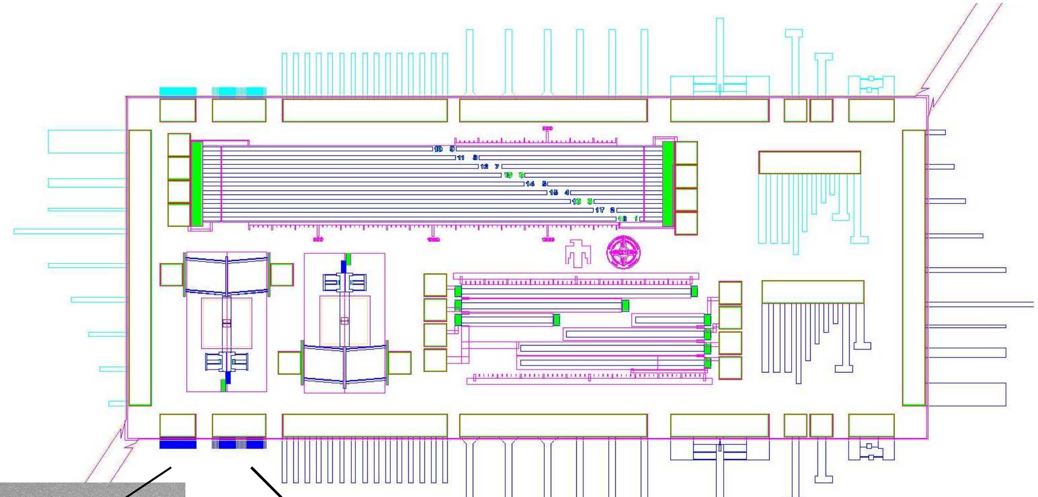
Increasing coupling breaks degeneracy of modes.

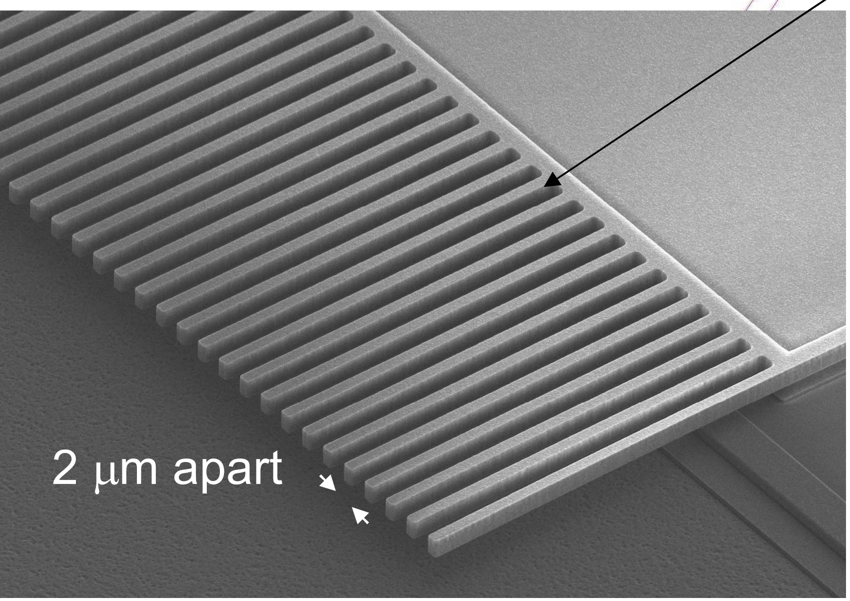


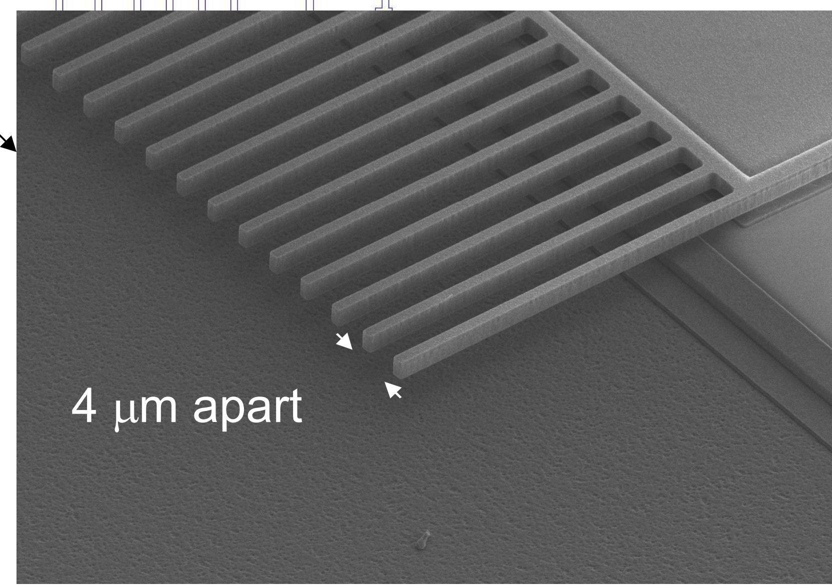


High density arrays show greater coupling.

chip 2

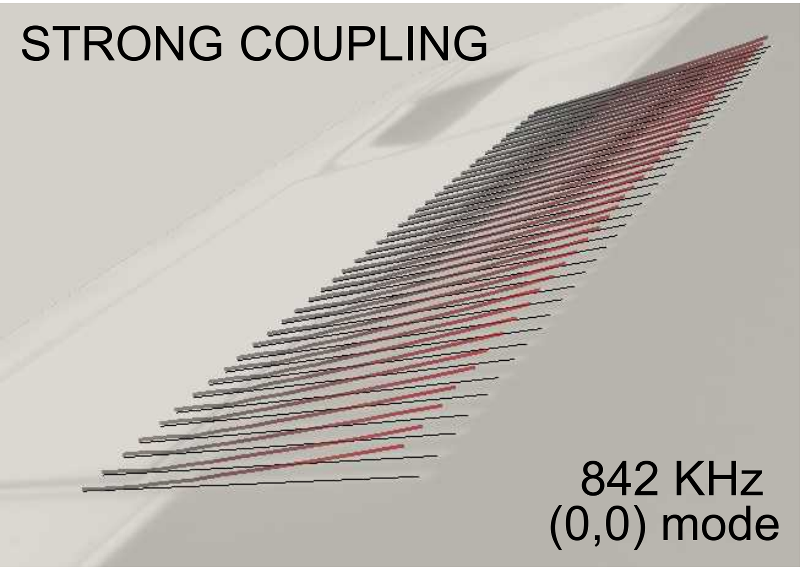




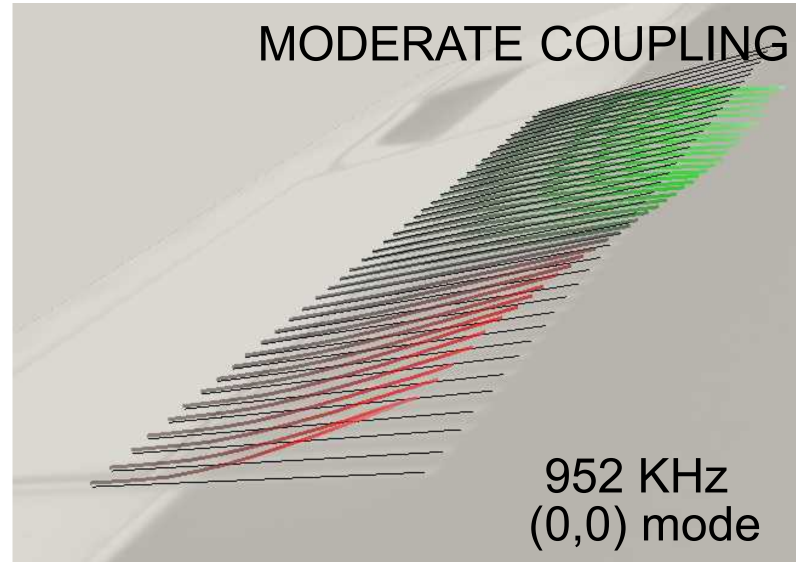


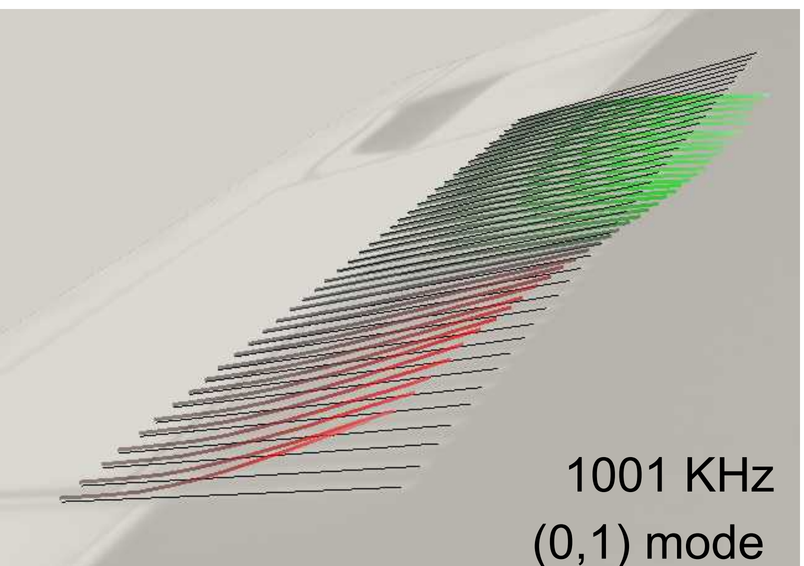
40 beams: 2 μm wide, 50 μm long

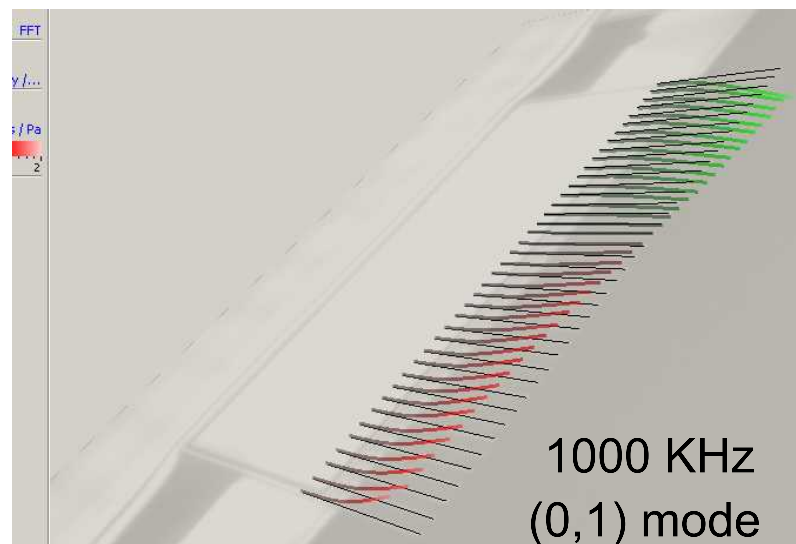
Strong coupling leads to a wide band of modes.



Laser doppler vibrometry data.

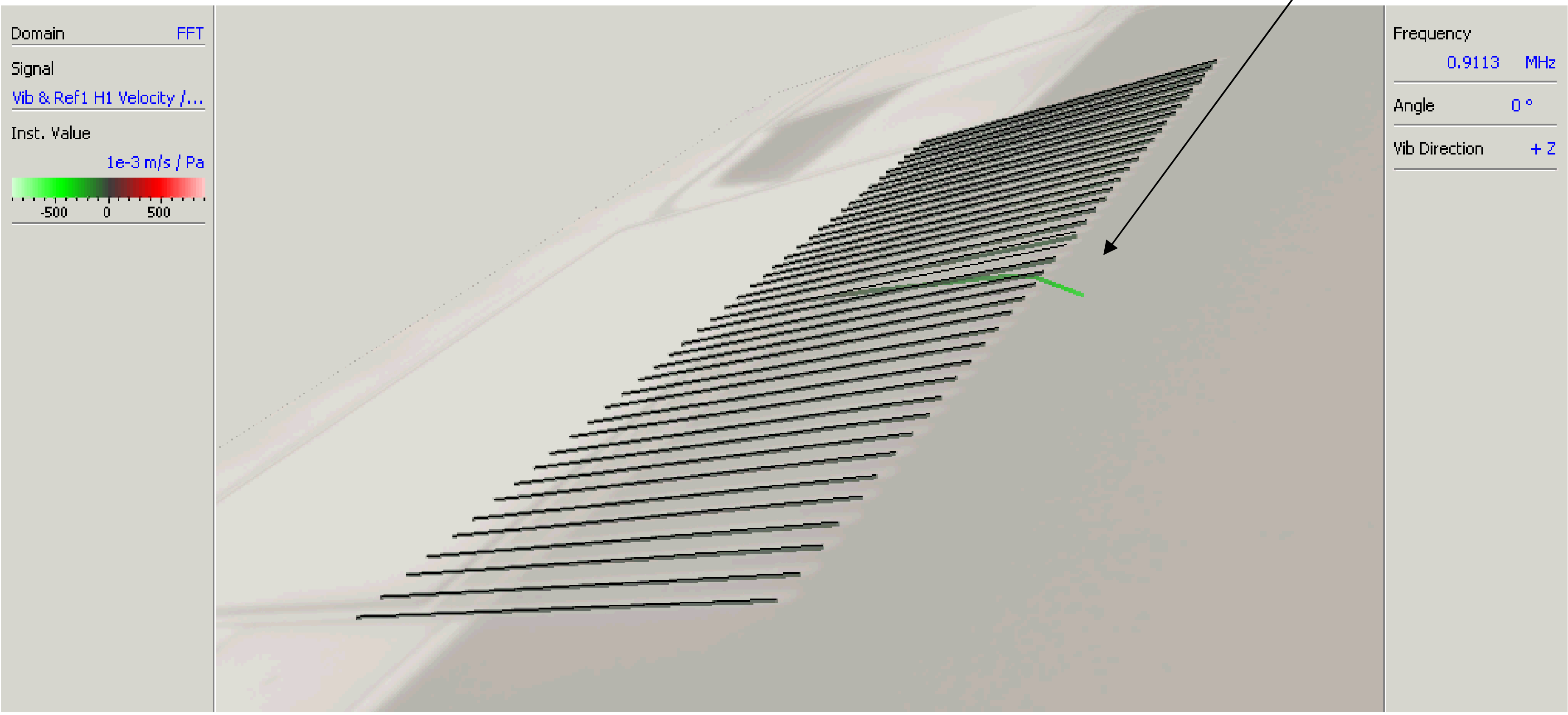






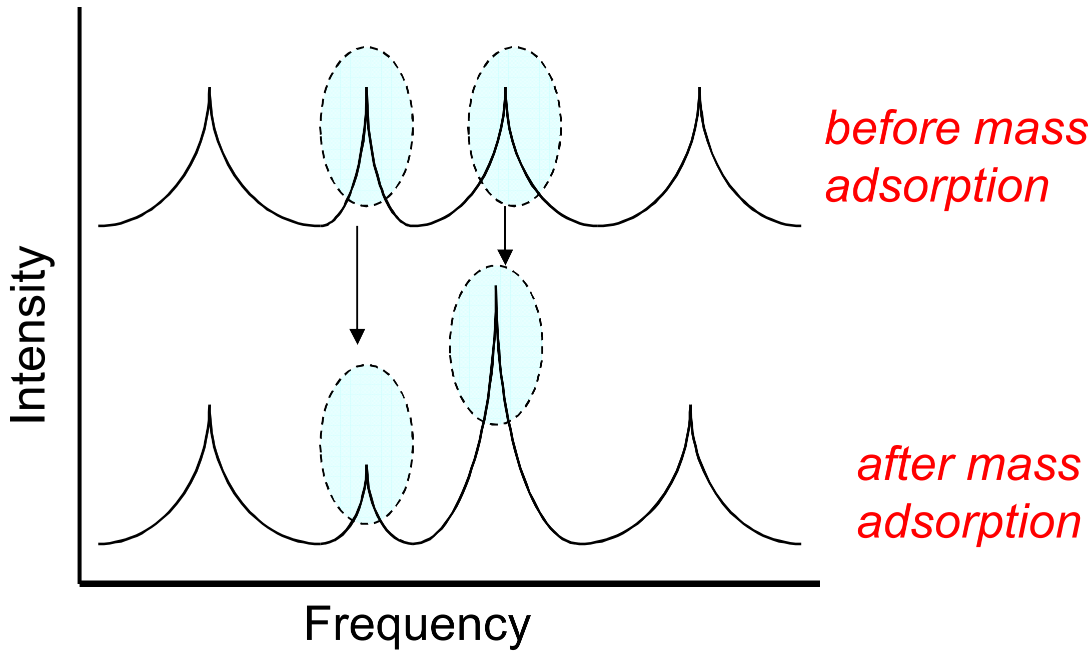
Strong coupling leads to localized modes.

Localized Mode at 911 KHz



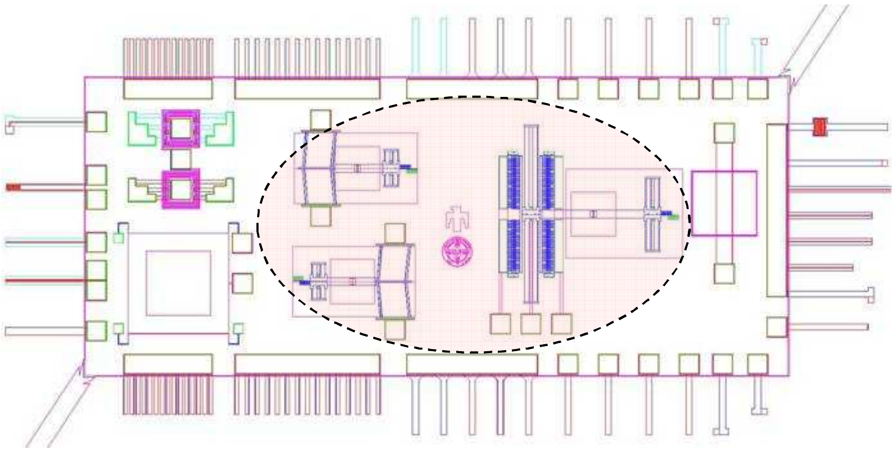
Laser doppler vibrometry data.

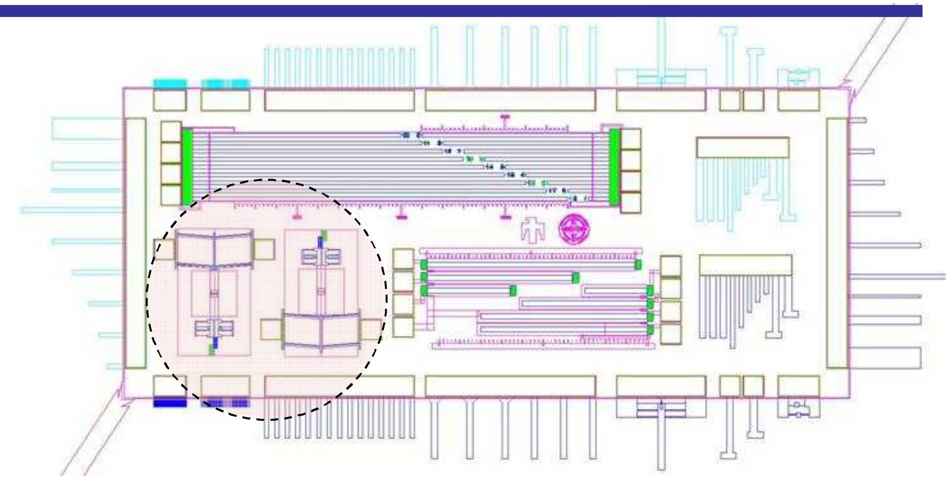
Changes in spectral response can be far more sensitive than changes in frequency.



*see for example, Spletzer, et al., APL **88**, '06.*

3. MEMS mechanics test structures (tension testing, fracture testing, *in situ* TEM)

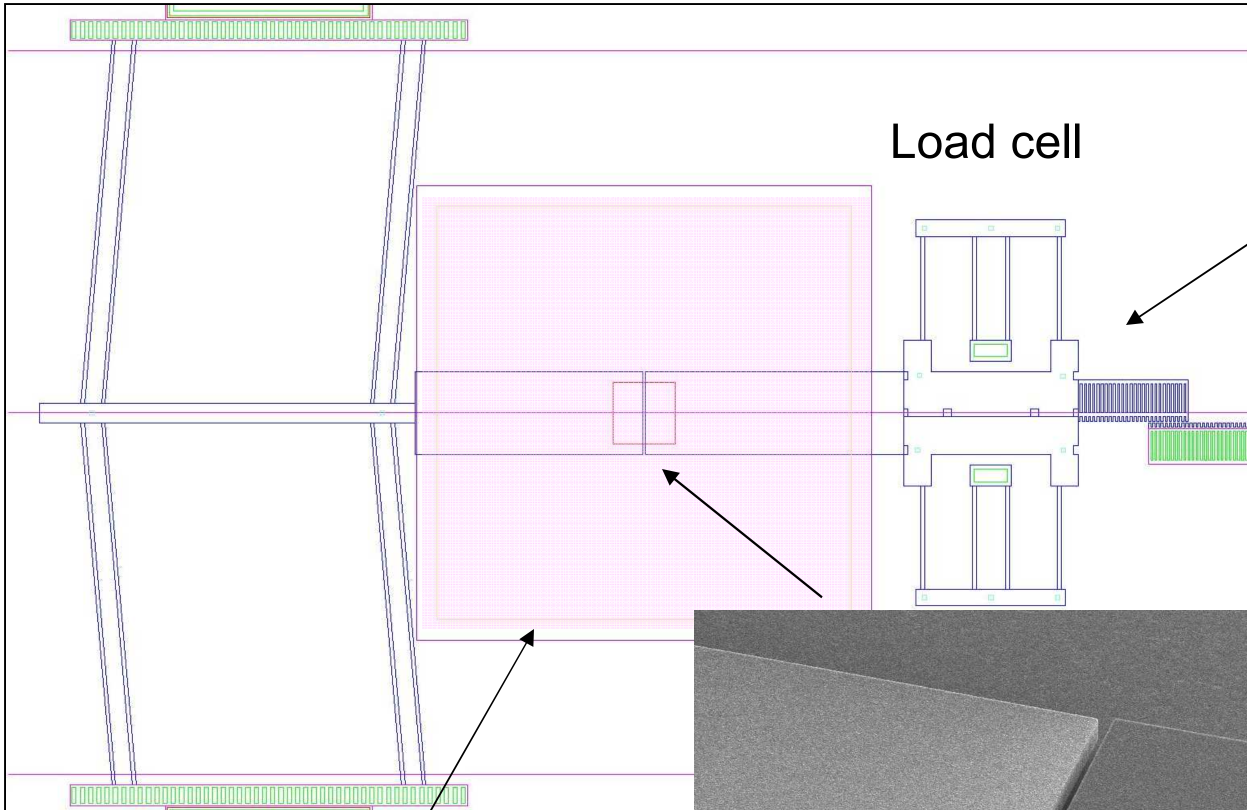




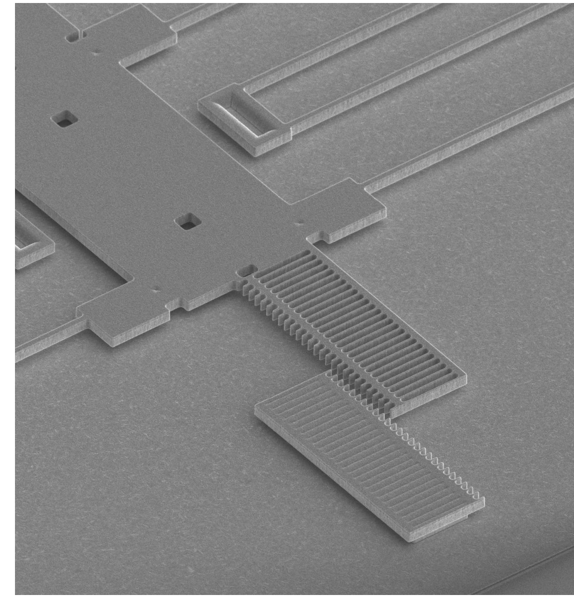
- MEMS actuators for in-plane loading of compliant materials: electrostatic comb drive (about 4 μN of force) and thermal actuator (about 80 μN of force at 2 μm displacement)

- Bosch etch hole enables *in situ* TEM measurements

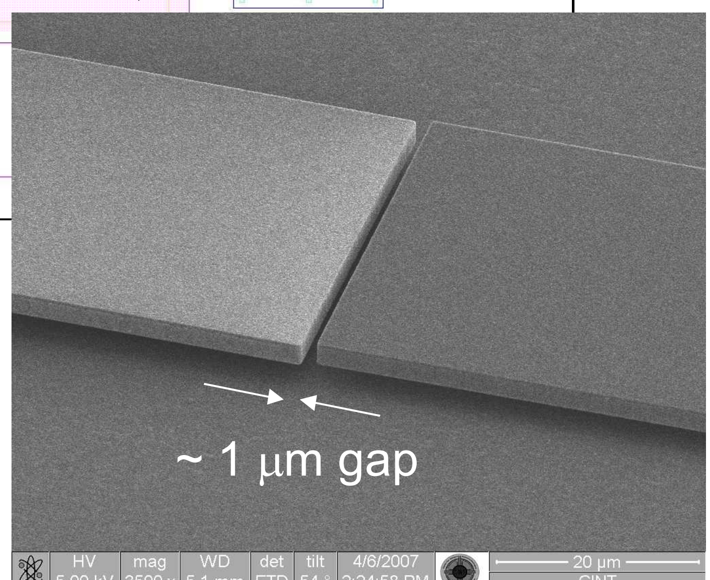
Thermal actuator (tensile loading).



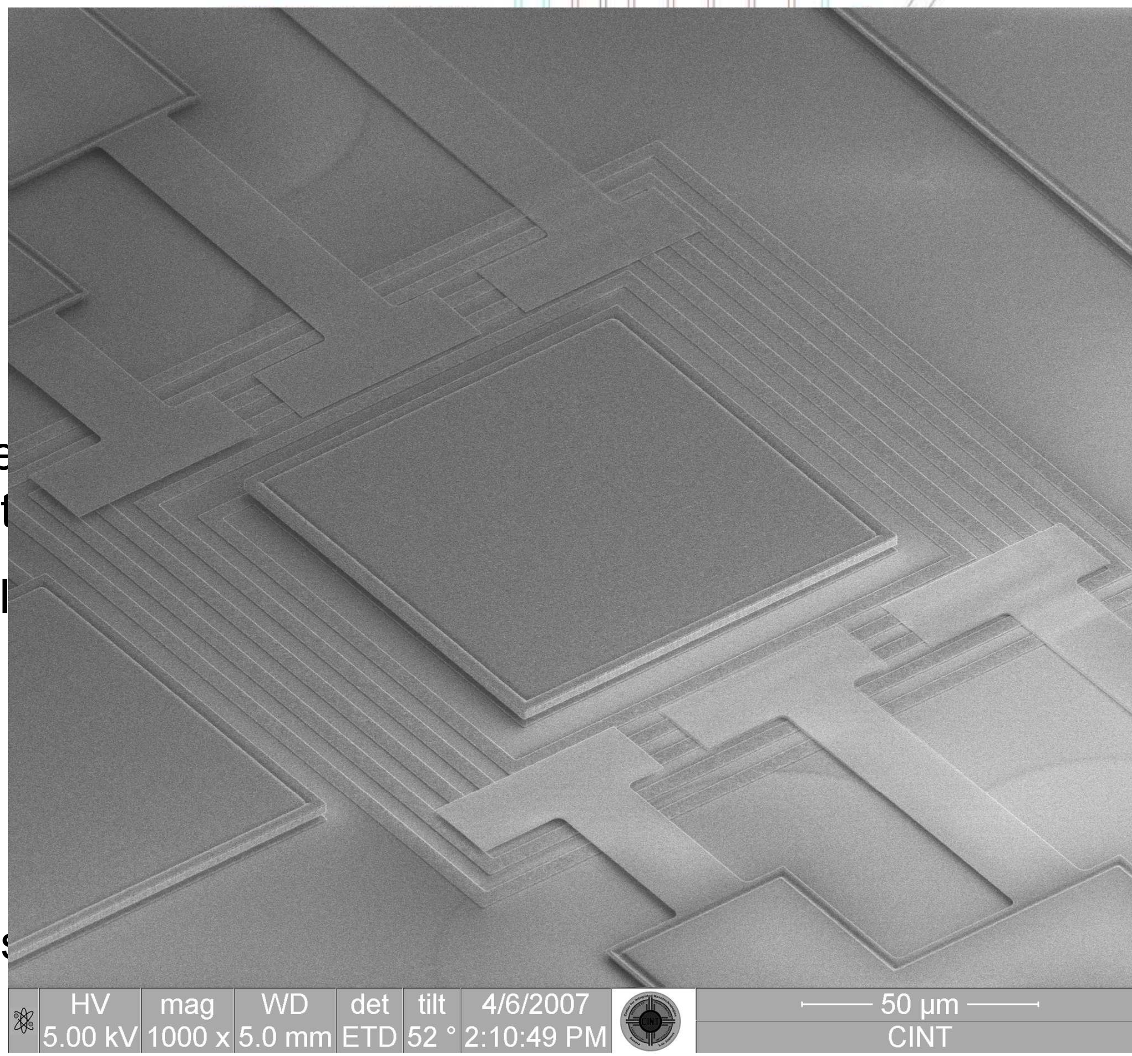
Load cell



thru-hole
for in situ
studies

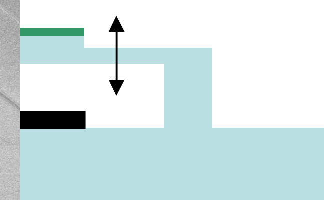


4. Magnetization studies



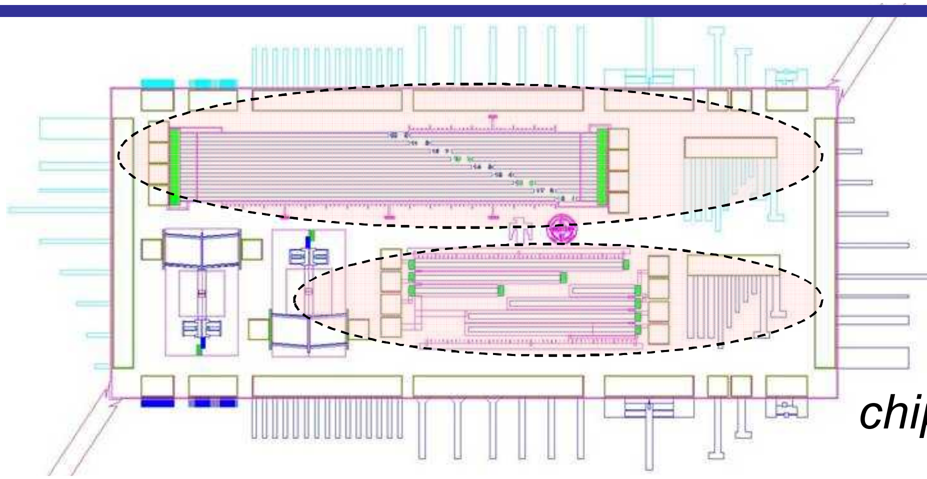
- specialize… testing of novel mat…
- floating pl…

test material



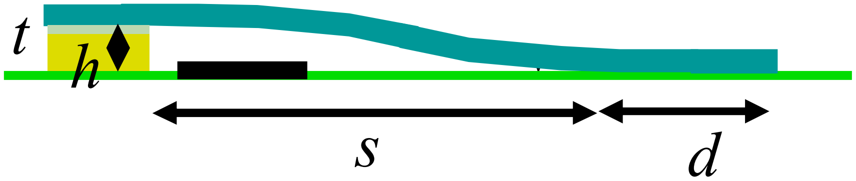
- Structures… …sional)

5. Surface studies (adhesion, stiction)



chip 2

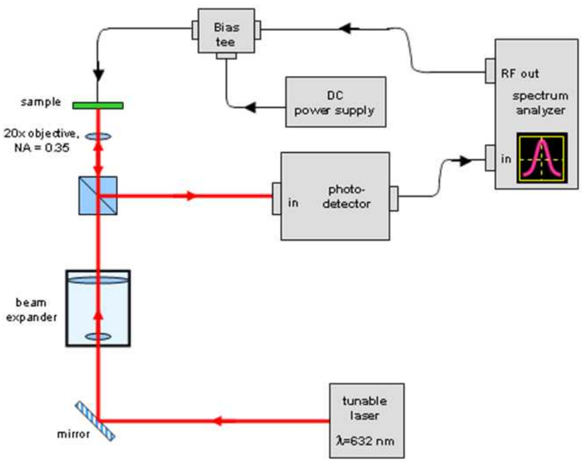
- cantilever beam arrays over a substrate with electrostatic actuation
- enables studies of surface adhesion, SAMS testing, stiction testing

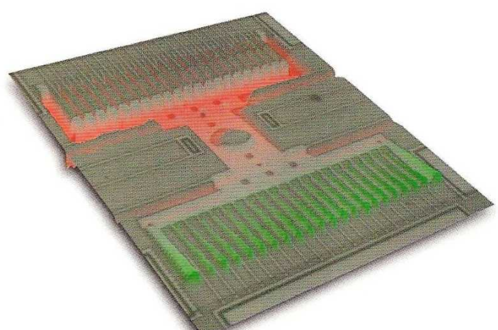


- can be used for capacitive detection of out-of-plane displacement (chem/bio sensing, magnetization, etc.)

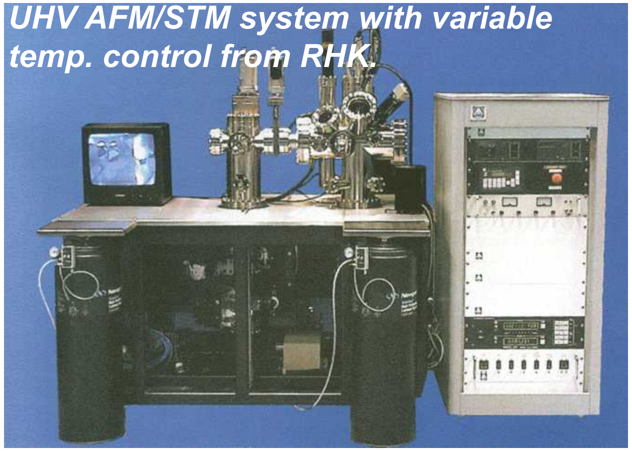
How to obtain/use/process the CADP.

- **The Cantilever Array Discovery Platform™ is *free* to Users with an approved User proposal (see cint.lanl.gov or contact jpsulli@sandia.gov)**
- **Experiments using the CADP can be performed at the User's home institute or at CINT**





Polytec MSA-400



UHV AFM/STM system with variable temp. control from RHK.

laser interferometry, scanning laser Doppler vibrometry, and AFM/STM at CINT