

MEMS and NEMS applications

There are a number of **current** and **proposed** applications for MEMS and NEMS.

These include:

- Integrated mechanical filters and switches
- Accelerometers
- Gyroscopes
- Optical switches and display devices
- Inkjet printers
- Data storage techniques
- Precision sensors

Plan to look at:

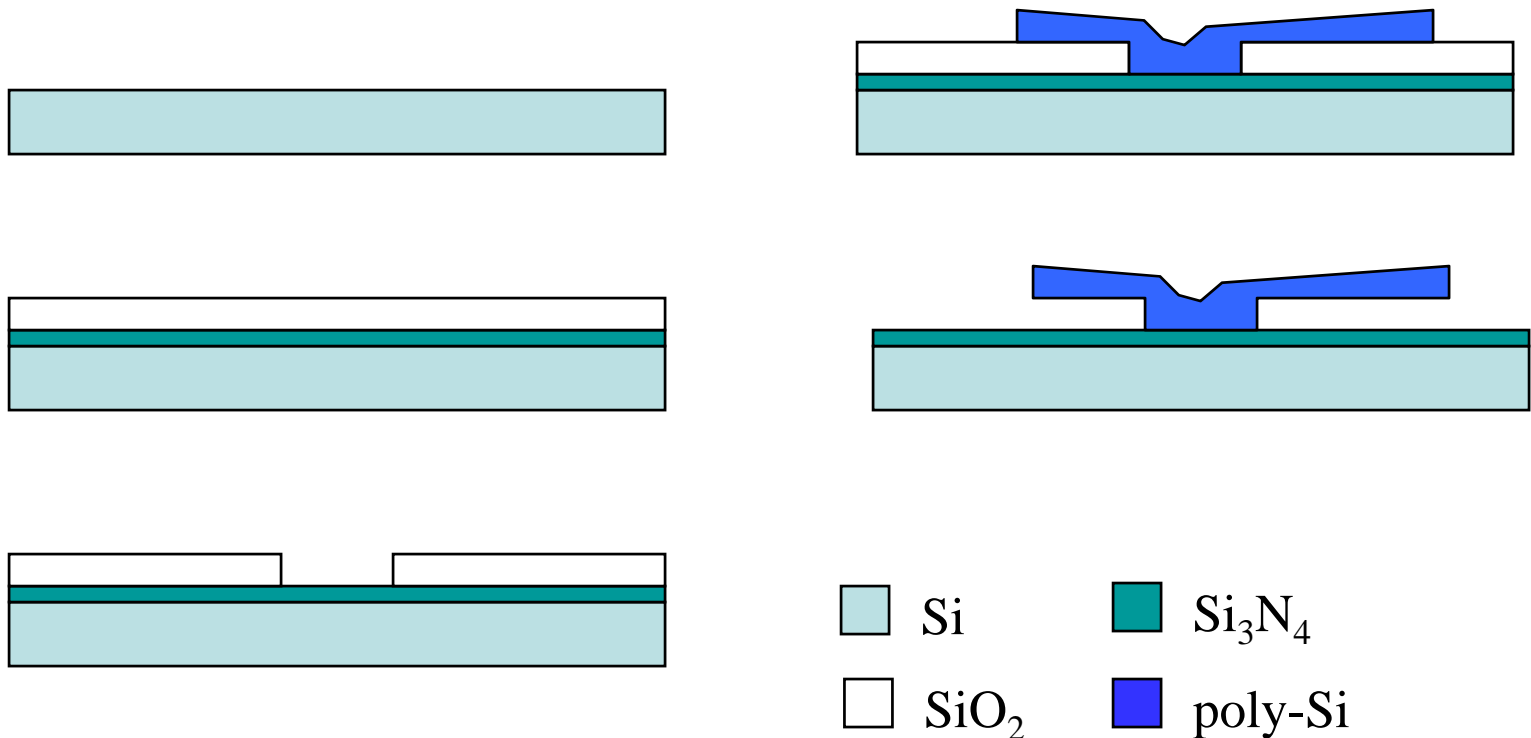
- Fabrication
- Enabling ideas + obstacles
- Applications

MEMS and NEMS fabrication

Basic idea of MEMS fabrication is to use same patterning and surface processing technologies as in the chip industry.

Objective: to build mechanical devices massively in parallel with small size, high reliability, easy interface with control circuitry.

Basic process:



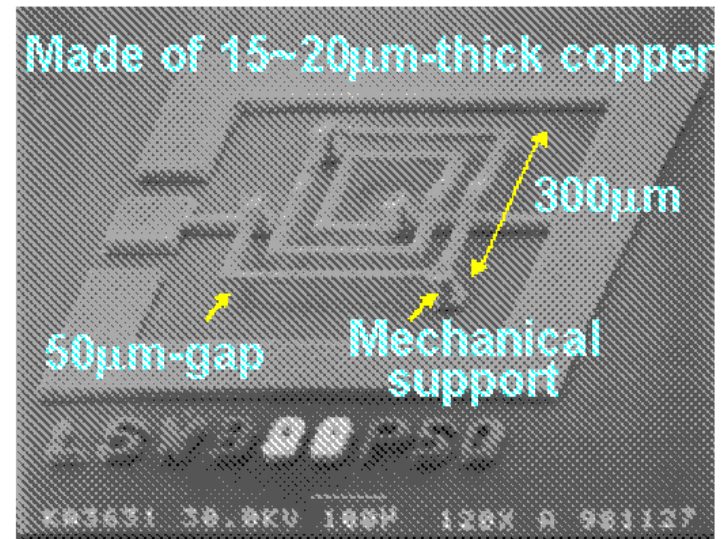
MEMS and NEMS fabrication

Additive processes

- Evaporation (metals)
- PECVD (SiO_2 , Si_3N_4 , poly-Si, SiC)
- Electrodeposition (metals)
- Spin-on (polymers, TEOS SiO_2)
- Wafer bonding

Pattern definition

- Photolithography
- Electron beam lithography



Wu, UCLA

MEMS and NEMS fabrication

Subtractive processes:

- “Wet” etches - HF to remove SiO_2 , KOH to etch Si in preferred directions.

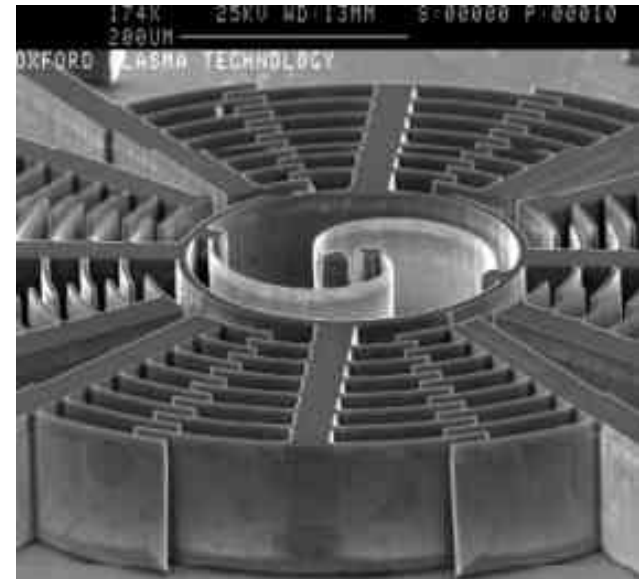
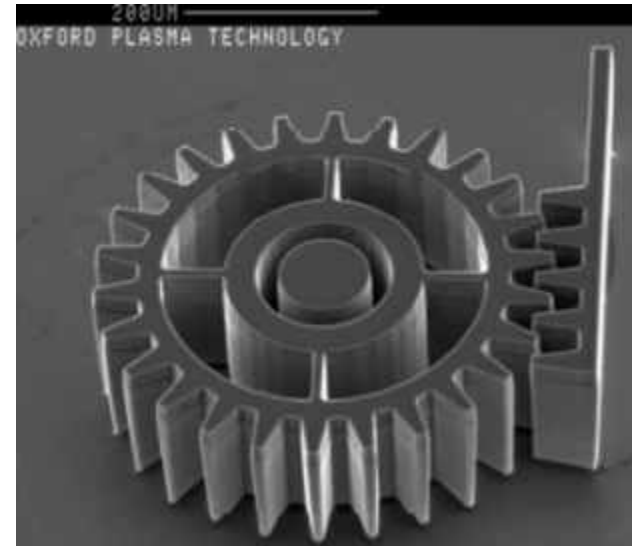
Quick, easy, but no directionality - need etch-stops

Surface tension issues!

- Reactive Ion Etching (RIE), Inductively Coupled Plasma (ICP)-RIE

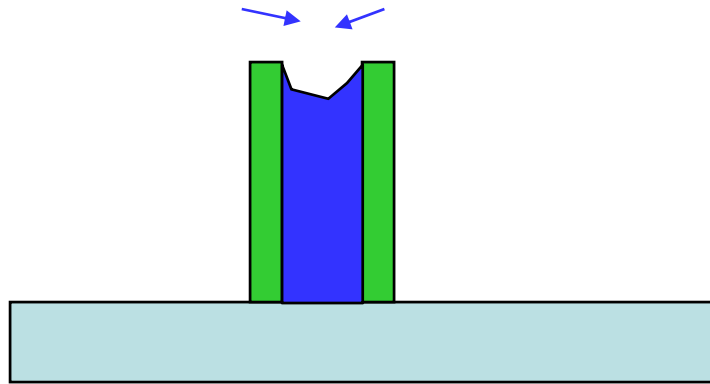
Highly directional, chemically selective, can be slow.

Vertical sidewalls, little or no undercut.



Supercritical drying

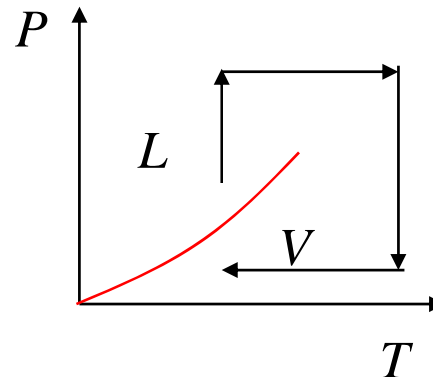
Surface tension forces can be large enough to be destructive, for nanoscale structures:



For water, surface tension at room temperature is 72 dynes/cm.

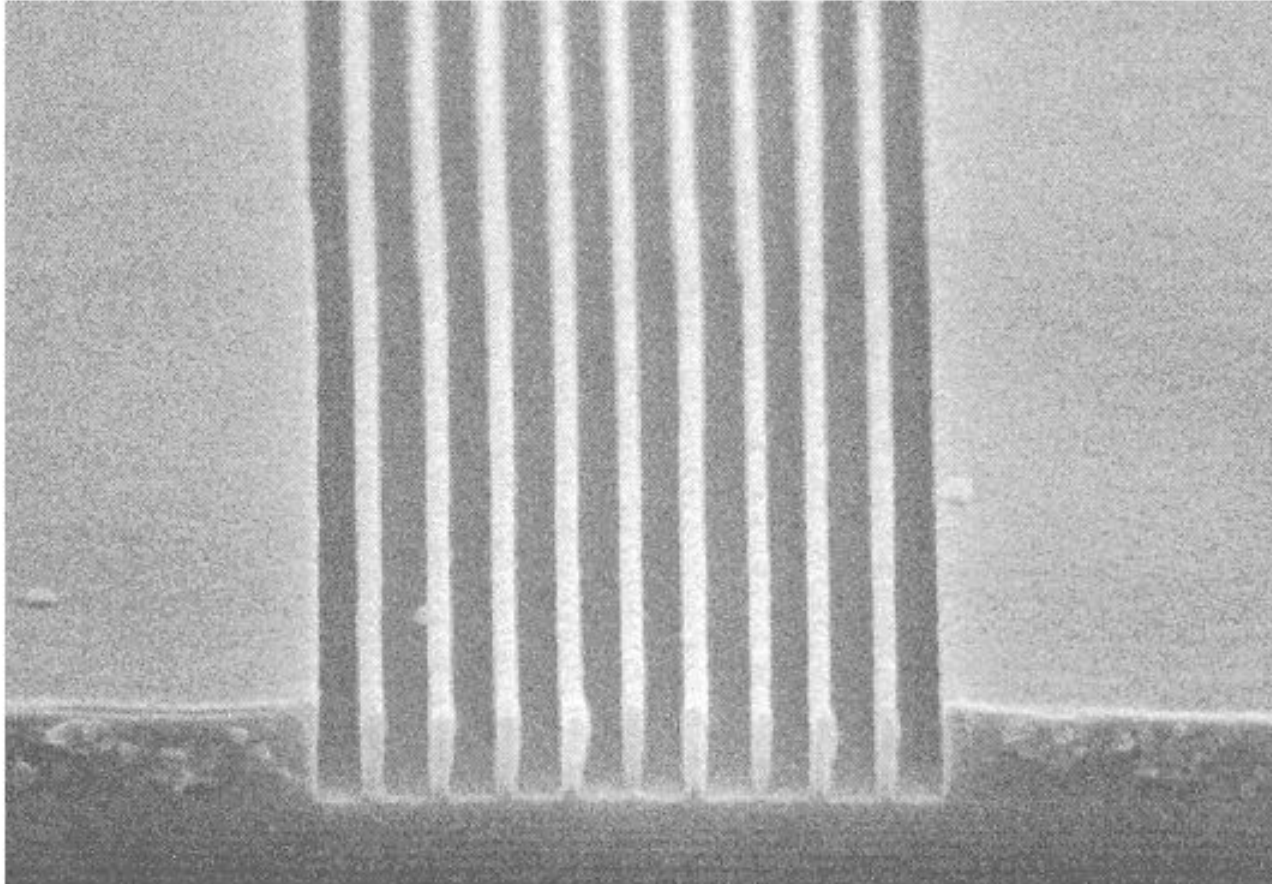
For photoresist ribs, the surface tension force can easily bend over and collapse the polymer.

Supercritical drying: go around critical point so that there's never a liquid-vapor interface....



Supercritical drying

Supercritical drying



Driving mechanisms

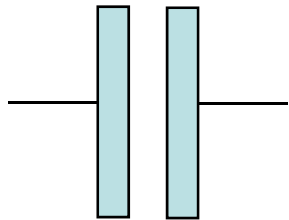
Several different means of driving MEMS devices:

- Mechanically

This is how AFM cantilevers work. Take clamped end of cantilever, and shake it up and down at the cantilever resonance frequency (done by piezos in AFM).

- Electrostatically

Have a metal electrode on the resonator, and another nearby. Run a dc + ac voltage difference between the two, and electrostatic attraction acts as the driving force.



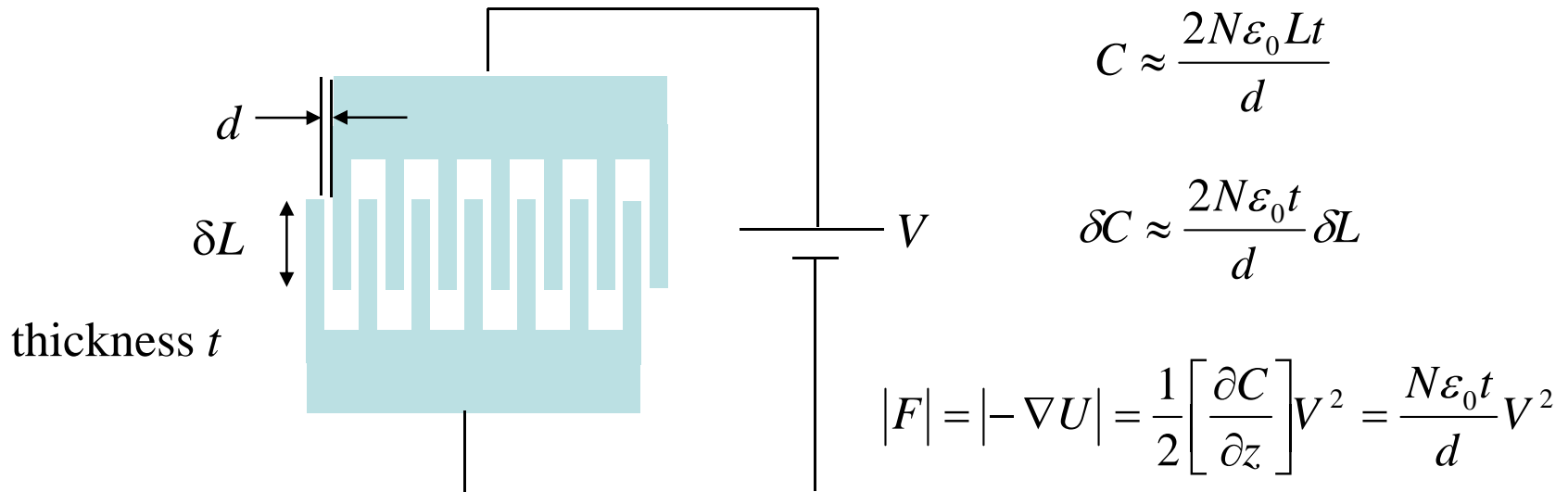
At given voltage, $F \propto C(V_{dc} + V_0 \exp(-i\omega t))^2$

$$\approx CV_{dc}^2 + 2CV_{dc}V_0 \exp(-i\omega t) + h.o.t.$$

Driving mechanisms

Electrostatics: “Comb drive”

Superior to straight parallel plate drive in one key respect: driving force is *independent of displacement* over a large range, for fixed voltage.



This lack of distance dependence more readily allows nice feedback control of positioning, for example.

Driving mechanisms

- Magnetostatically

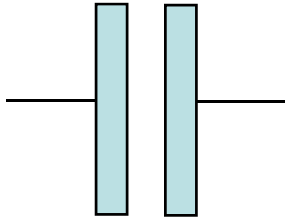
Attach a small piece of ferromagnet to a (soon-to-be) antinode of the resonator. Apply a time-varying magnetic field gradient from nearby, leading to a dipole-field gradient force.

- Magnetodynamically

Have a current-carrying wire on the resonator. Place the resonator in a large background dc magnetic field. By alternating the current in the wire, can drive resonator using Ampere's law forces.

Sensing mechanisms

Most common displacement sensing approach is *capacitive*.



Consider charging up these plates through a large resistor R , so that the characteristic time RC is much longer than the timescale of the motion you want to detect.

Now move the plates a small amount. $\delta Q = 0 = C\delta V + V\delta C$

$$\frac{\delta V}{V} \sim -\frac{\delta C}{C} \sim \frac{\delta d}{d}$$

So, voltage change is given by bias voltage times fractional change in plate spacing. For a bias of a few volts and a spacing of 100 nm, and knowing that it can be relatively easy to measure microvolts, we see that displacements of a fraction of an Angstrom are detectable.

Disadvantage: needs large resistors incorporated into setup.

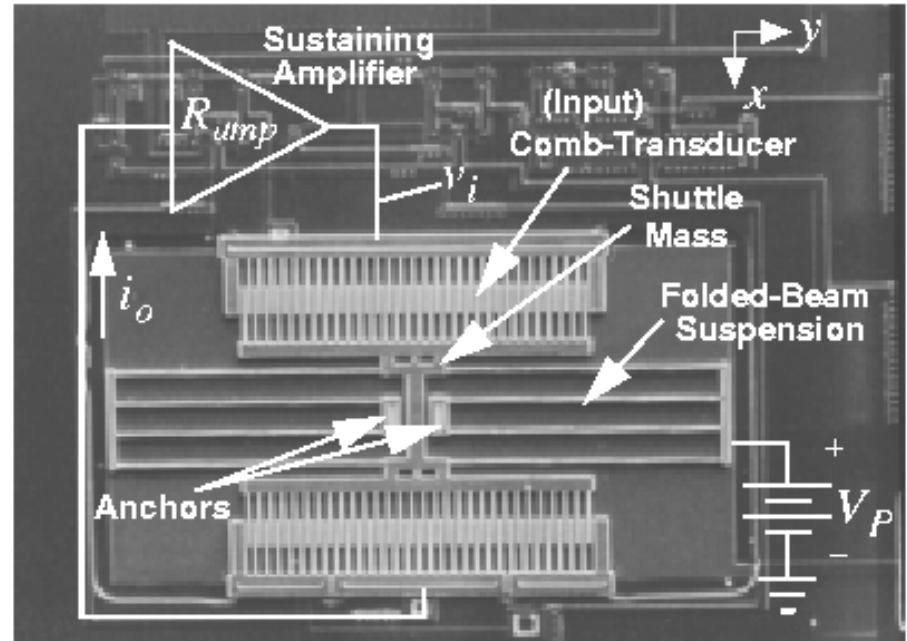
Sensing mechanisms

Nguyen, Proc. IEEE, 1997

Alternately, operate at fixed voltage bias between the resonator and a sense electrode.

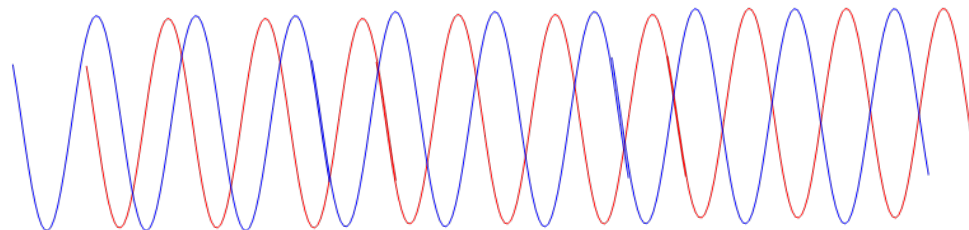
Changing the capacitance leads to a changing current:

$$Q = CV \rightarrow i = V_{dc} \frac{\partial C}{\partial z} \frac{\partial z}{\partial t}$$



To run the device as an oscillator, this signal is amplified and applied back to the drive electrode.

Remember, at resonance, the drive signal should be $\pi/2$ out of phase with the displacement. That is automatically achieved with this technique.



Sensing displacements

Straight capacitance measurement

Can use a bridge technique to compare two capacitances to a part in 10^7 relatively easily. Assuming sensible numbers, again one finds displacement sensitivity \sim fractions of an Angstrom.

Piezoresistive sensing

Generally, any material whose resistance changes with strain is piezoresistive.

Ex: doped silicon – band structure alters slightly under strain (change in mobility with lifting of valley degeneracy).

Tunneling

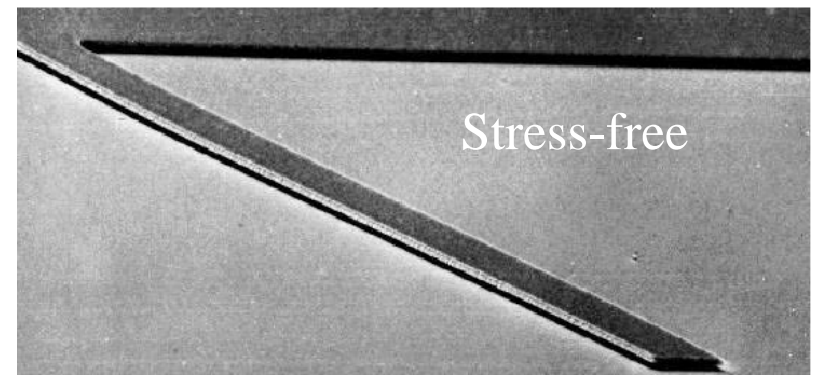
Tunneling current is an exponentially sensitive transduction method, but requires great stability and very small separations to be useful.

Internal film stresses

PECVD poly-silicon (and other materials) often are deposited in a manner that leads to internal film stresses.

This causes bowing after the release step.

These can often be relieved by careful process control and annealing.

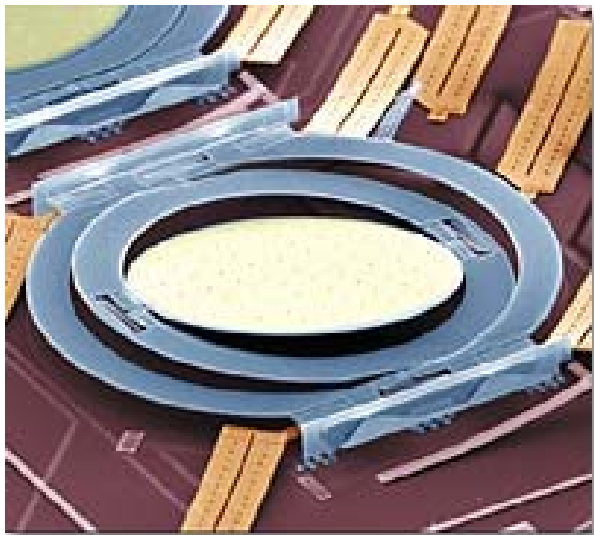


Internal film stresses

Stresses can be engineered deliberately into metal films.

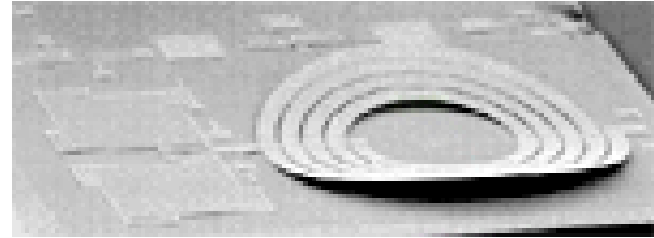
For example, Q of LC resonators on chips can be much higher if the inductor is far from the doped substrate.

Solution: upon release, metal curls up away from wafer.

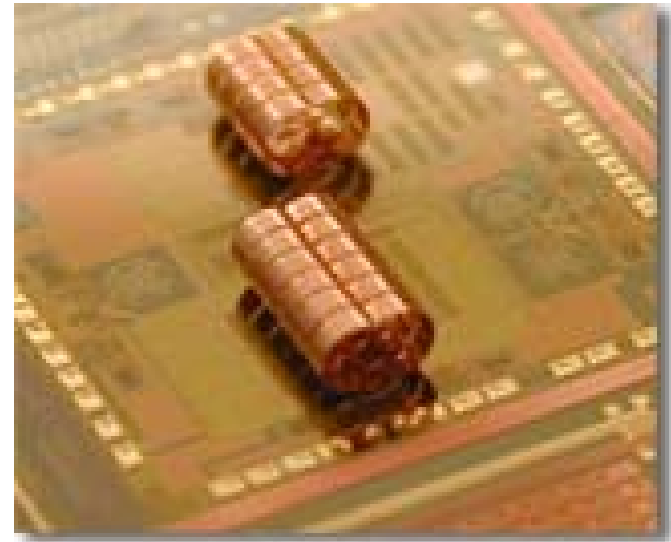


Lucent

Lucent



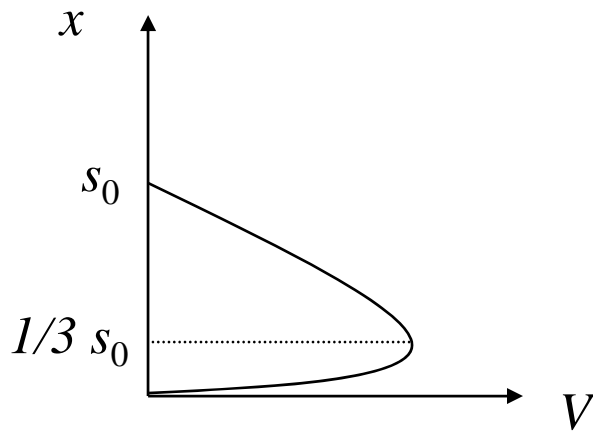
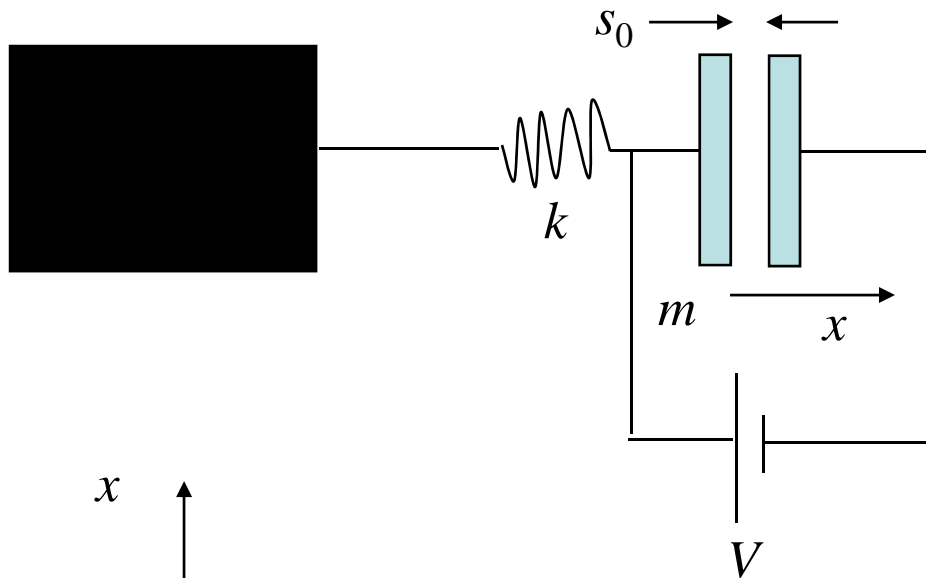
Xerox



Similarly, use prestressed metal structures to lift components off wafer surface for more movement clearance.

Electrostatic instability

Also called “pull-in” or “snap-down” instability.



$$F = \frac{1}{2} \frac{\epsilon_0 A V^2}{(s_0 - x)^2} = kx$$

$$V = \sqrt{\frac{2kx}{\epsilon_0 A}} (s_0 - x)$$

$$\frac{\partial V}{\partial x} = 0 \rightarrow x^* = \frac{1}{3} s_0$$

$$V^* = \sqrt{\frac{8ks_0^3}{27\epsilon_0 A}}$$

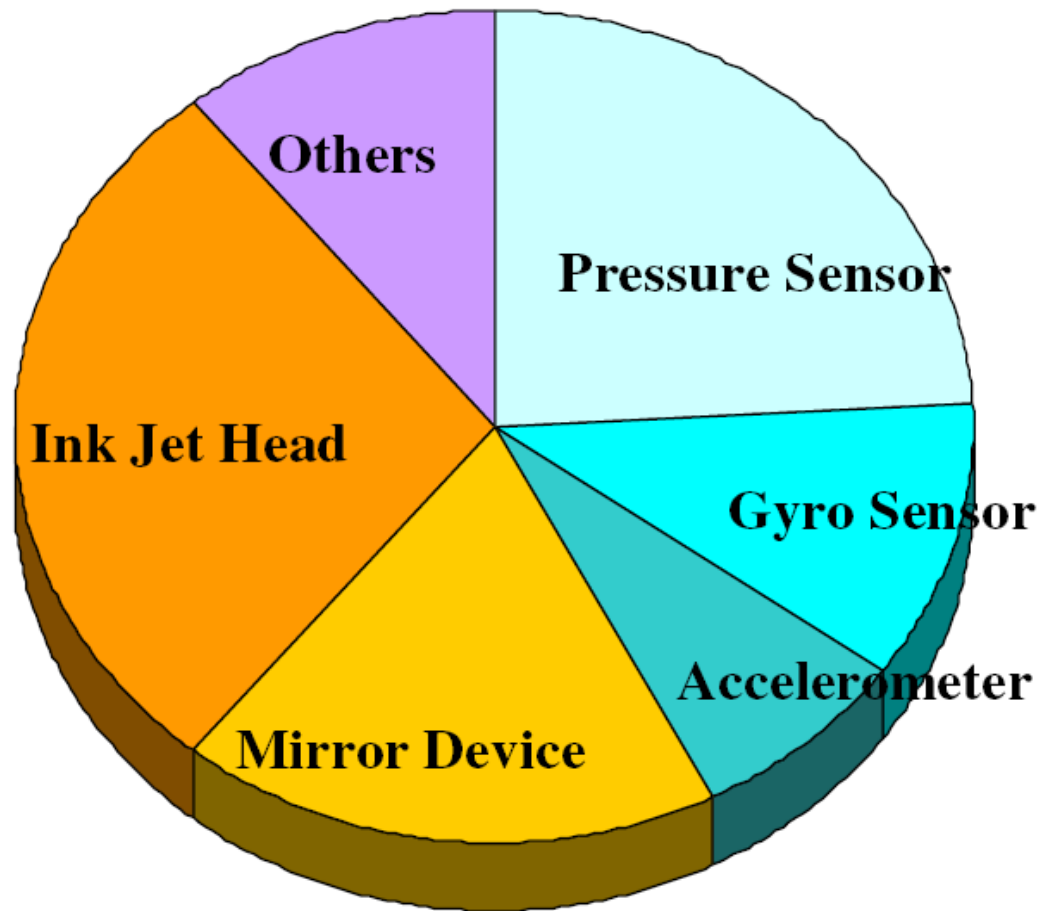
Electrostatic instability

The real downside of the snap-down instability is that structures can remain stuck permanently.

Short-range forces (Van der Waals, hydrogen bonding, etc.) can be larger than what can be overcome by reverse biasing.

Solutions:

- Live with restricted movement range
- Do on-chip charge control to do feedback. Must be on-chip because capacitance of wirebond pads acts like charge reservoir when going off-chip.
- Take advantage of nonlinearity in force with displacement to have an effective tunable spring constant (and therefore tunable resonance frequency).



Total = \$5.4 billion

Fig. 1. 2005 MEMS market.

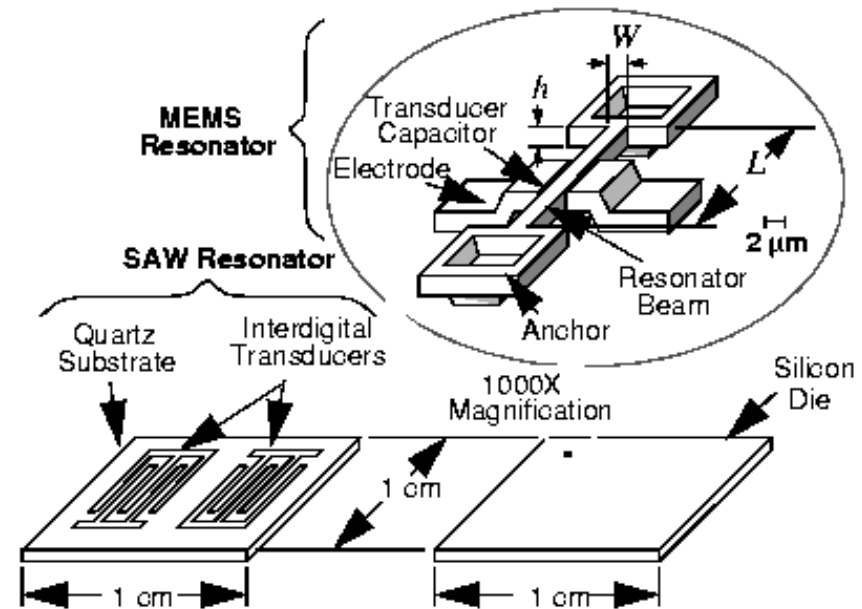
Filters

Nguyen, Proc. IEEE, 1997

One can imagine using any decent resonator as a filter.

Consider sending a broadband high frequency signal into the drive of a resonator.

The Q of the resonator picks out only the component at the natural frequency, which is then detected at the output.



Advantages of MEMS or NEMS filters over competing technologies:

- Much smaller footprint than SAW devices.
- Comparatively easy direct integration with drive electronics (doesn't require piezoelectric substrate).
- High Q s and reproducible frequency response better than all electronic filters.

Filters

Nguyen, Proc. IEEE, 1997

What if we want a *bandpass* filter with larger bandwidth, not just a single frequency?

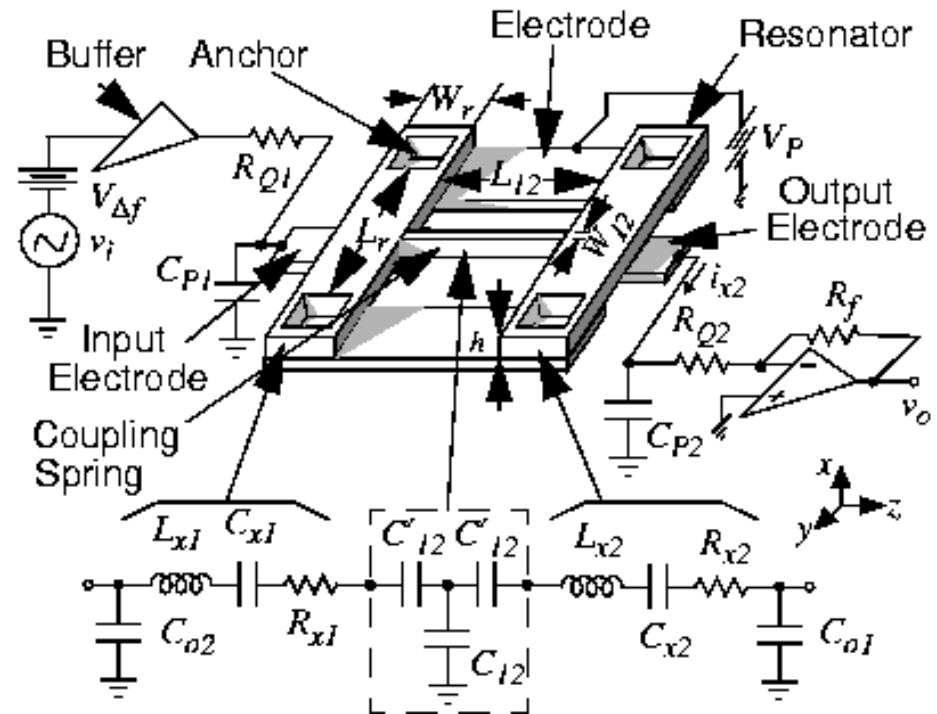
Start with two identical resonators.

Couple them weakly via a “coupling spring.”

Result is completely analogous to what we’ve seen many times in quantum:

Coupled resonator system has two resonances centered in frequency around the original (isolated case) frequency.

- Bandpass center defined by individual resonators.
- Bandwidth set by strength of coupling.



Filters

Nguyen, Proc. IEEE, 1997

Again, what's the advantage?

- Much easier than trying to make high Q multipole LC filters on-chip.
- Footprint is small, and if anything gets smaller with higher frequencies.

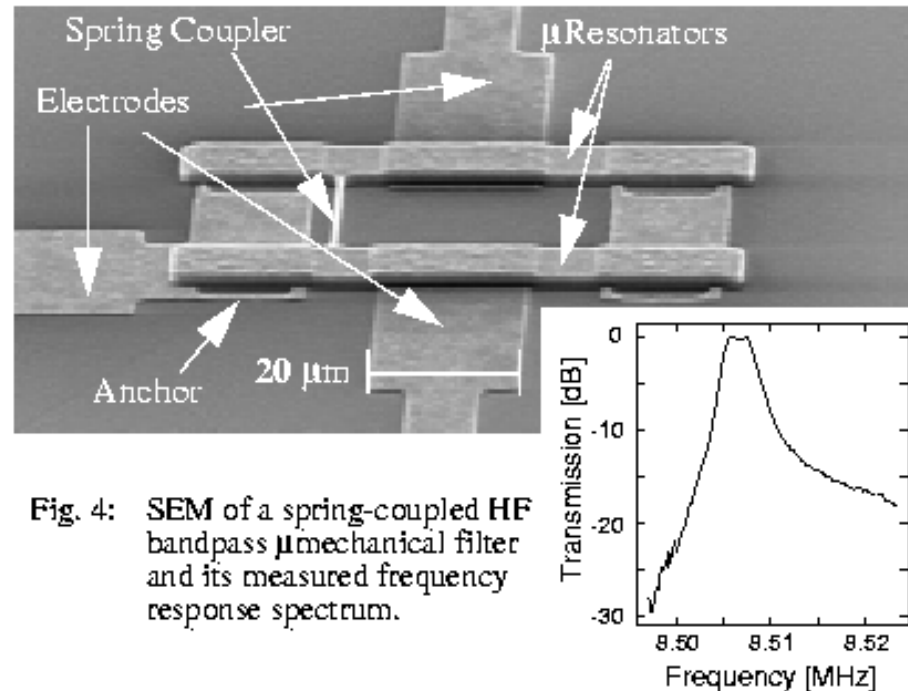


Fig. 4: SEM of a spring-coupled HF bandpass μ mechanical filter and its measured frequency response spectrum.

Applications of these gadgets: wireless technology.

Accelerometers

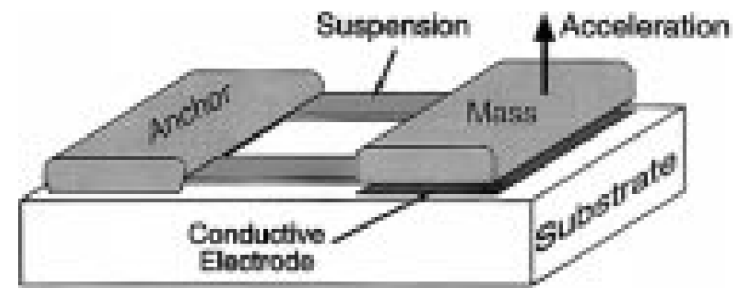
Yazdi *et al.*, IEEE 1998

Inertial sensors are a broad class of MEMS products.

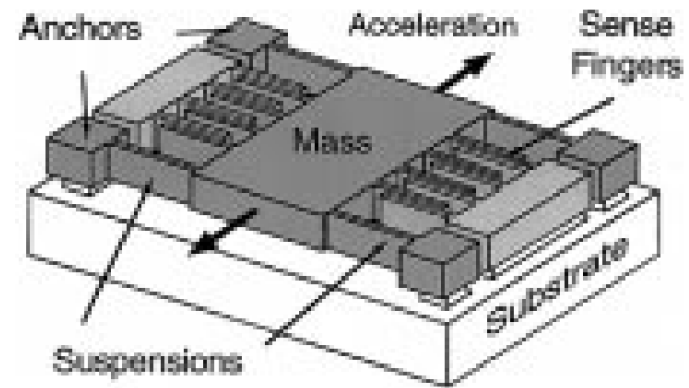
Basic idea: have a test mass suspended or held laterally by micromachined springs.

Under acceleration, in the accelerating frame the test mass experiences inertial forces and torques.

Sense displacements using the methods outlined above.



(a)

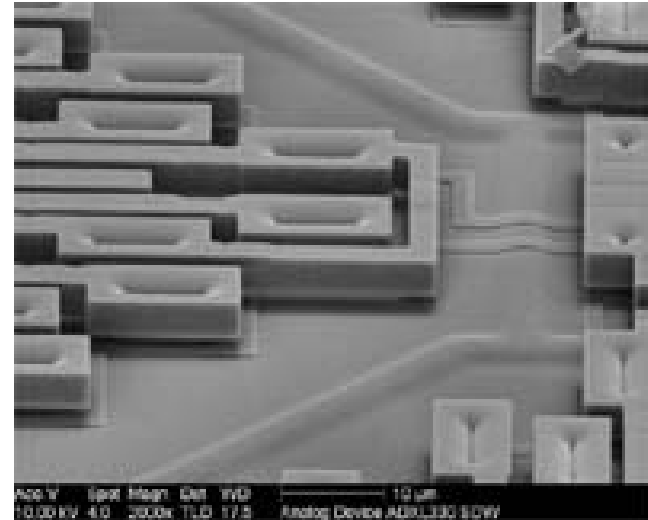
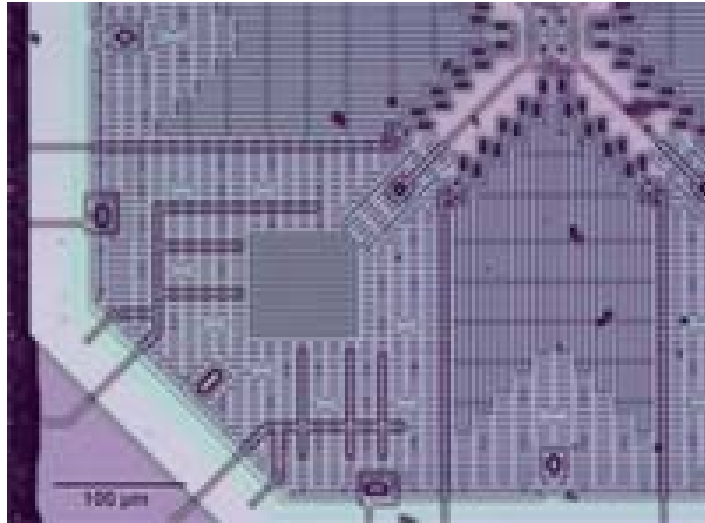


(b)

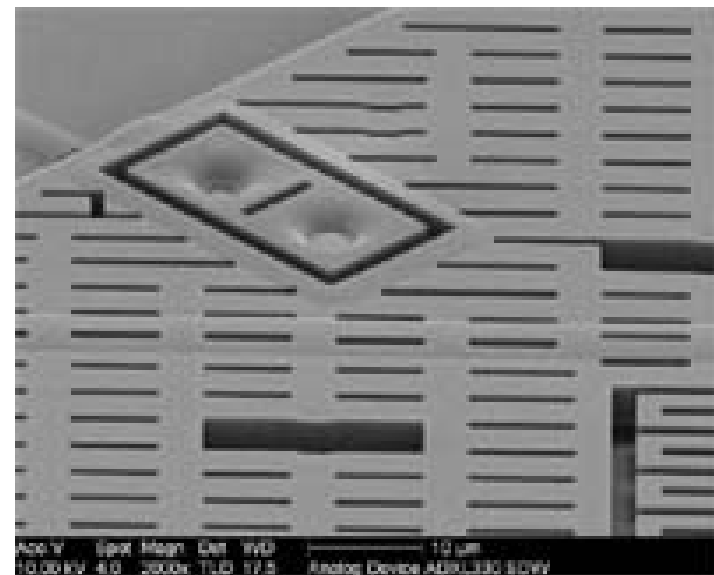
Disadvantage of MEMS: test masses (and thus inertial forces) tend to be small.

Advantages: high precision displacement sensing, cheap manufacture, high reproducibility.

Accelerometers



Analog Devices **ADXL330**



Gyroscopes

Yazdi *et al.*, IEEE 1998

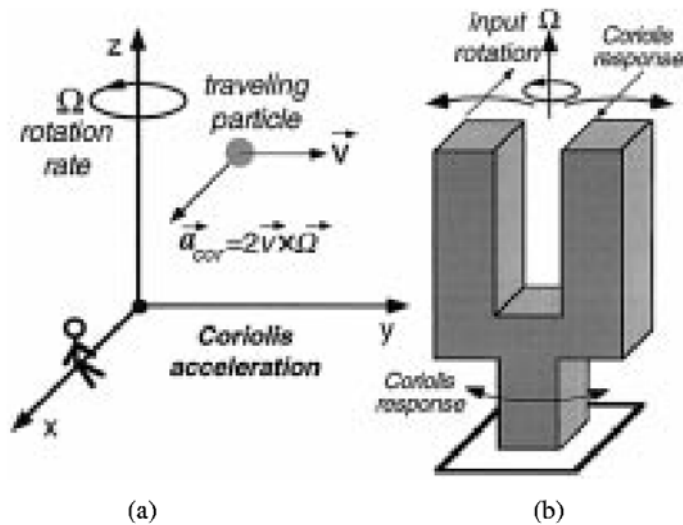


Table 2 Performance Requirements for Different Classes of Gyroscopes

<i>Parameter</i>	<i>Rate Grade</i>	<i>Tactical Grade</i>	<i>Inertial Grade</i>
Angle Random Walk, °/√h	>0.5	0.5-0.05	<0.001
Bias Drift, °/h	10-1000	0.1-10	<0.01
Scale Factor Accuracy, %	0.1-1	0.01-0.1	<0.001
Full Scale Range (°/sec)	50-1000	>500	>400
Max. Shock in 1msec, g's	10 ³	10 ³ -10 ⁴	10 ³
Bandwidth, Hz	>70	~100	~100

Rotation rate and tilt sensing are also very useful.

Same advantages apply to MEMS structures.

Above gyroscope based on Coriolis force. While displacements in MEMS resonators are small, frequencies can be substantial. Amplitude of 0.1 nm and frequency of 100 MHz gives velocity of 1 cm/sec, not crazy.

Lateral displacement of tuning fork fingers sensed.

Gyroscopes

Yazdi *et al.*, IEEE 1998

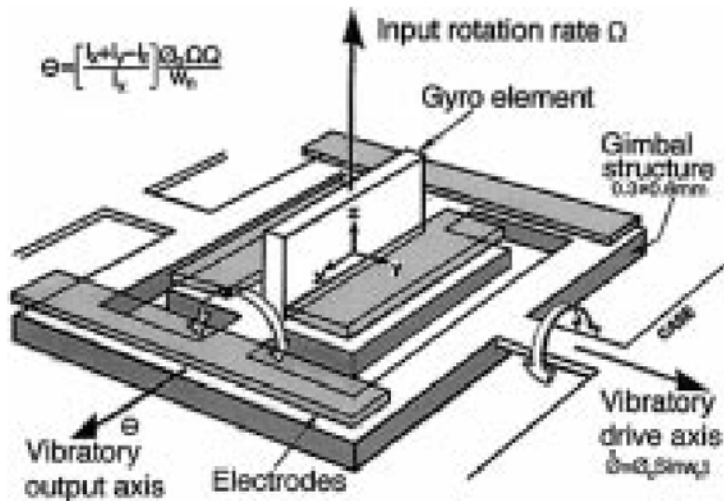


Fig. 10. Draper's first silicon micromachined double-gimbal vibratory gyroscope (1991) [100].

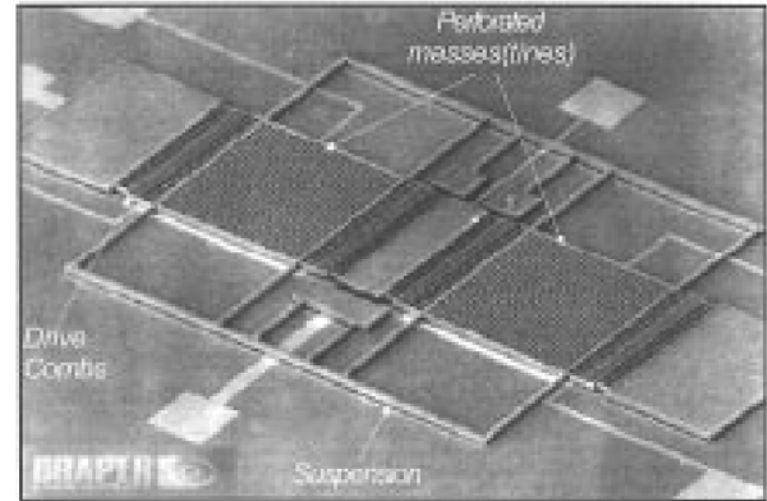


Fig. 11. SEM view of Draper's single-crystal silicon-on-glass tuning-fork gyroscope [103].

Another mechanically clever design. Torsional resonator instead of tuning fork.

Coriolis force on gyro test mass excited transverse resonator. Gains benefit of Q factor of sense resonator.

Gyroscopes

Yazdi *et al.*, IEEE 1998

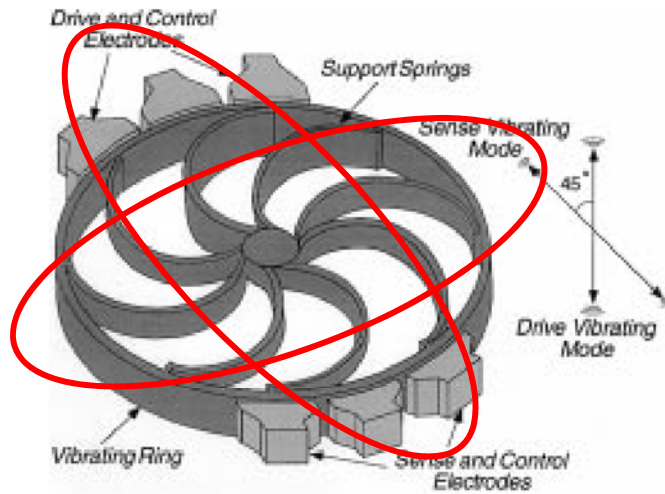


Fig. 15. Structure of a vibrating ring gyroscope.

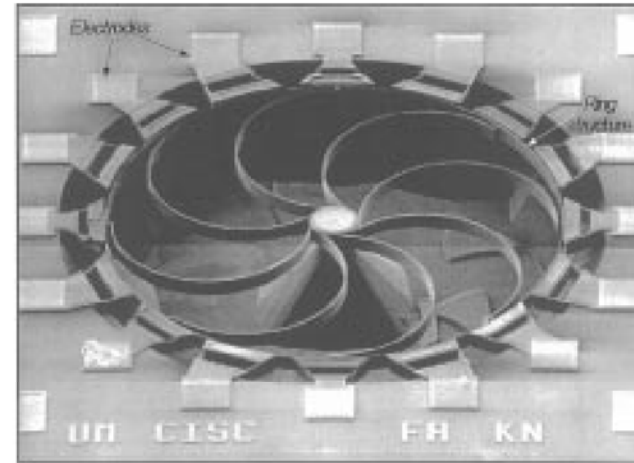


Fig. 16. SEM view of a PRG [123]. The polysilicon ring is 1 mm in diameter, 3 μm wide, and 35 μm tall.

Vibrating ring design from General Motors.

Ring is resonated in elliptical mode as shown. Under rotation, a 45 degree out-of-plane mode gets excited by Coriolis effects.

Optical switching – mirrors

Ho, Stanford

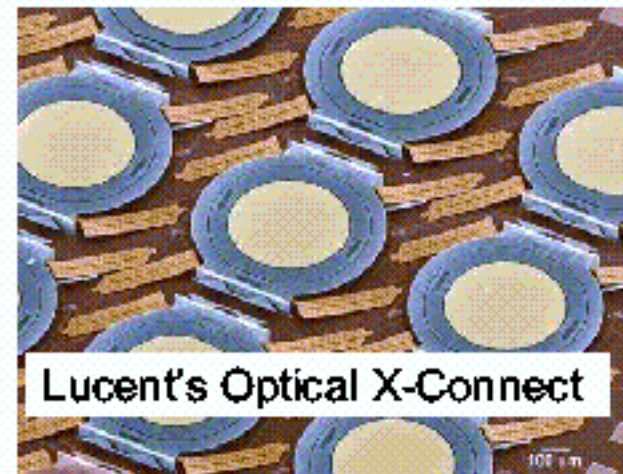
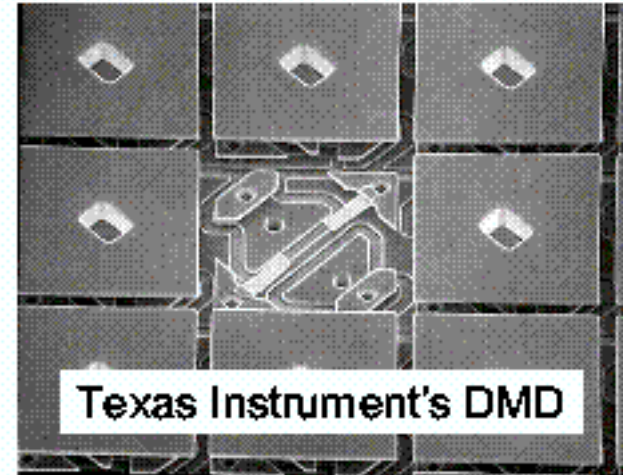
Beyond inertial sensing, there is potentially a huge (eventual) market for optical MEMS.

For example, one can do optical switching by having micromachined mirrors that may be moved by electrostatic actuation.

Small footprint, mass fabrication, properties of individual optical elements not necessarily critical.

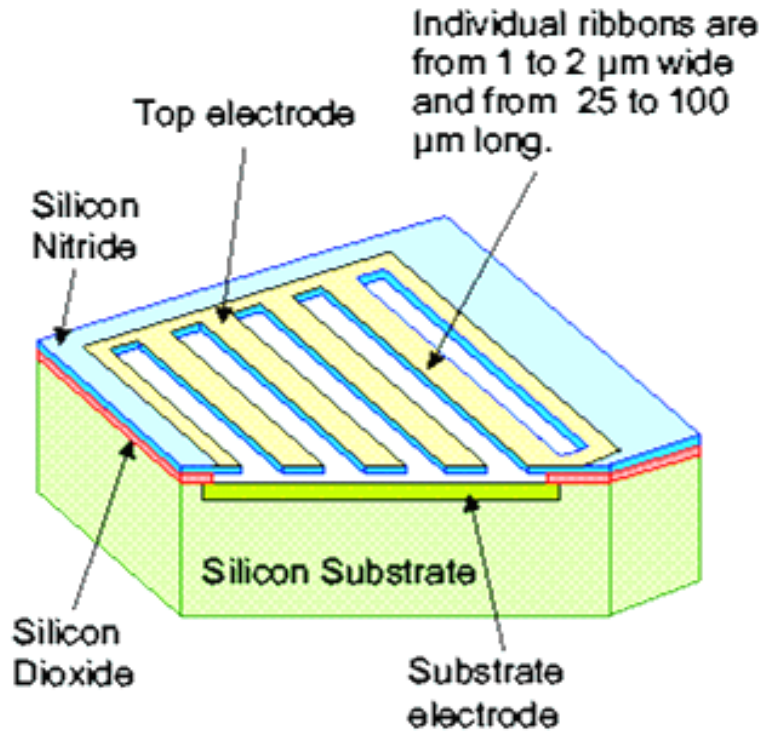
Downsides:

Alignment; high operating voltages; packaging and reliability



Optical switching – diffraction gratings

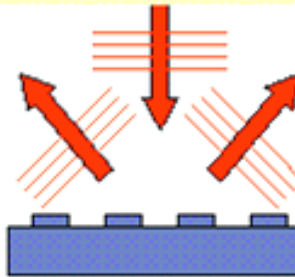
Ho, Stanford



Beams up, reflection



Beams down, diffraction

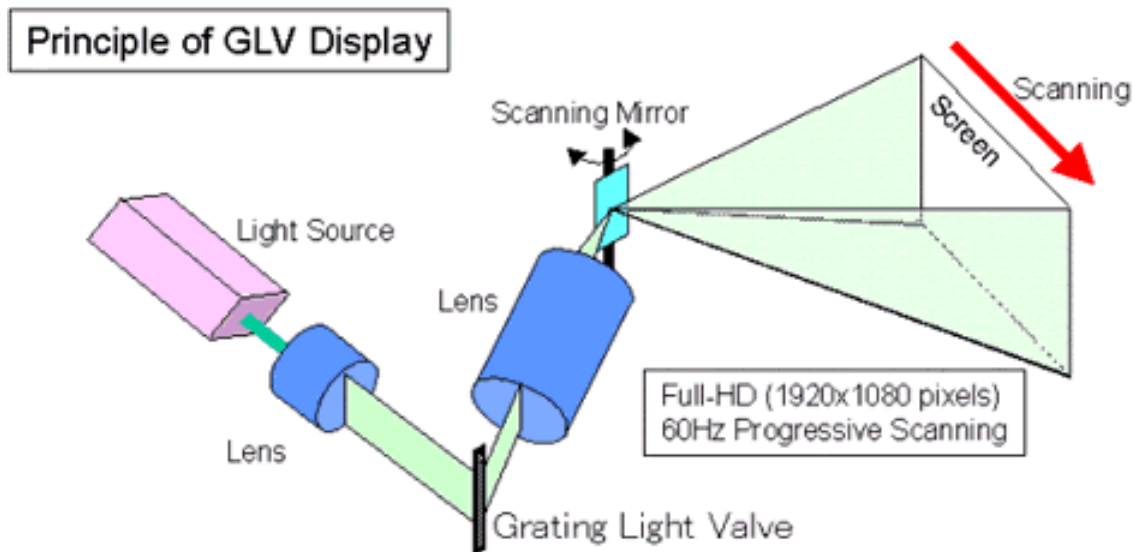
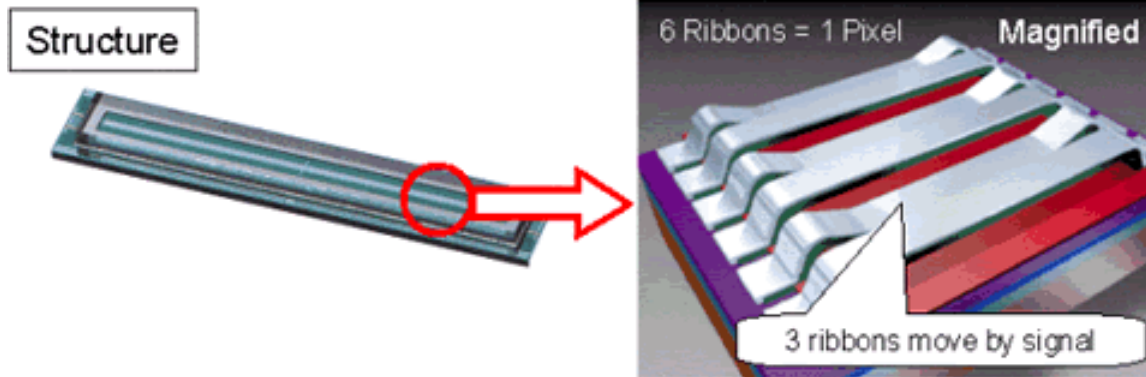


Cross section

“Grating light valve” (Silicon Light Machines).

Used in optical switching, displays, projectors....

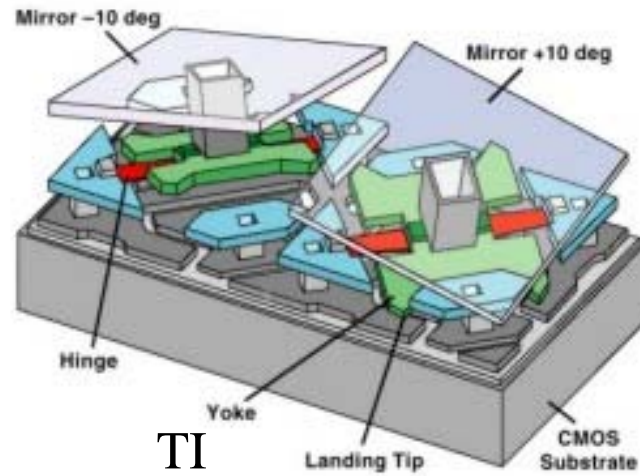
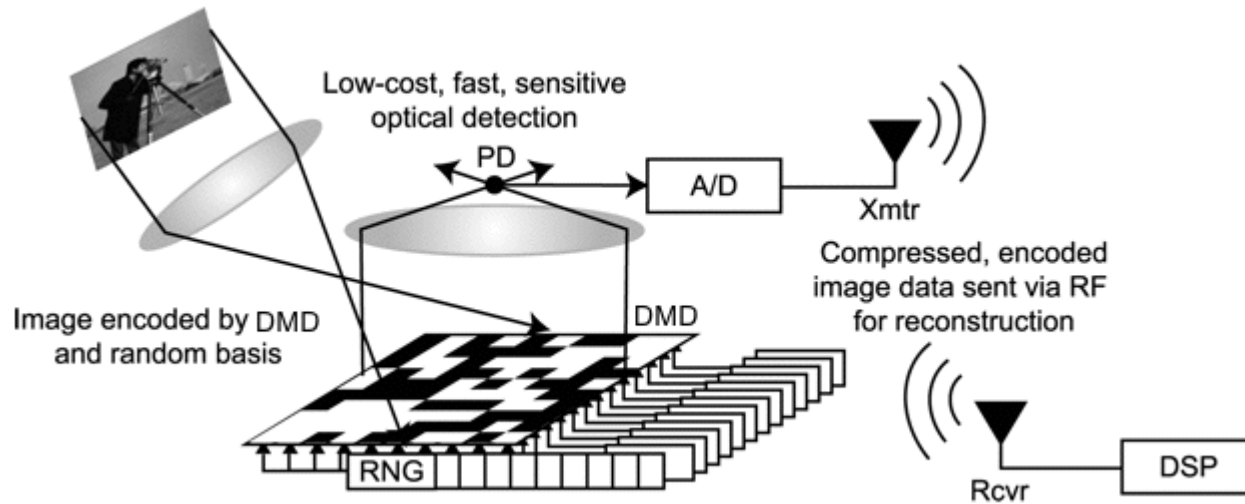
Grating light valve



Sony

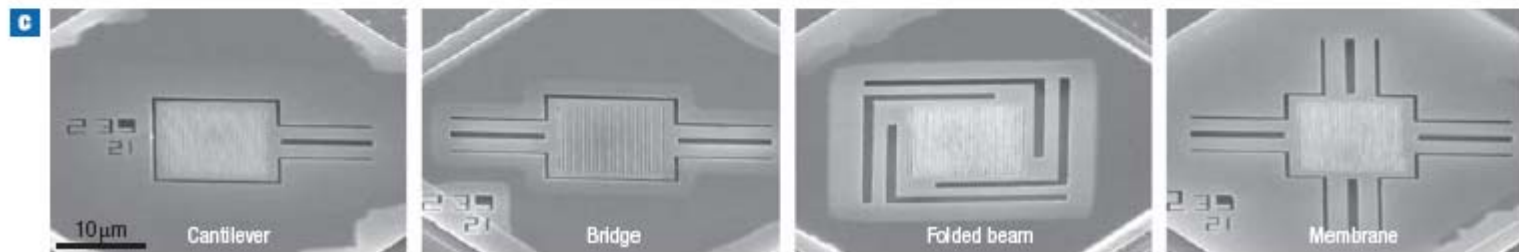
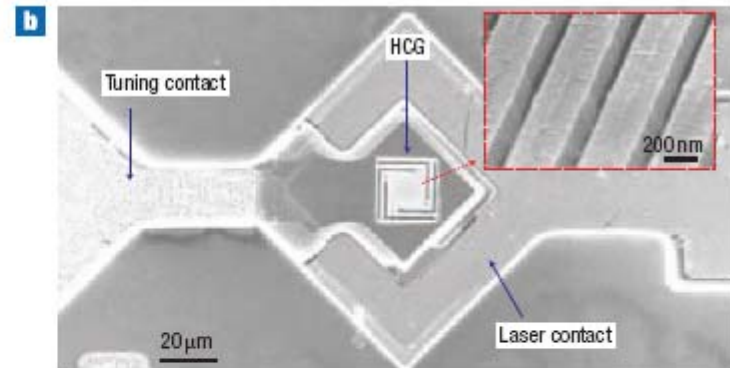
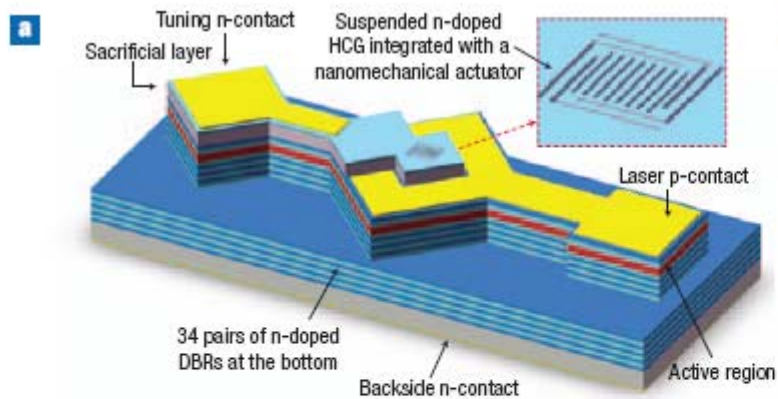
For projection high definition video....

Single-pixel camera

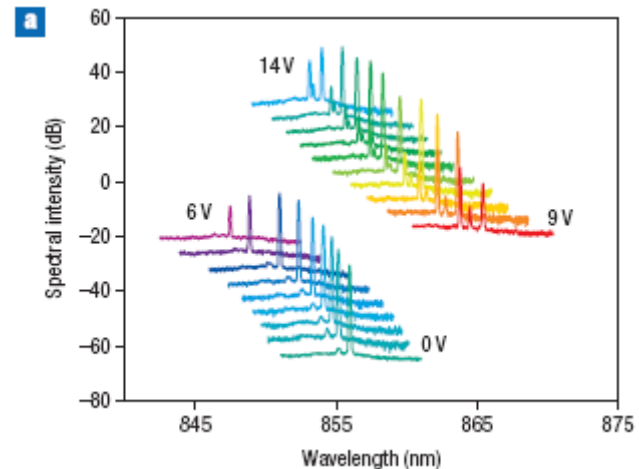


MEMS-tuned laser

Huang *et al.*, Nature Photonics **2008**, 10.1038/nphoton.2008.3

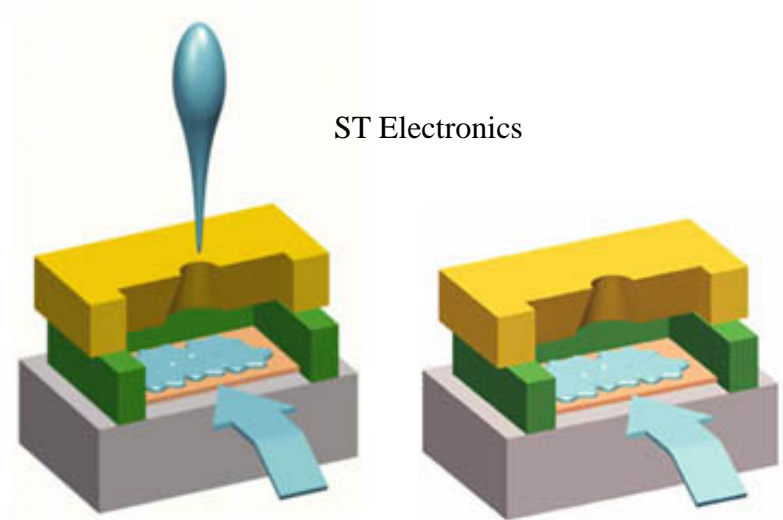
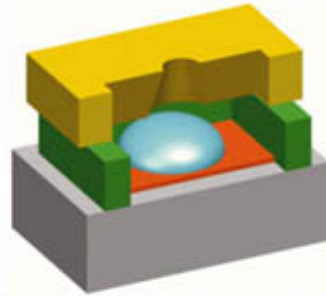
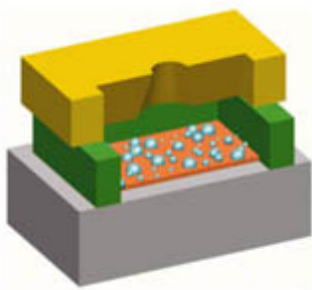


- High-contrast grating as top mirror
- MEMS actuator moves suspended top mirror, altering cavity shape.
- Different lasing modes tuned in and out of threshold by bias voltage.

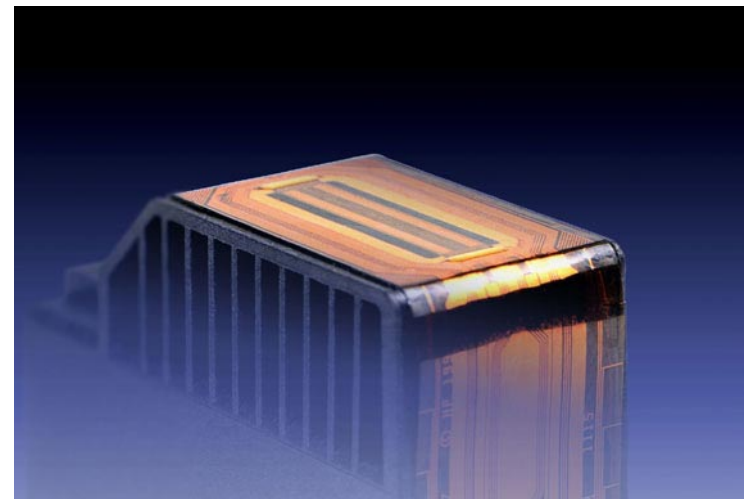


Inkjet printers

One ubiquitous application of MEMS techniques is the micromachining required to make the print heads and nozzles for inkjet printers:



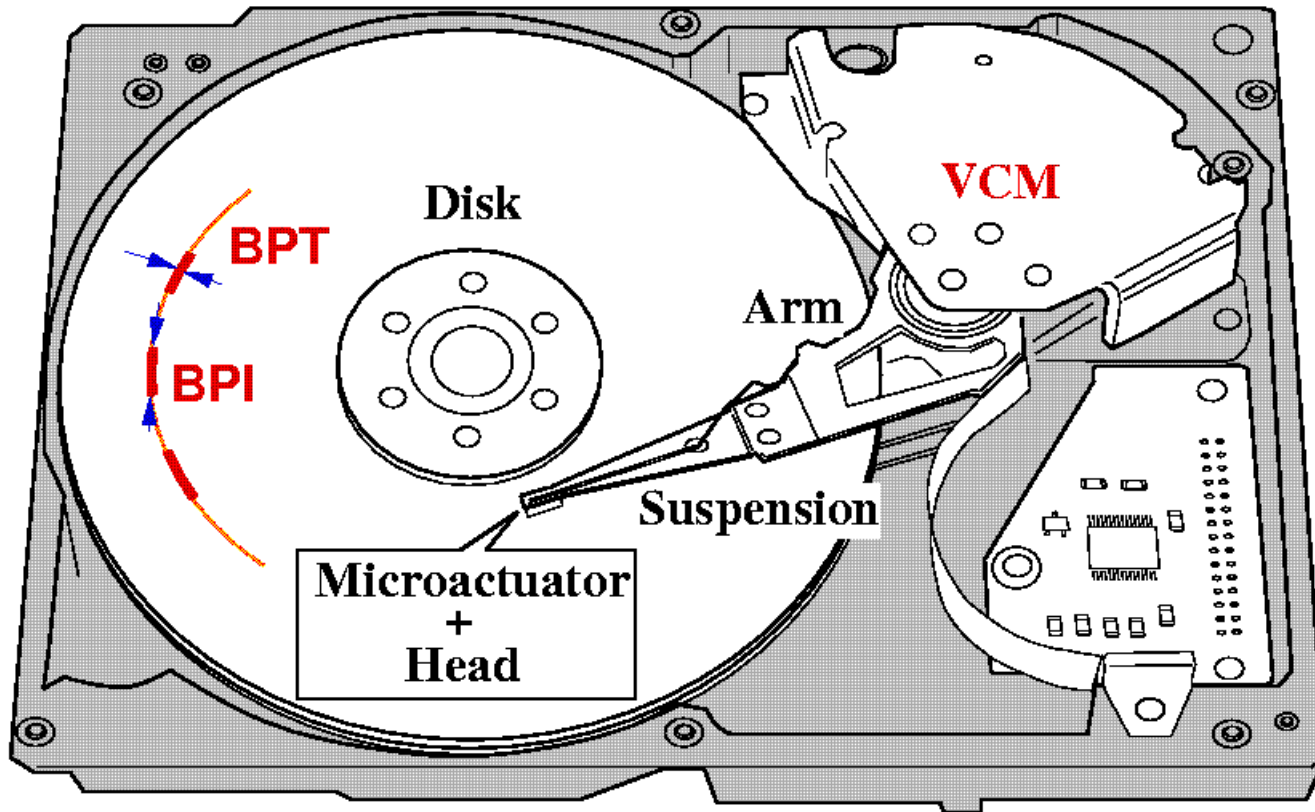
True 2400 dpi printing = 10 micron droplets ~ few micron nozzles.



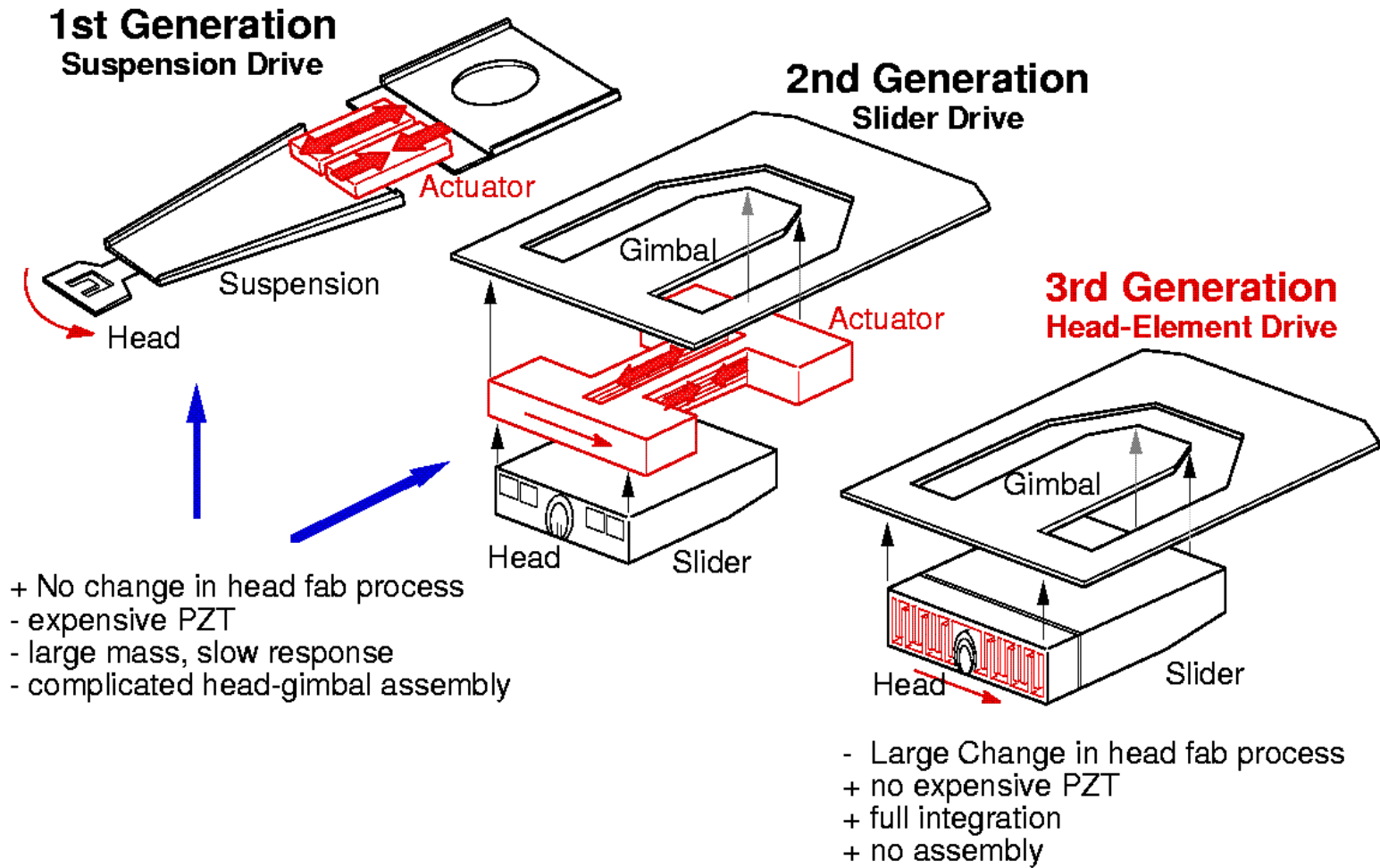
Data storage

MEMS already play an active role in the data storage industry:

- Positioning hardware for hard drive read/write heads



Data storage - Hard drives

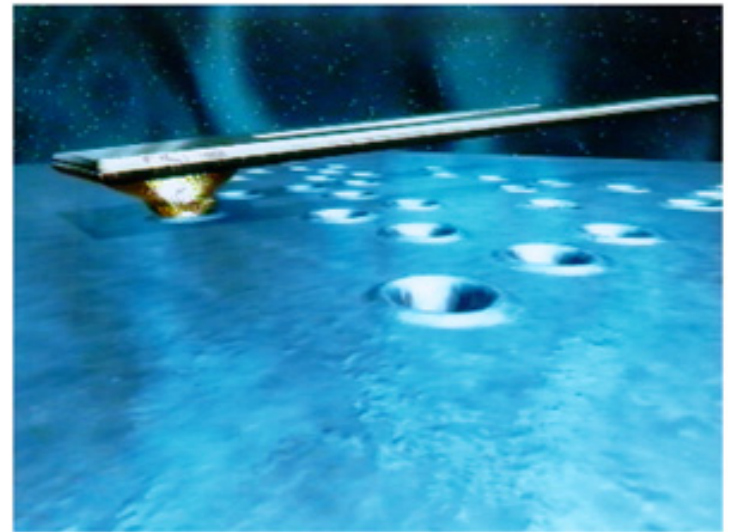
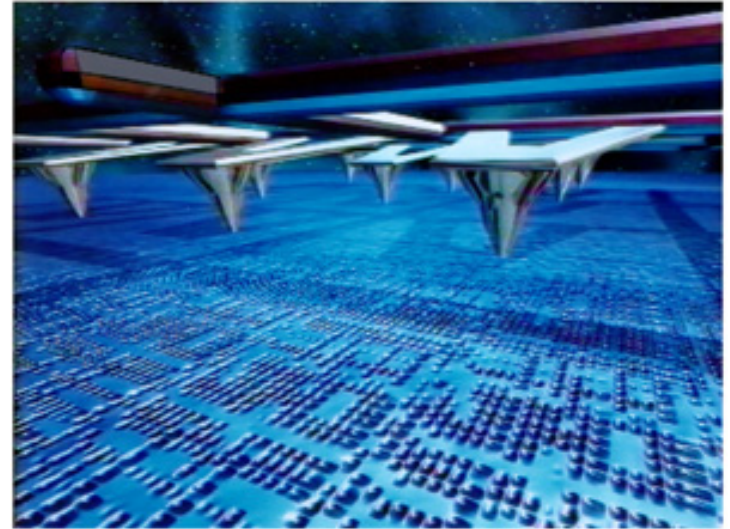


Data storage

Multiple ideas for MEMS-based data storage.

One big contender: the Millipede from IBM

- Array of 1024 AFM cantilevers
- Positions sensed and manipulated piezoresistively
- Each cantilever has a fixed xy position, while storage medium is maneuvered around beneath the array via comb drive.

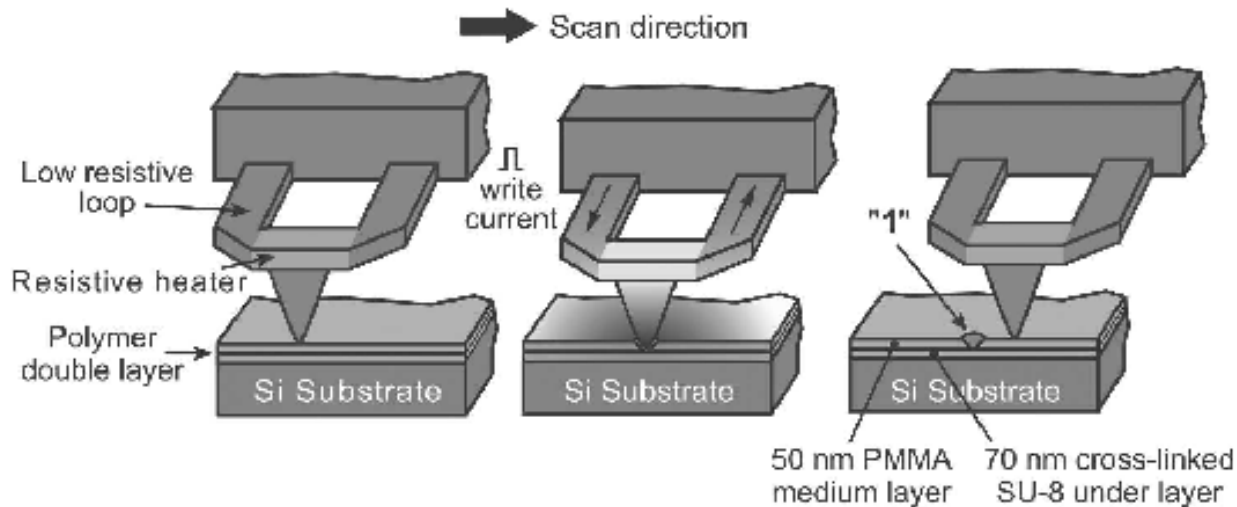


Data storage: Millipede

Each cantilever is highly doped, and has a built-in heating element at the tip.

Writing is accomplished by heating the particular tip until its temperature exceeds the glass transition temperature for the PMMA medium.

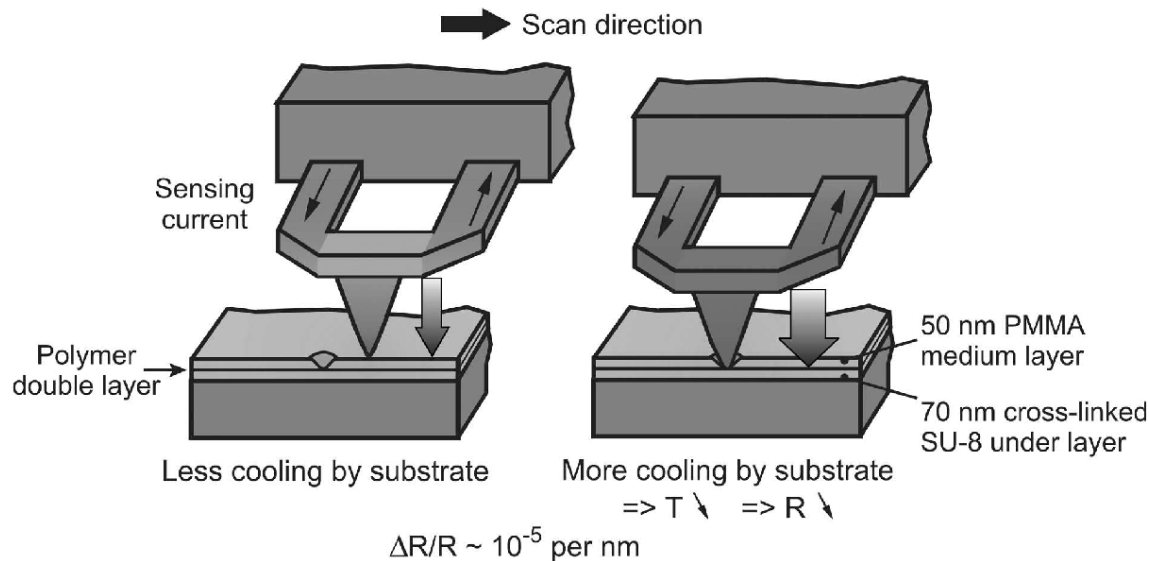
Underlayer is SU-8 photoresist (higher T_g) that acts as a stop.



Data storage: Millipede

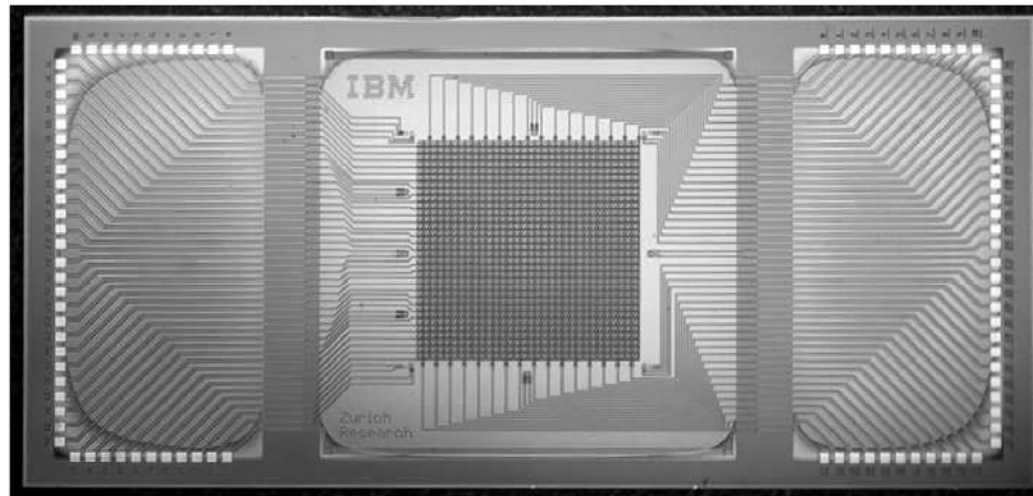
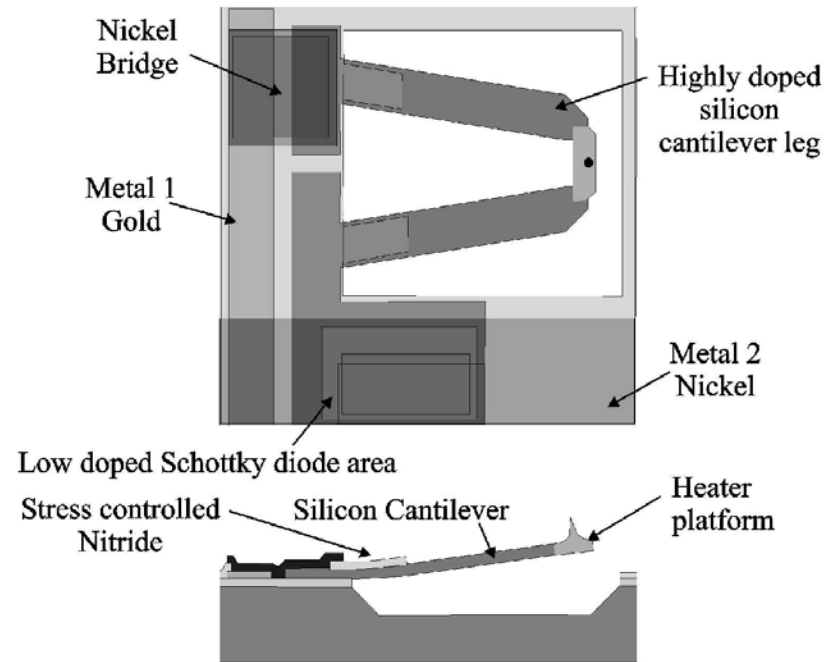
Read process is similar: cantilever T sensed by resistance measurement. Allow cantilever to self-heat (lower than T_g of PMMA) at fixed heater power.

When tip is in a pit (“1”), the tip becomes better thermally coupled to the substrate: T falls, R falls, and bit can be sensed.



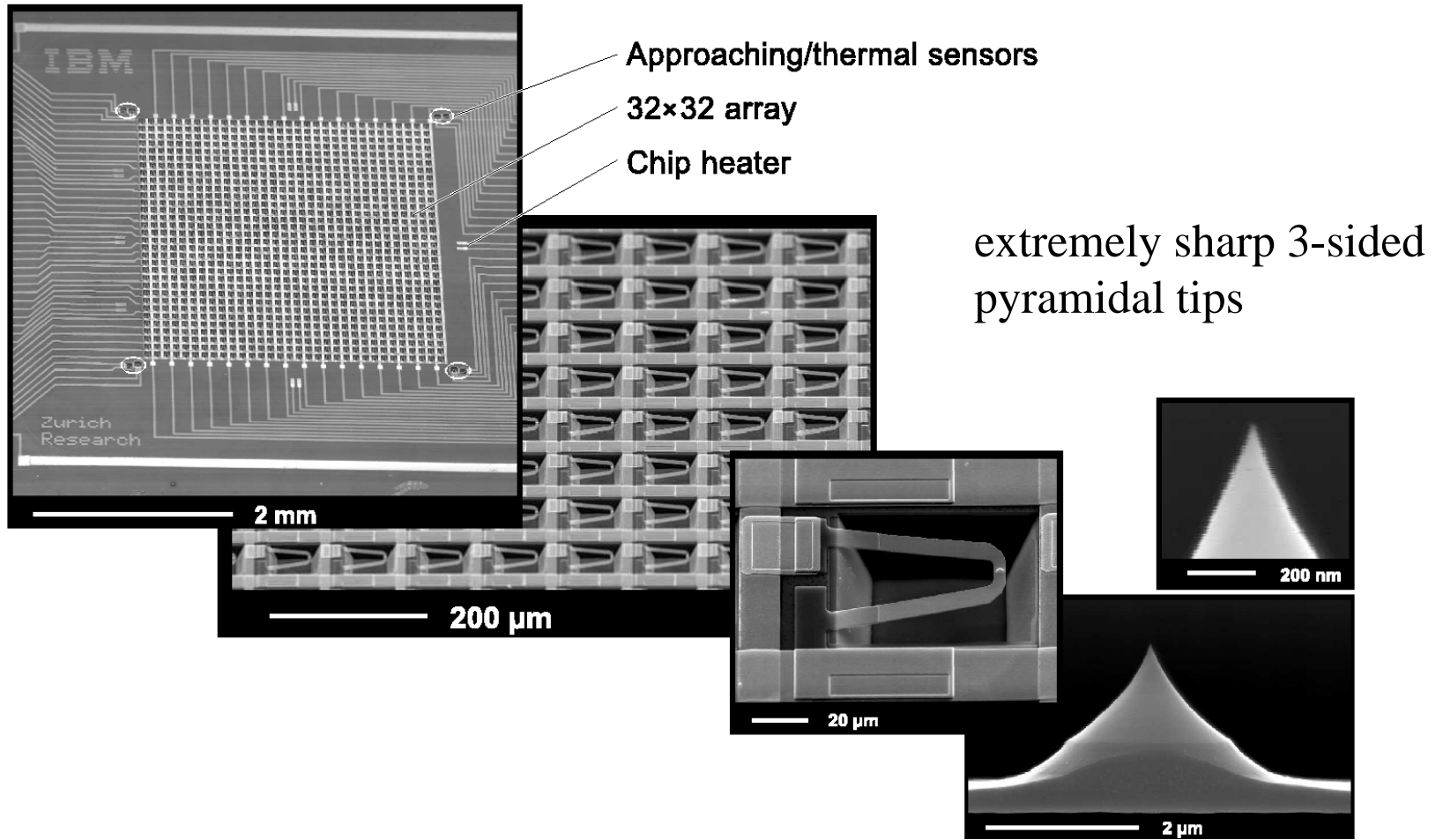
Data storage: Millipede

Beauty of MEMS is that these structures can be batch-fabricated, with all the readout and writing electronics directly integrated.



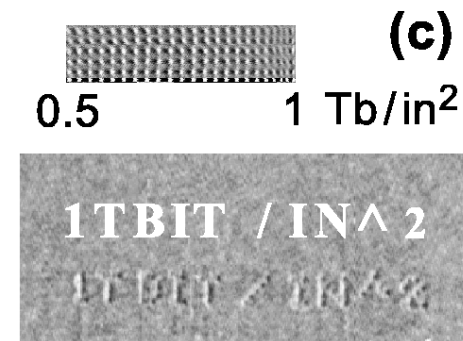
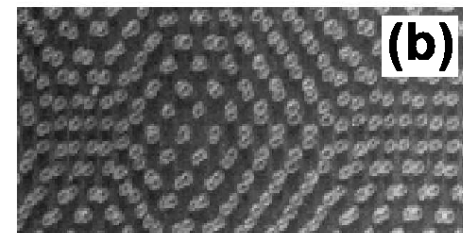
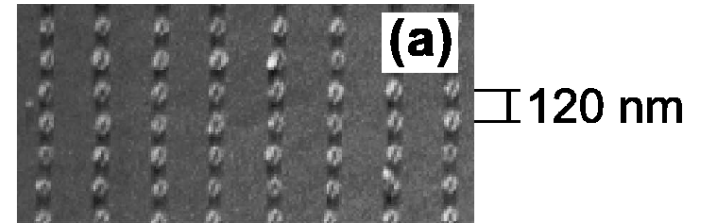
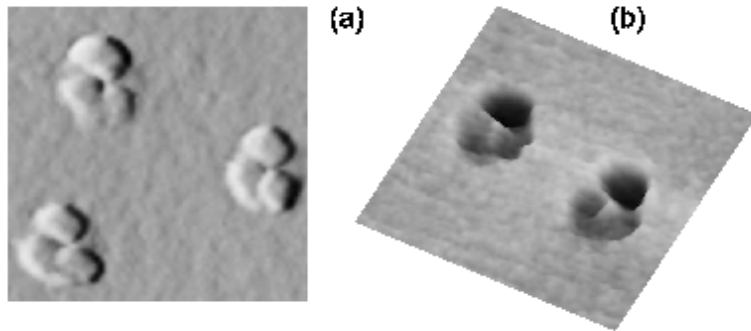
2 mm

Data storage: Millipede



Data storage: Millipede

When tweaked, can get 1 TB/in² densities, better than the best magnetic media.

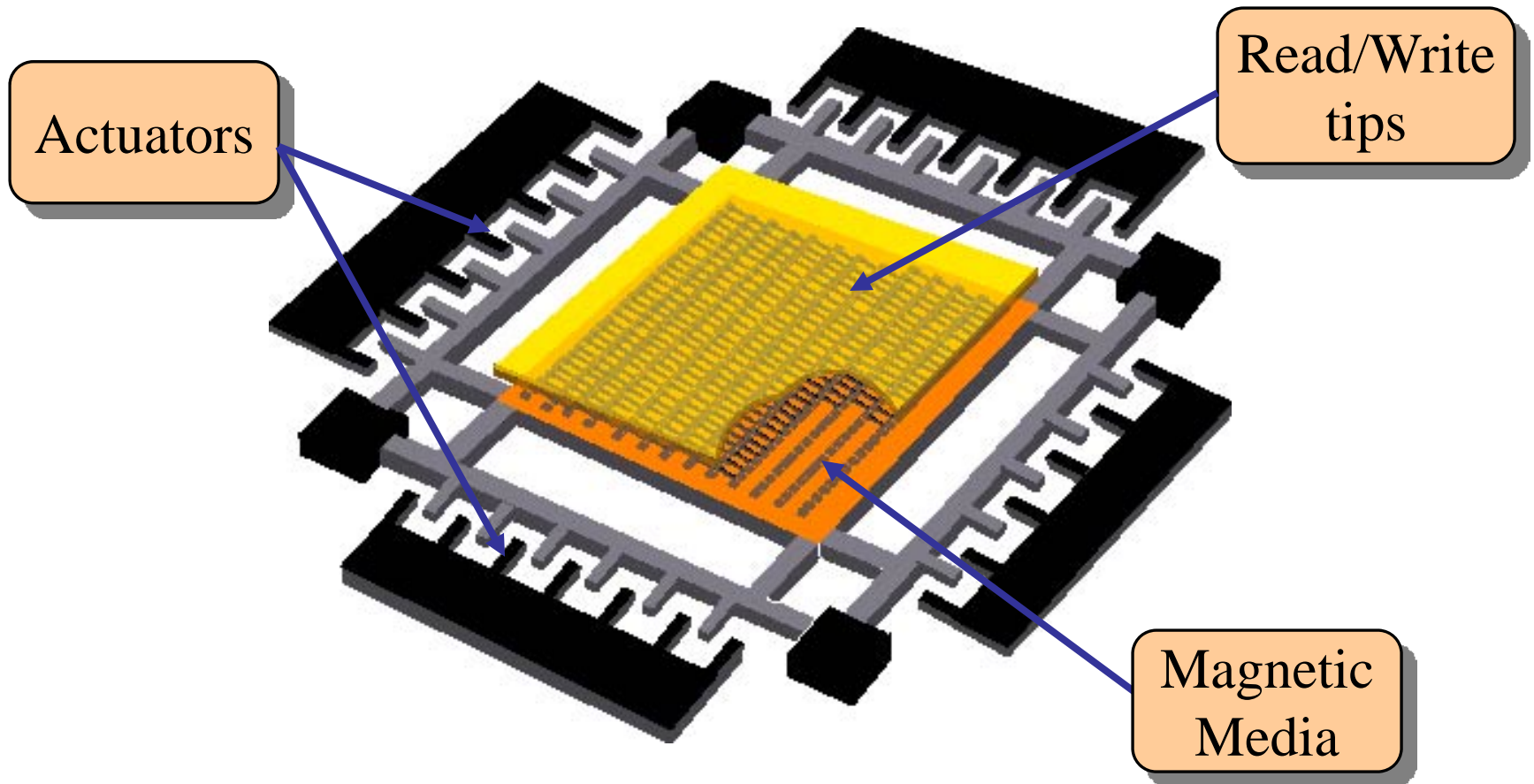


Data storage: “Disk on a chip”

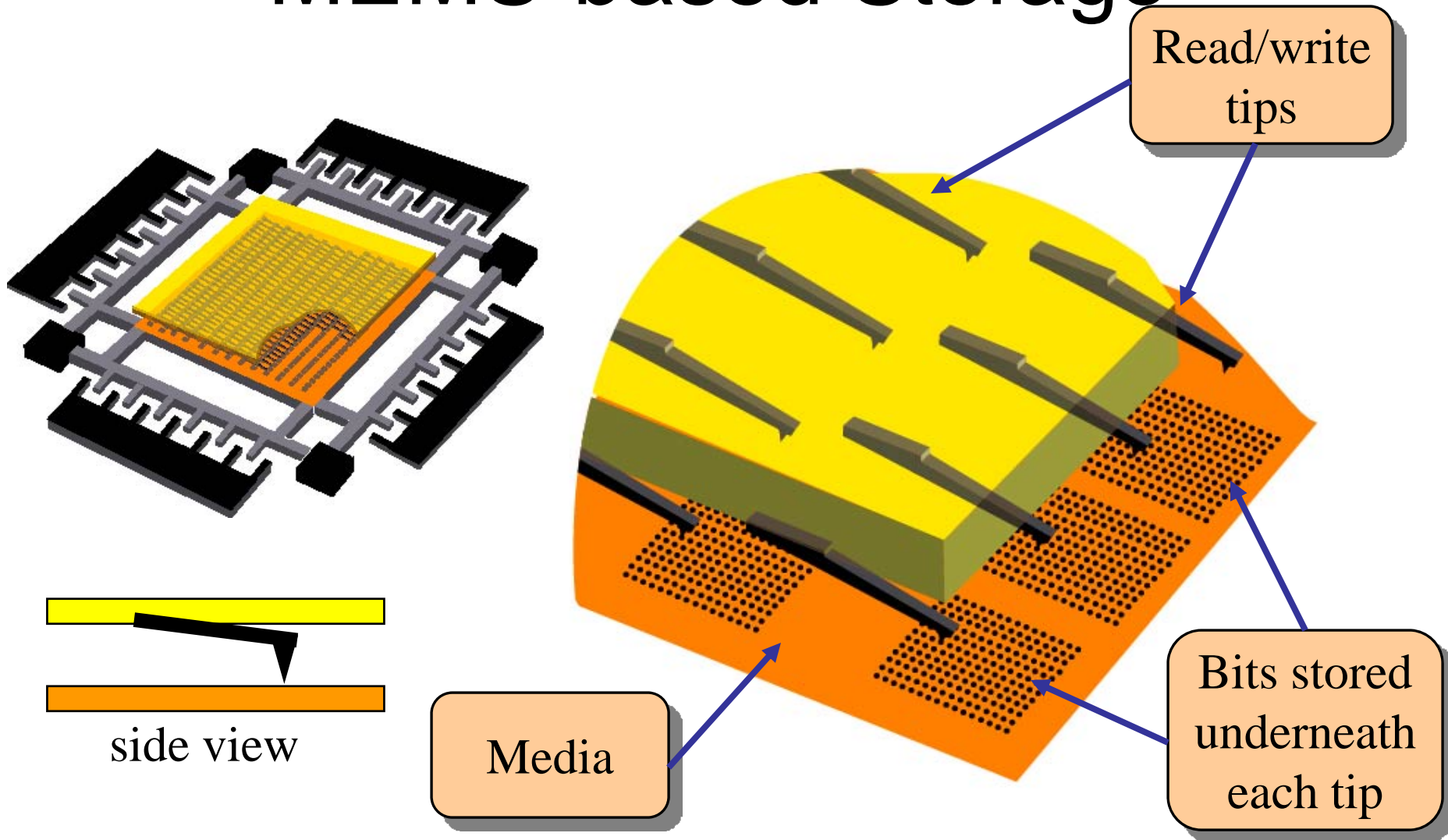
The following viewgraphs are taken from a presentation by these folks from Carnegie Mellon:

- David Nagle, Greg Ganger, Steve Schlosser, and John Griffin
- <http://www.chips.ece.cmu.edu/>

Data storage: “disk on a chip”

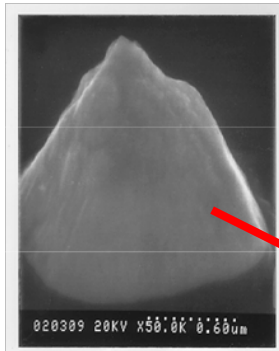


MEMS-based Storage

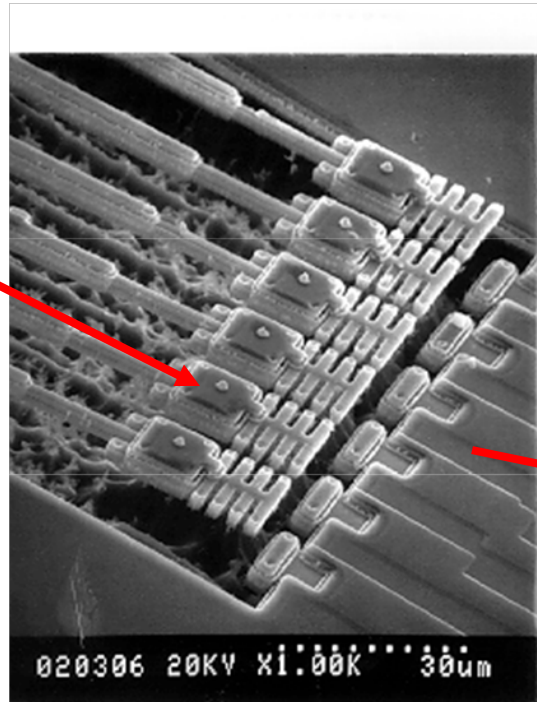


MEMS-based Storage

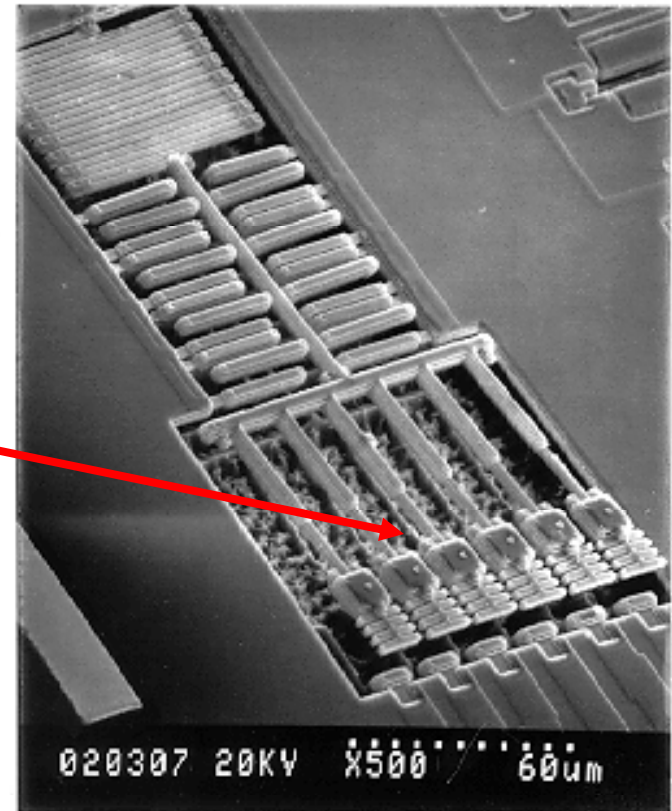
- Read/write probe tips



1 μm
probe tip



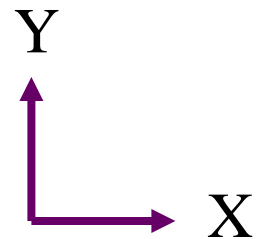
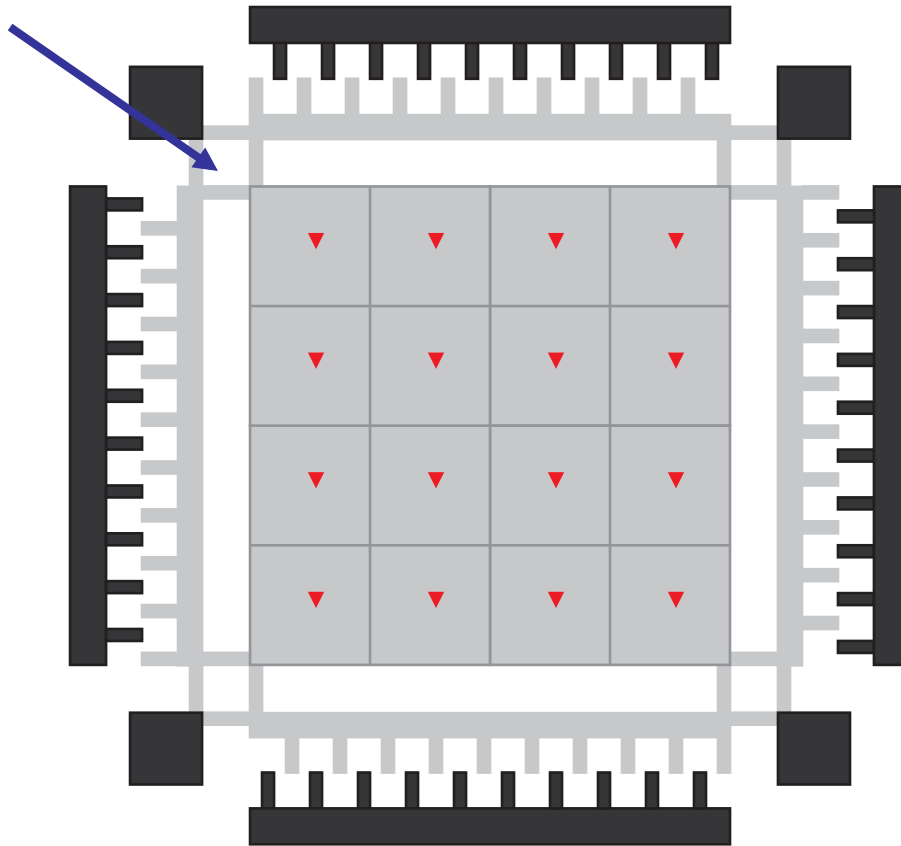
group of six tips



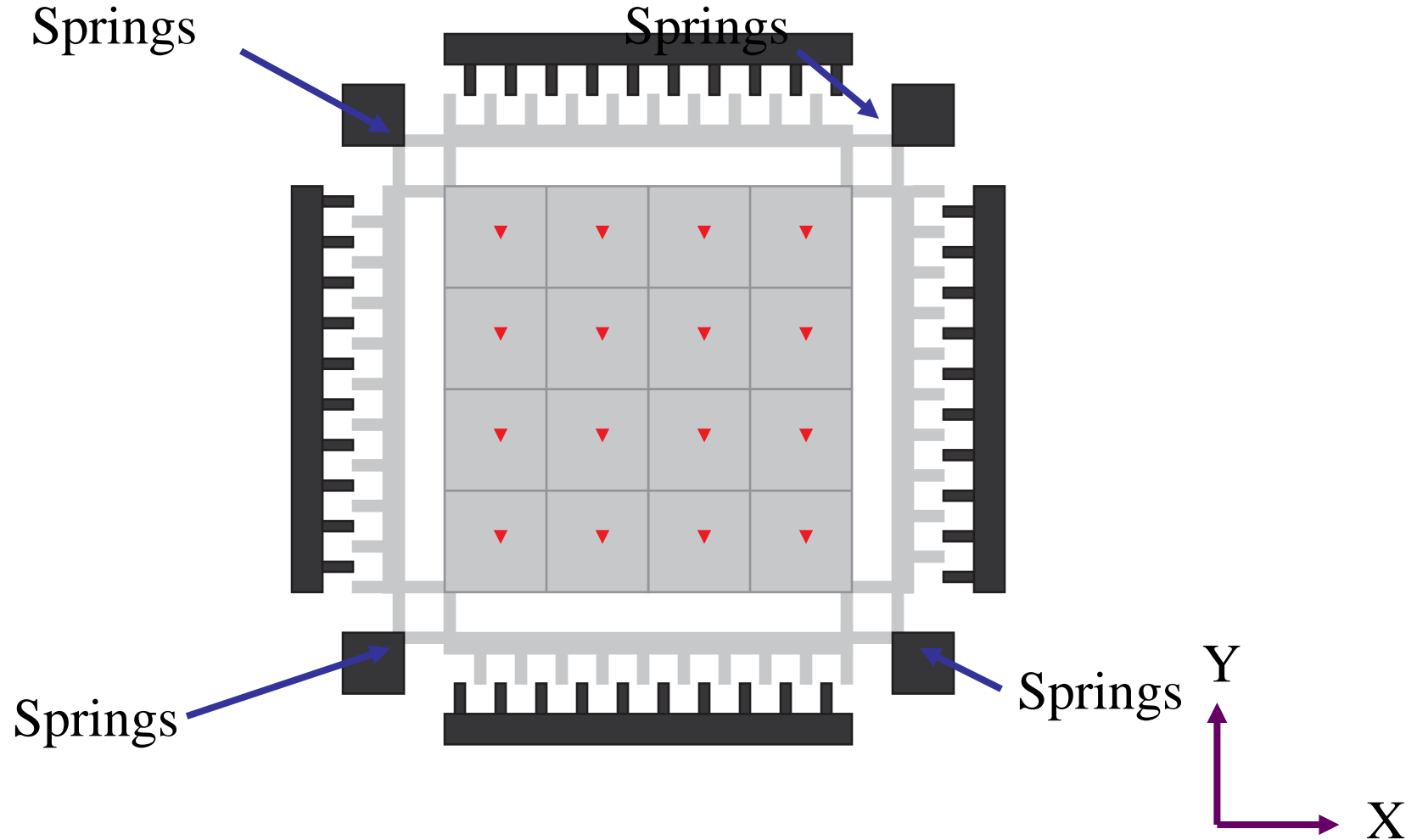
100 μm

MEMS-based Storage

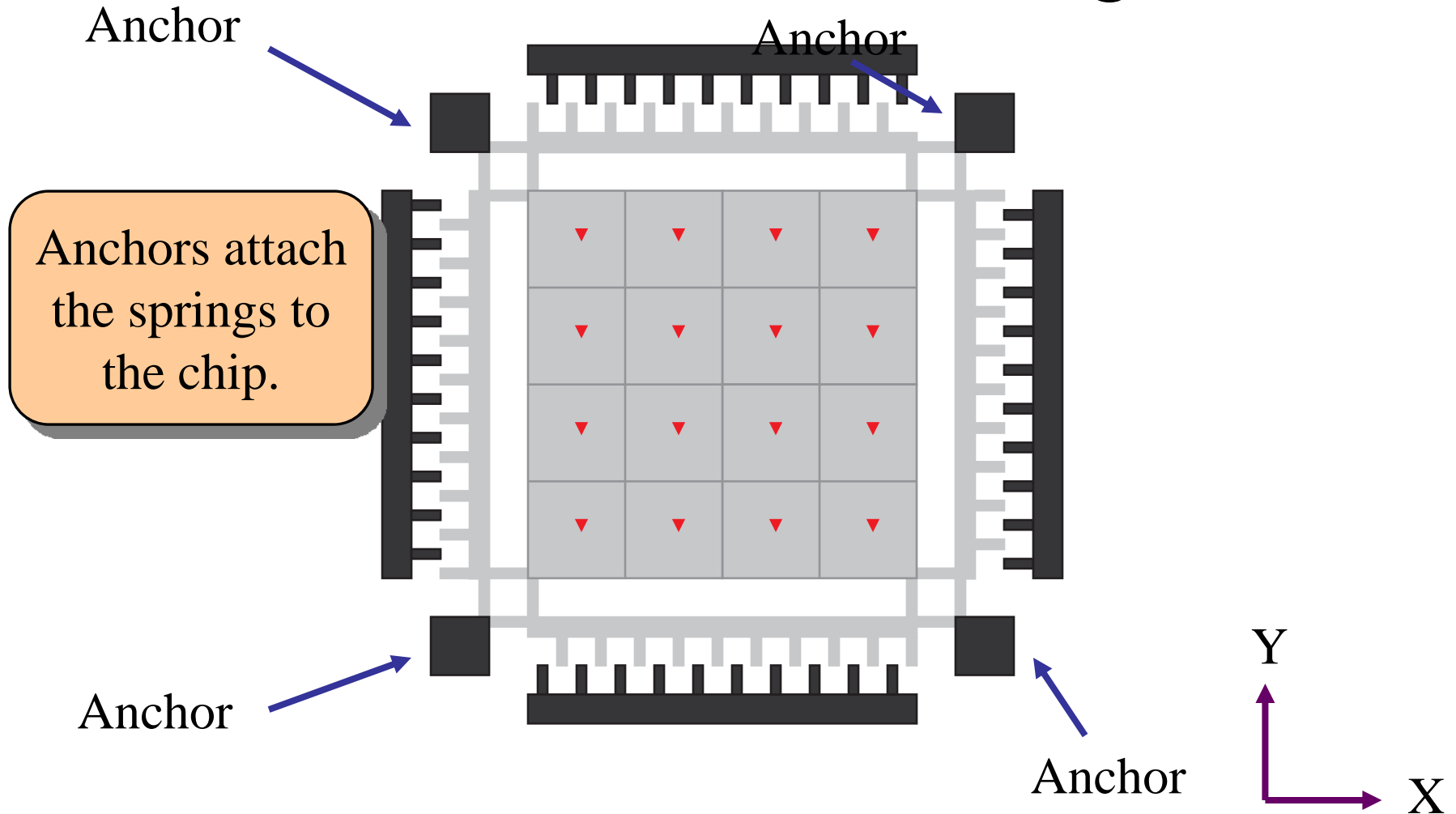
Media Sled



MEMS-based Storage

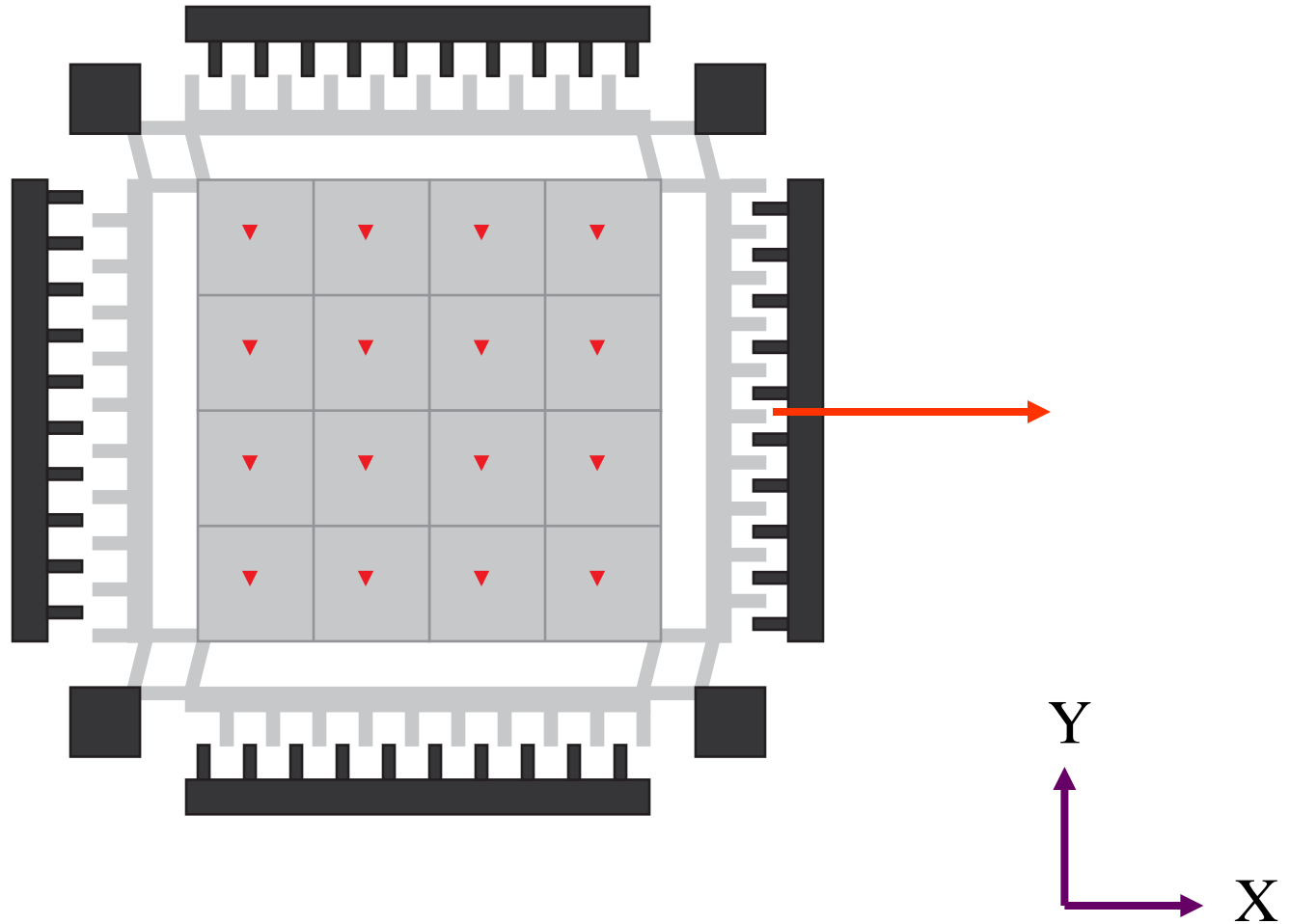


MEMS-based Storage



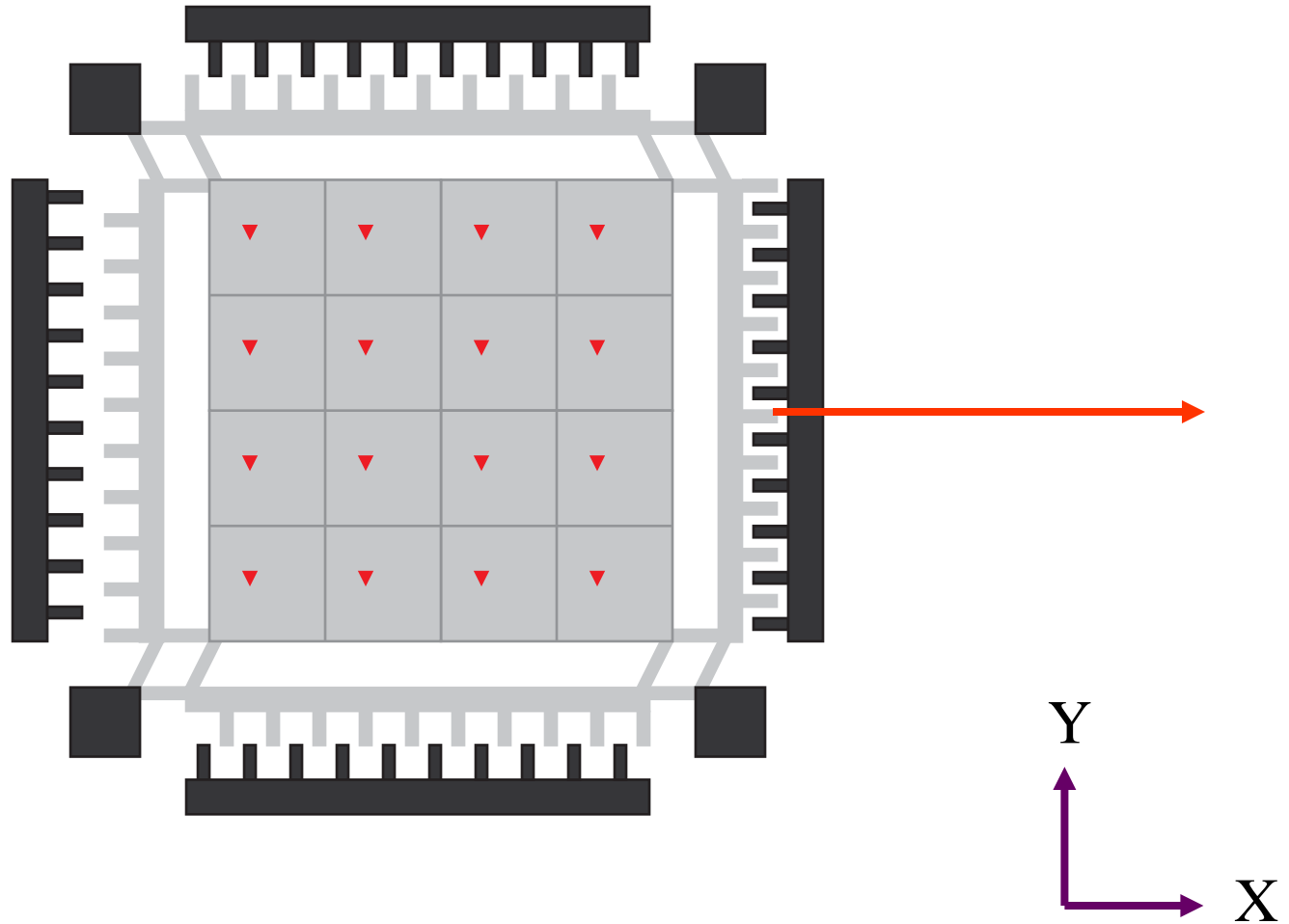
MEMS-based Storage

Sled is free to move



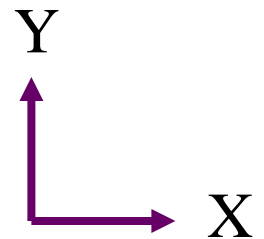
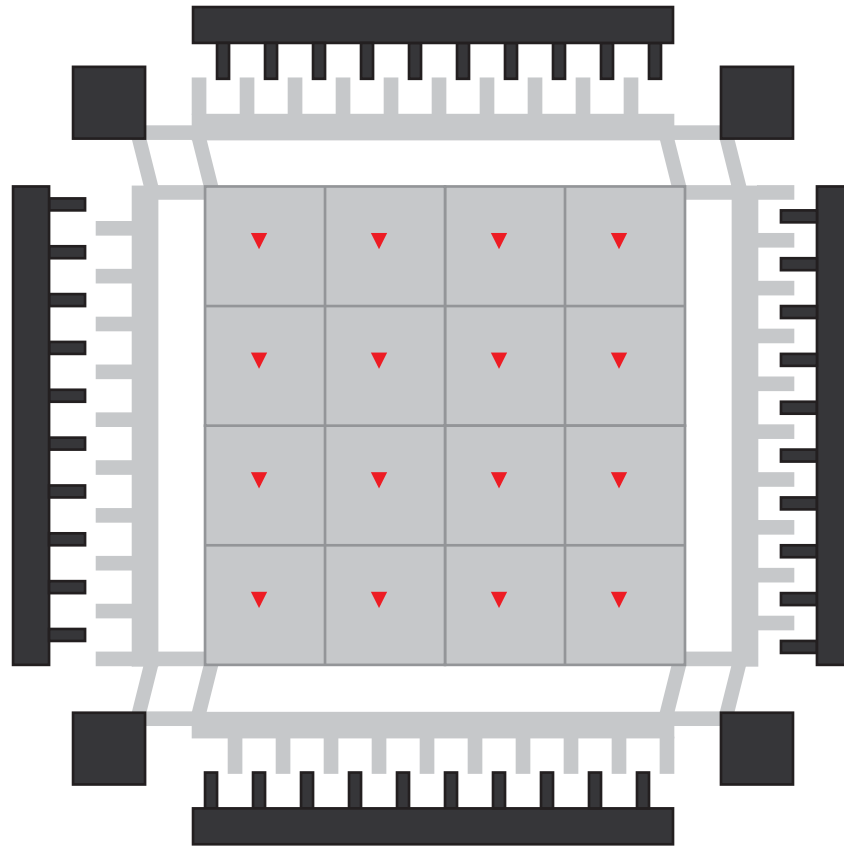
MEMS-based Storage

Sled is free to move



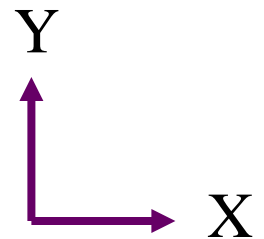
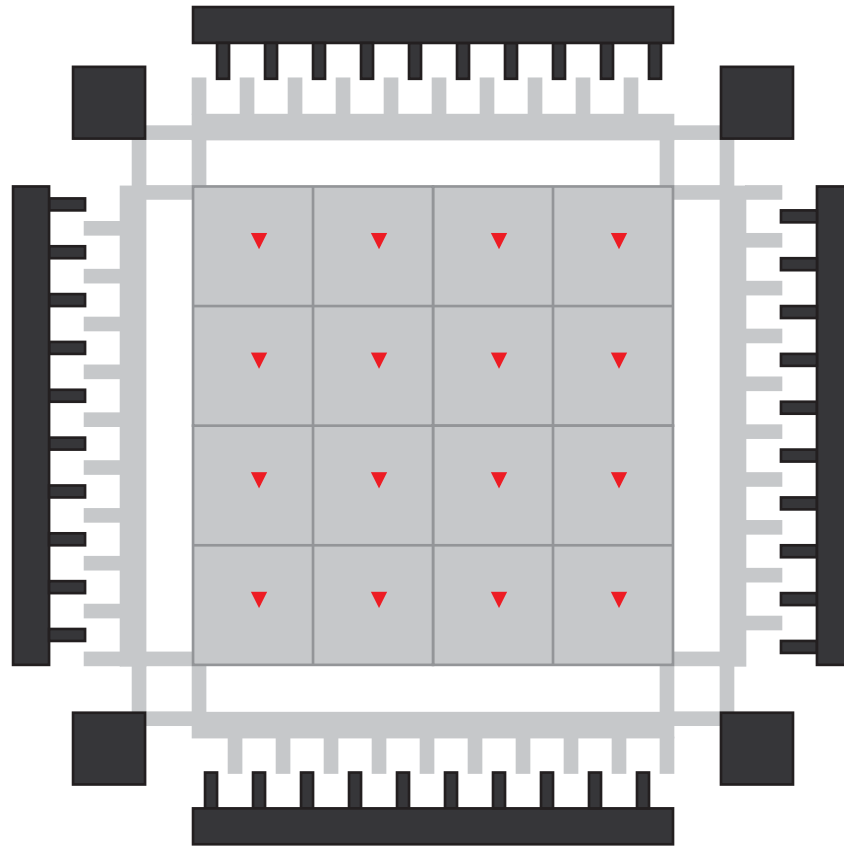
MEMS-based Storage

Springs pull
sled toward
center

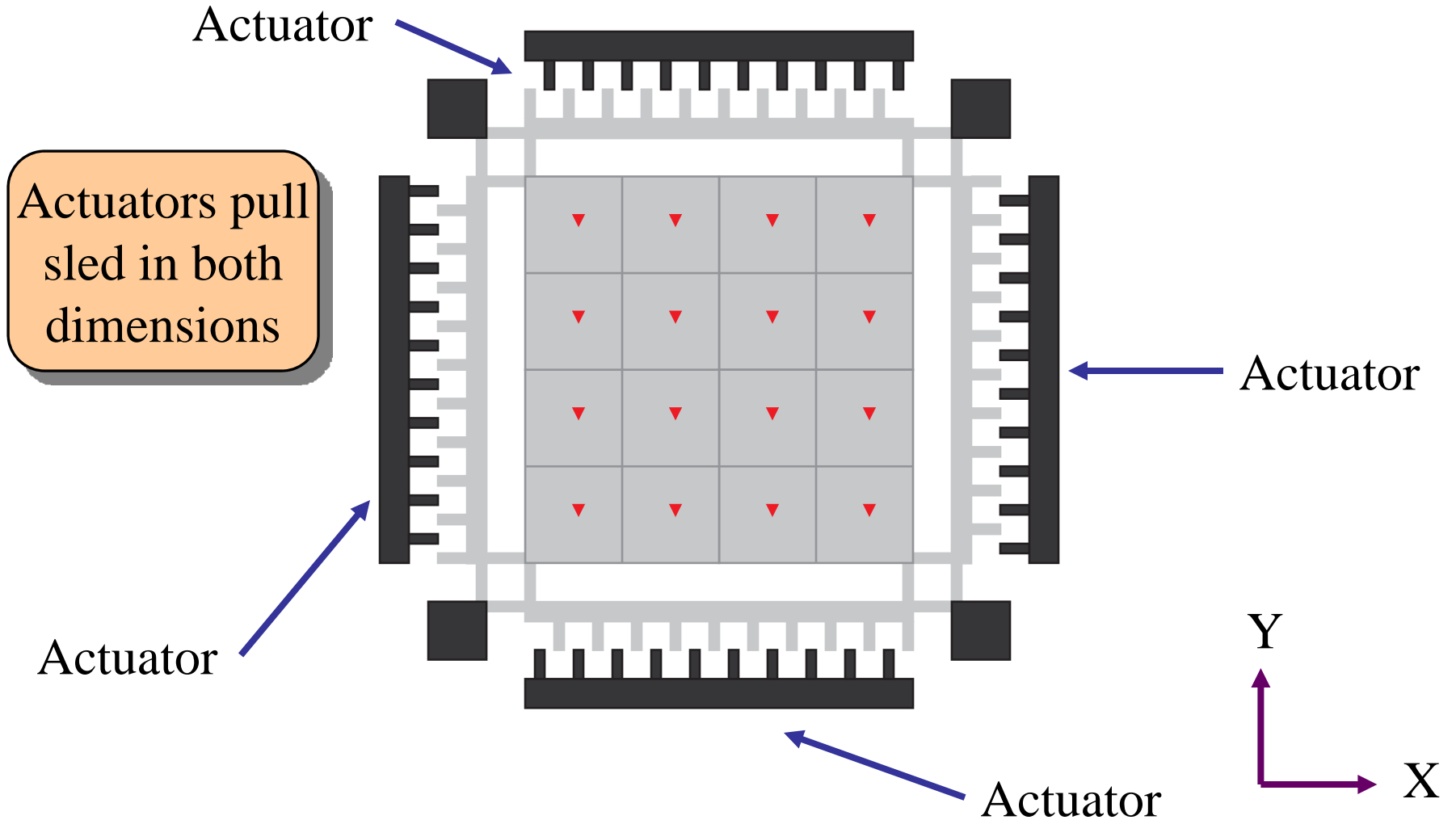


MEMS-based Storage

Springs pull
sled toward
center

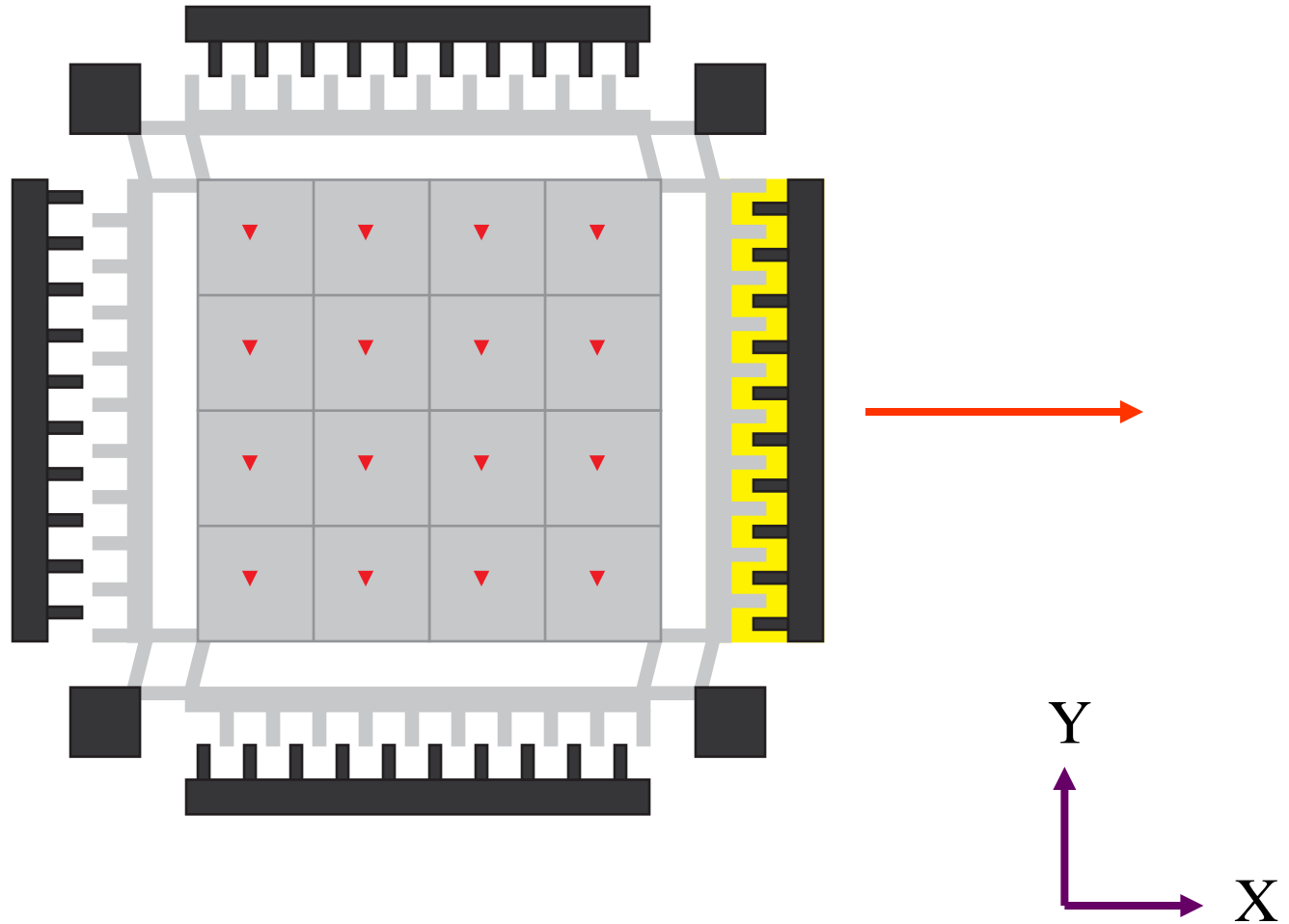


MEMS-based Storage



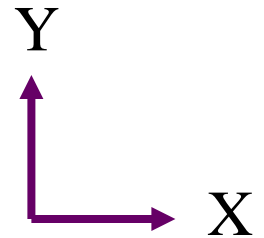
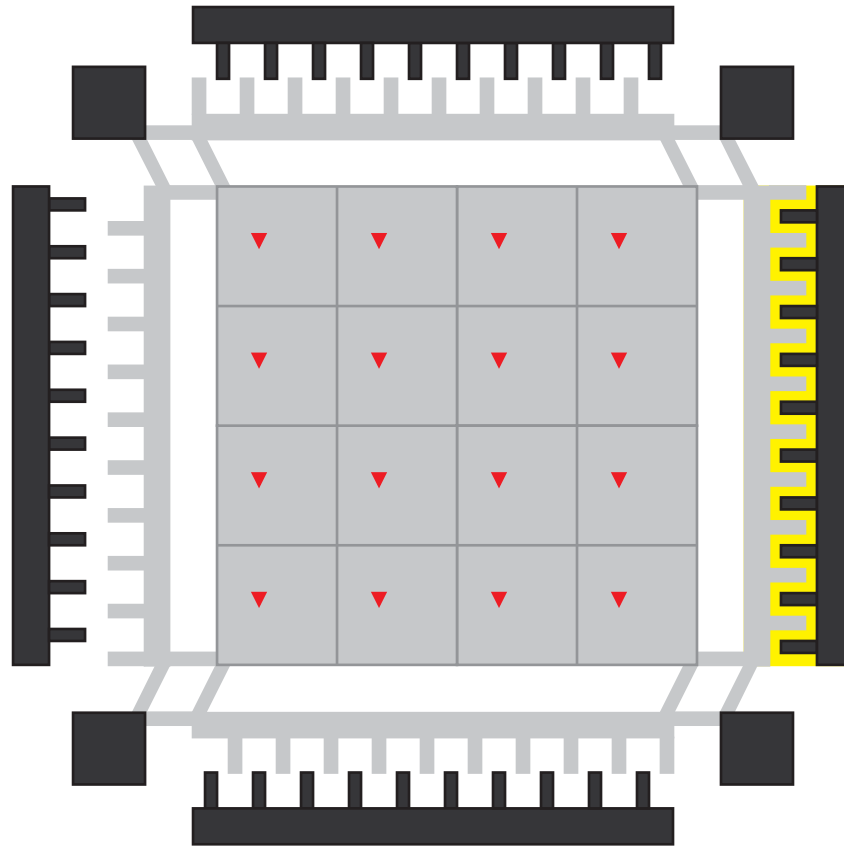
MEMS-based Storage

Actuators pull
sled in both
dimensions



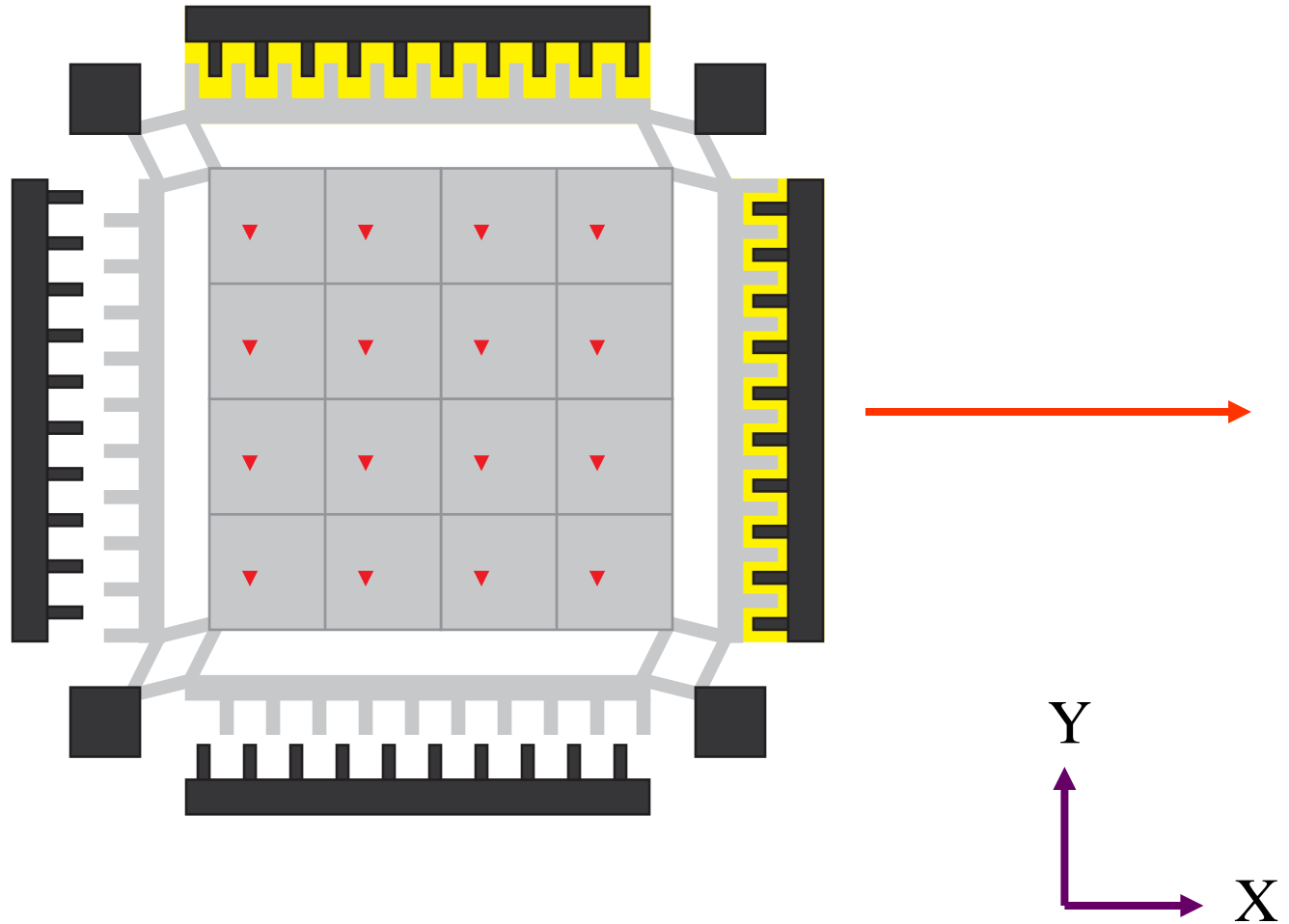
MEMS-based Storage

Actuators pull
sled in both
dimensions



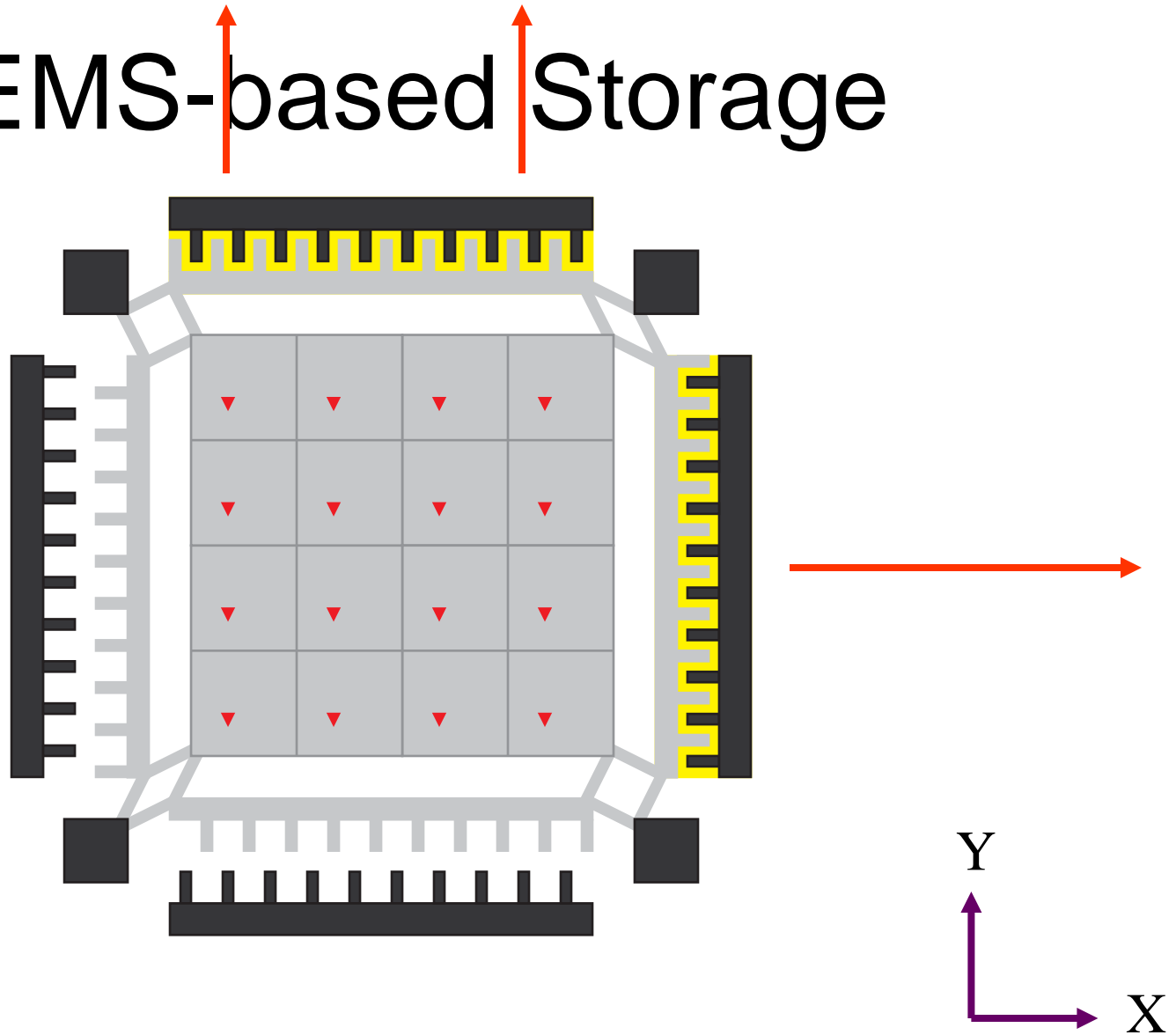
MEMS-based Storage

Actuators pull sled in both dimensions

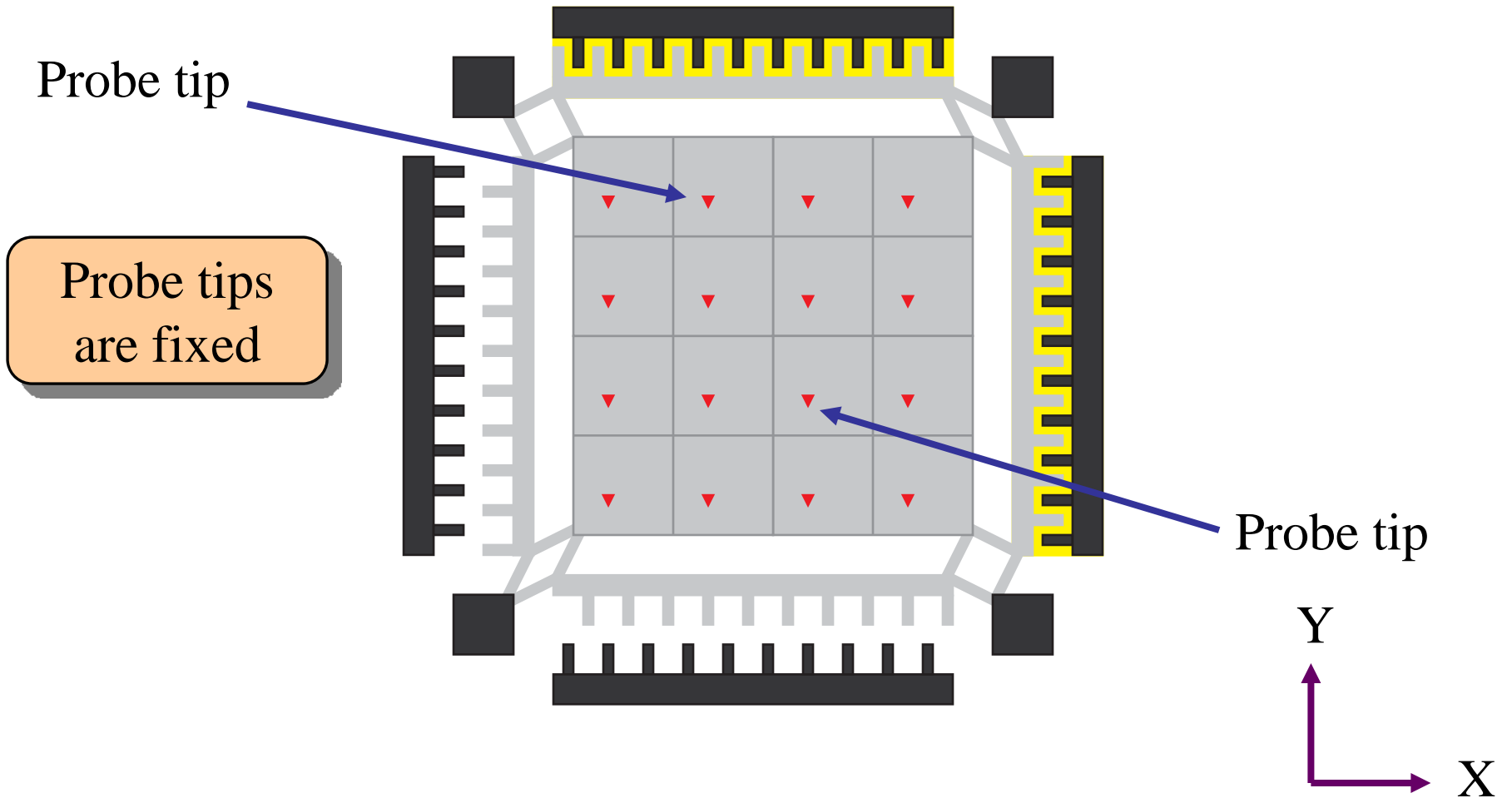


MEMS-based Storage

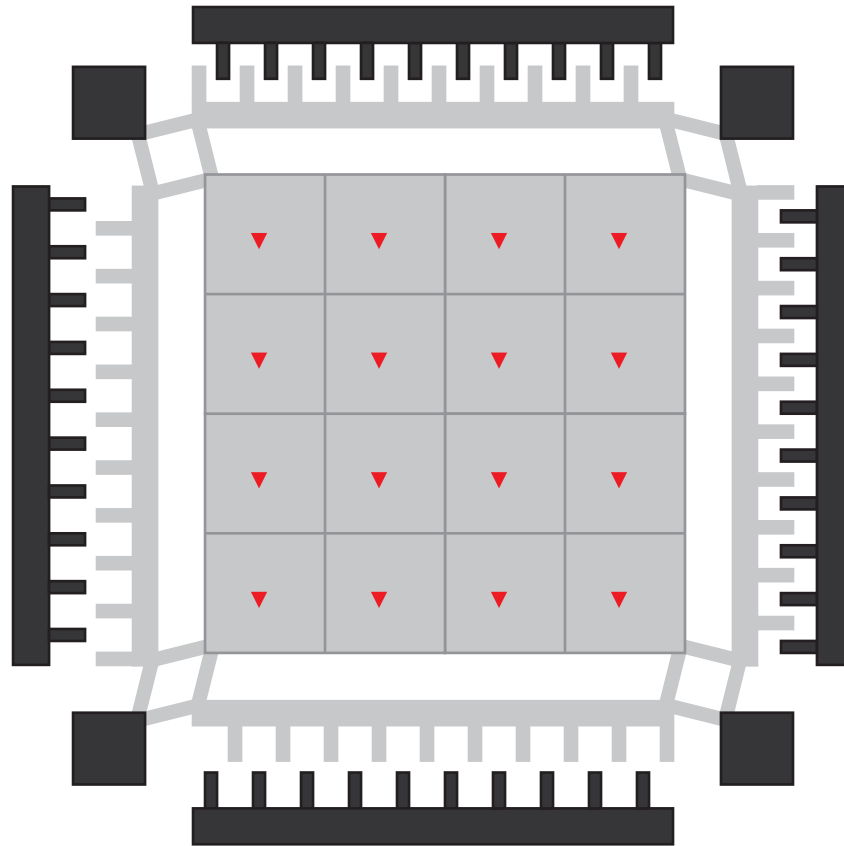
Actuators pulled in both dimensions



MEMS-based Storage

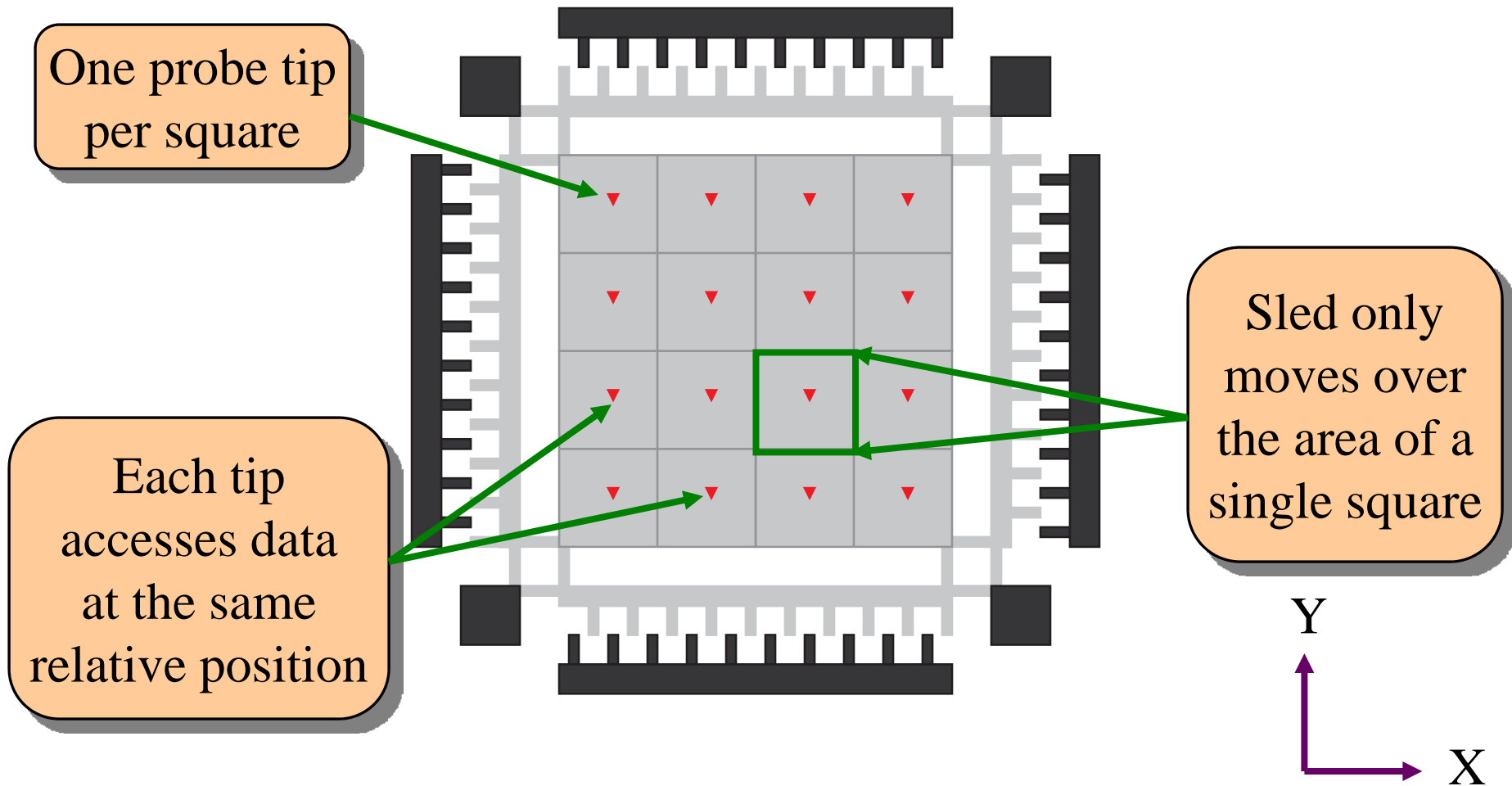


MEMS-based Storage



Probe tips
are fixed

MEMS-based Storage



Why Use MEMS-based Storage?

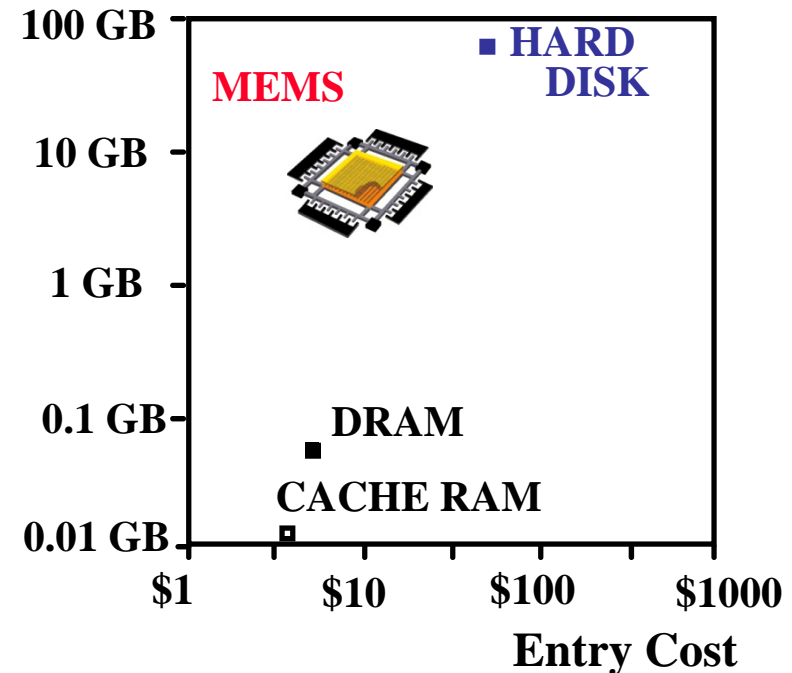
Capacity @ Entry Cost

- **Cost !**

- 10X cheaper than RAM
- Lower cost-entry point than disk
 - \$10-\$30 for ~10 Gbytes
- New product niches
- Can be merged with DRAM & CPU(s)

- **Example Applications:**

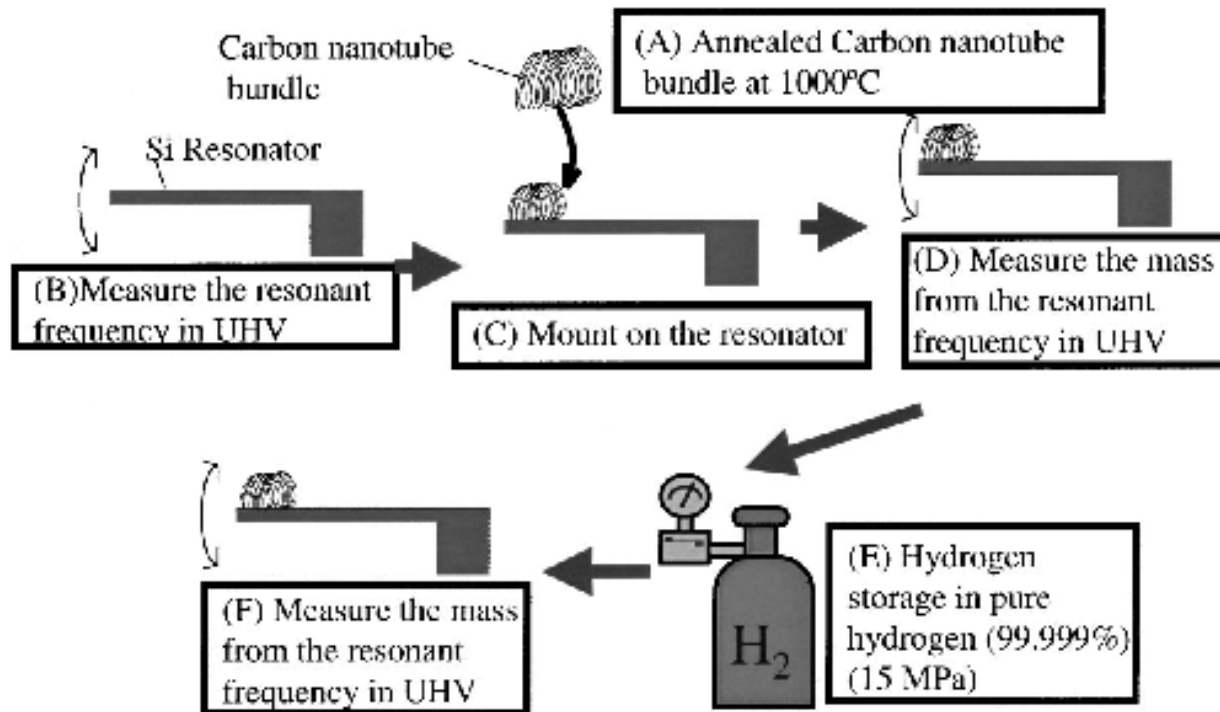
- “throw-away” sensors / data logging systems infrastructure monitoring; e.g., bridge monitors, concrete pours, smart highways, condition-based maintenance, security systems, low-cost speaker-independent continuous speech recognition, etc.
- Ubiquitous use in everyday world ... every appliance will be smart, store information, and communicate



Sensors

There are several proposed applications for MEMS-based sensors beyond the simple inertial transducers discussed above.

For example, the resonance frequency shift of a vibrating cantilever may be used to determine changes in mass loading:

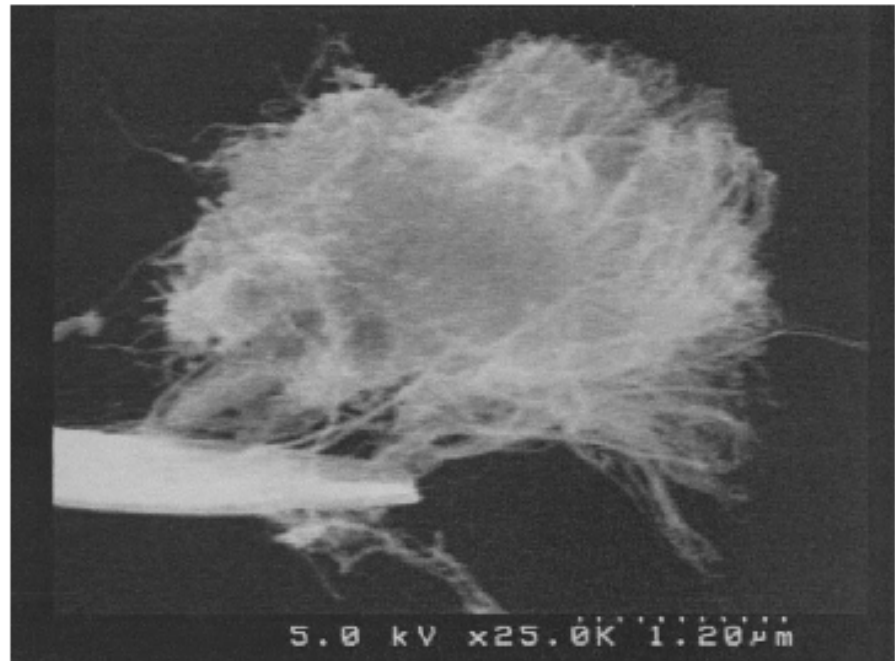


Sensors

With proper treatment, can get their cantilevers to have $Q \sim 50000$ with resonant frequencies ~ 100 kHz.

This gives mass sensitivities as good as 10^{-21} kg (!).

The fantasy version of this gadget has a fancier detection scheme and operates at a much higher resonant frequency.



Ono *et al.*, Rev Sci Instr **74**, 1240 (2003)

Vision: doing mass spectrometry by watching discrete changes in resonator frequency as analytes are adsorbed.

Sensors

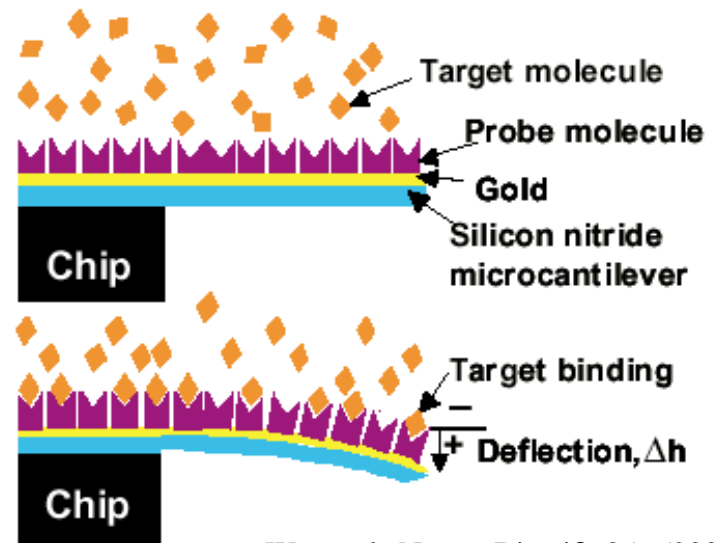
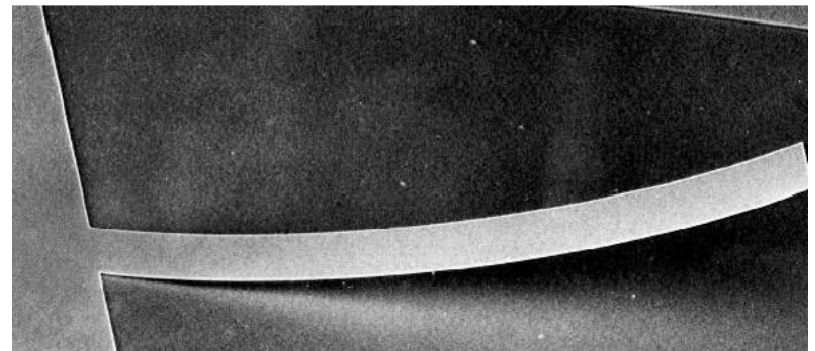
One can also look at steady state displacement of a cantilever.

Recall our picture of surface stress effects in thin members:

Consider functionalizing the top surface of a cantilever to selectively bind to an analyte.

That binding changes surface stress, which in turn changes cantilever bending.

Example: gadget to test for prostate cancer!



Summary

- MEMS are a logical extension of silicon fab techniques into the realm of mechanical devices.
- Advantages of MEMS: uniformity, cost of mass production, integration with microelectronics
- Many applications already, including automotive, sensing, displays, and inkjet printers.
- Potential for additional applications is also very exciting, including data storage technology, other sensor applications, and even power generation (!).

Next time:

NEMS, quantum effects, and the frontiers of mechanics

Frontiers of MEMS / NEMS

Nanoelectromechanical systems

Properties

Motivation

Detection schemes

Physical limits: damping, quantum effects

Nanotribology

Origins of friction

Superlubricity

Nanoelectromechanical systems

- Typical resonance frequencies up in the rf:

Consider a Si beam 50 nm thick, 50 nm wide, and 600 nm long, clamped at both ends.

$$\nu_1 = \frac{1}{2\pi} \sqrt{\frac{EI}{\rho A}} \left(\frac{4.73}{L} \right)^2 \quad E = 1.69 \times 10^{11} \text{ Pa}, \rho = 2330 \text{ kg/m}^3$$

$$\longrightarrow \nu_1 = 1.18 \text{ GHz}$$

- Displacements tend to be small, however, because of high stiffness and small forces.

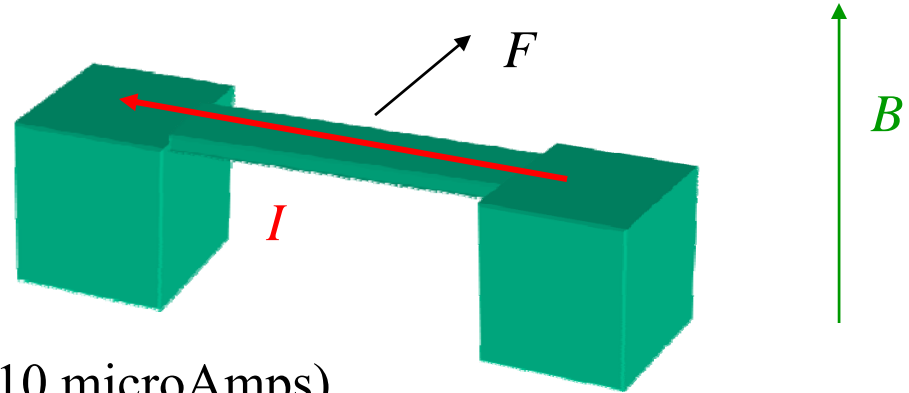
Quick estimate: effective spring constant should be roughly twice that of a cantilever of half the length.

$$k = \frac{Ewt^3}{4L^3} \longrightarrow \text{Total } k = 19.6 \text{ N/m.}$$

Nanoelectromechanical systems

Consider magnetic drive, with force due to current in the beam, assuming a 1 T magnetic field.

Total lateral force on the wire is ILB .



For a reasonable current (10 microAmps), total force is ~ 6 pN.

This would imply a maximum displacement of ~ 300 fm (0.1 % of an atomic diameter).

Peak velocities, however, would still be nontrivial, on the order of 0.3 mm/sec.

Motivation

Why study mechanical systems at these scales?

- Potential for mechanical rf filters and oscillators
- High bandwidth sensors and active devices (charge pumps, switches)
- Fundamental quantum mechanics issues

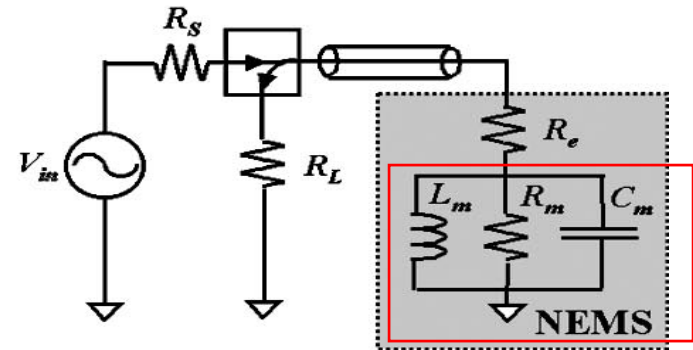
Collective modes with frequencies such that $\hbar\omega > k_B T$ possible:

- Macroscopic objects in pure quantum states?
- Entanglement?
- Nature of decoherence / quantum measurement studies.
- Sensitivity to exotic physics (Casimir effect)

Detection schemes

Ekinci *et al.*, APL **81** 2253 (2002)

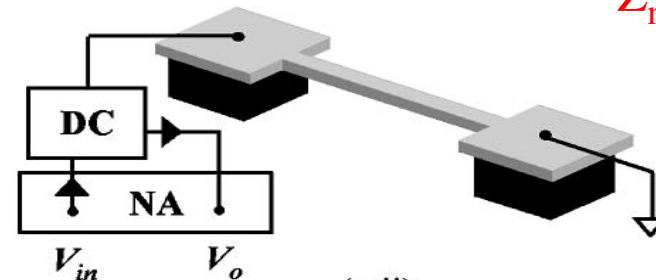
Usually consider NEMS resonator as an equivalent RLC network, and do some kind of impedance measurement.



(a-i)

$Z_m(\omega)$

At high frequencies, typical approach is to terminate a coax with the resonator drive. Changes in oscillator motion mean changes in termination impedance + reflected power.



(a-ii)

Problem: backgrounds! Usually, $R_e \gg |Z_m(\omega)|$,

$$\longrightarrow V_0(\omega) \approx V_{in}(\omega) \frac{R_e + Z_m(\omega)}{R_L + R_e}$$

Large background makes signal detection difficult....

Magnetomotive detection - sensing motion by “back action” on drive rather than directly detecting displacement.

Realistic oscillator analysis

Beam length L_{beam} , current carrying electrode of length L , in magnetic field B , effective spring constant k .

$$m \frac{\partial^2 y}{\partial t^2} + \gamma \frac{\partial y}{\partial t} + ky = F(t) \quad \text{Drive by current } I_d(t)$$

Detected EMF due to motion of conductor in magnetic field:

$$V_{EMF}(x, t) = \frac{\partial y(x, t)}{\partial t} B \sin \theta(x) \rightarrow V_{avg}(t) \approx 0.53LB \frac{\partial y(t)}{\partial t}$$

Fourier transform:

$$V_{avg}(\omega) \approx \frac{0.53 \times i \omega \omega_0 L L_{\text{beam}} B^2 / k}{\omega_0^2 - \omega^2 + i(\gamma / m)\omega} I_d(\omega)$$

This is a Lorentzian line around the resonance frequency.

$$Q = \frac{\omega_0 m}{\gamma}$$

Realistic oscillator analysis

Near resonance,
$$V_{avg}(\omega) \approx \frac{0.53 \times LL_{beam} B^2 \omega_0}{k} Q I_d(\omega)$$

This implies that we can define an effective mechanical resistance:

$$R_m \approx \frac{0.53 \times LL_{beam} B^2 \omega_0}{k} Q$$

From the form for the whole response, including phase effects, we can also find equivalent capacitance and inductance for an effective *RLC* network describing the connection between drive current and detected voltage:

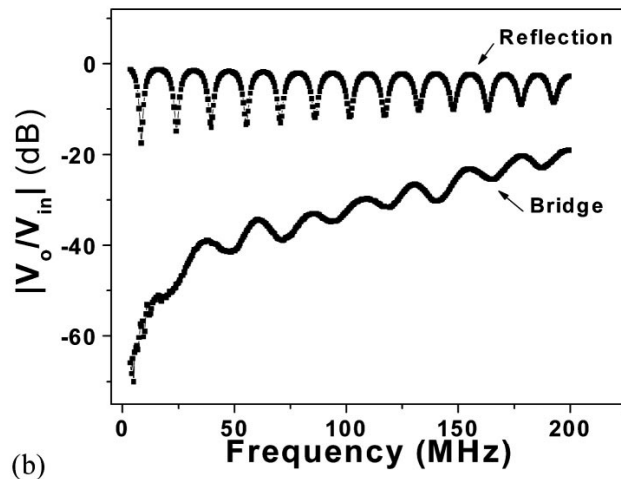
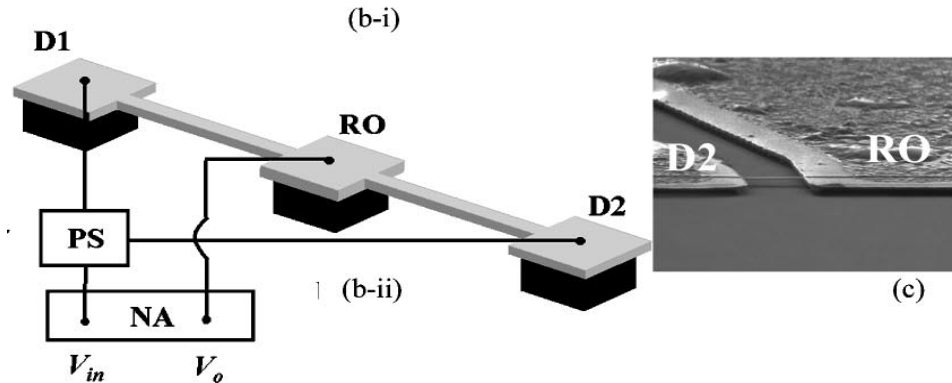
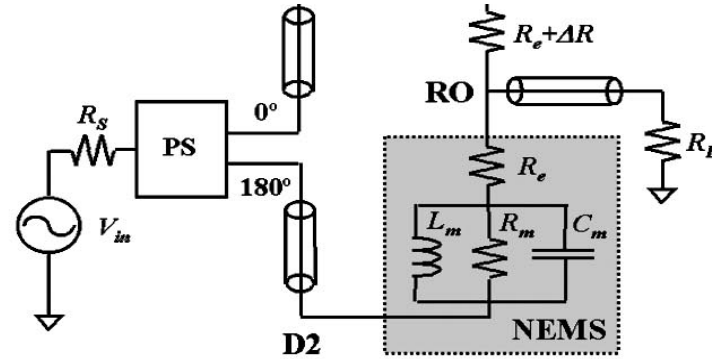
$$C_m \approx \frac{k}{0.53 \times LL_{beam} B^2 \omega_0^2} \qquad L_m \approx \frac{0.53 \times LL_{beam} B^2}{k}$$

Detection schemes

Alternative is to use *bridge* technique (naturally a null measurement).

Two nominally identical resonators driven out of phase with each other.

Difference in response of two shows up as nonzero voltage on middle pad.



Result is a reduction in background voltage by a factor of 200 or more for a particular mode of one of these beams.

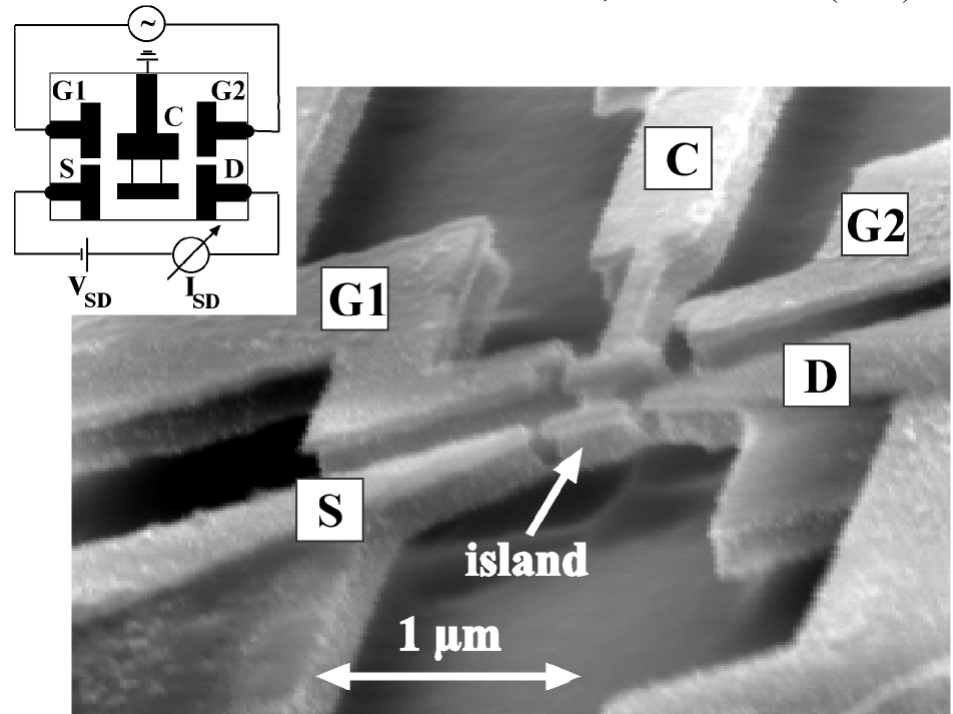
Coupling mechanical and charge motion

Erbe *et al.*, PRL **87** 096106 (2001)

It's also possible to couple mechanical and charge motion together in subtle and interesting ways.

Ex.: mechanical charge shuttle.
Oscillations of “clapper” periodically alter tunneling barriers between island and source/drain.

Result is a pumping of charge due to mechanical motion.



Room temperature: typically pumped ~ 1000 electrons per oscillation (@87 MHz)

4.2 K: pumped ~ 0.11 electrons per oscillation (@120 MHz)

If system were sufficiently well-controlled, could try to get single electron pumping even at room temperature....

Physical limits: damping

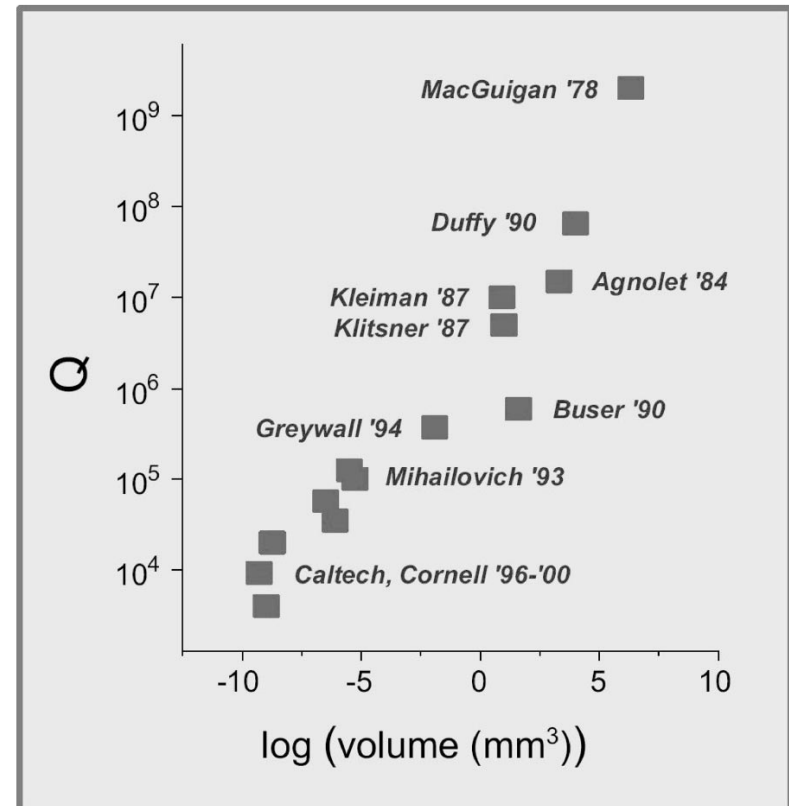
As we saw previously, the mechanical damping of nanomechanical resonators is problematic:

Mohanty *et al.*, PRB **66**, 085416 (2002)

Rewriting in terms of the internal friction Q^{-1} , we find that $Q^{-1} \sim L$ (size).

Other interesting clues:

- $Q^{-1} \sim$ weakly with T at low T
- $Q^{-1} \sim B^2$ in magnetically driven oscillators
- Q^{-1} exhibits hysteresis on thermal cycling, + “aging” effects at constant T .



Physical limits: damping

What actually sets the fundamental limits on damping of nanomechanical resonators?

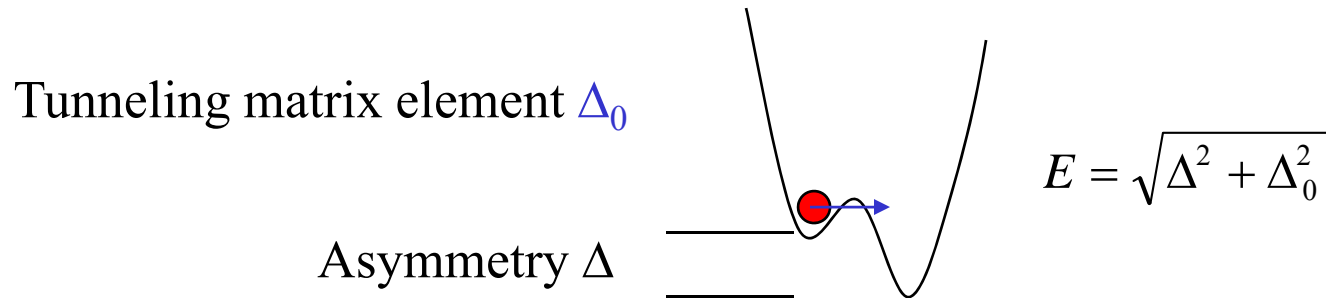
A number of things to be concerned with:

- Noise due to driving and measuring electronics
- Thermometry: what temperature is oscillator really?
- Intrinsic phonon coupling between oscillator and bulk substrate
- Anharmonic mode coupling
- Thermoelastic losses
- Bulk and surface dynamical defects

Tunneling two-level systems

Localized excitations apparently common to all amorphous (disordered) materials at low temperatures.

Simple picture: an atom or group of atoms experiences a double-welled potential as a function of some configurational coordinate.



Simplest assumption: in a disordered system, there will be a broad statistical distribution of these parameters.

Assume Δ is flat in energy from 0 out to some cutoff ($\sim 100\text{K}$).

Assume $\ln \Delta_0$ is flat in energy with low ($\sim 0.1 \text{ mK}$) and high energy (100K) cutoffs.

Tunneling two-level systems

This model is by Anderson, Halperin, and Varma, and independently by J.C. Philips (1972).

Leads to correct power laws for specific heat vs. T and thermal conductivity vs. T in glassy insulators.

To allow these excitations to thermally equilibrate with the phonons, must assume some elastic coupling to strain (typically perturbs Δ).

Result: TLS have a well-defined effect on both the speed of sound and the internal friction. If TLS have some effective time-varying charge distribution, expect to see quadratic dependence of Q^{-1} on B , as observed,

Scaling of dissipation with surface to volume ratio suggests that most of the damping is related to dynamical (TLS-like) surface defects.

Quantum effects: noise

Can have the mechanical analog of Johnson noise in mechanical systems!

Recall that Johnson noise can be considered due to thermal (and at low enough temperatures quantum) population of cavity modes in a cavity terminated by two resistors.

These cavity modes lead to equilibrium charge fluctuations across the resistors, that show up as current (or voltage) noise.

Alternately, one can consider terminating an electromagnetic cavity with these mechanical oscillator transducers.

Result: *displacement* (or *force*) noise on the oscillator!

At high temperatures, force noise power: $S_F = \sqrt{\frac{4k_B T k}{0.53 Q \omega_0}}$

Quantum effects: Casimir force

Very small distance scales also make it possible to observe physics that seems rather exotic at first glance: the Casimir force.

Consider two perfectly conducting plates separated by a distance d .

One dramatic way of describing this physics: there are zero-point fluctuations of the electromagnetic field throughout all space.

Since this background is the same everywhere, we usually can't detect it.



However, because of the *boundary conditions* on the plates, there is a *cutoff* in the allowed modes between the plates. That is, there can't be zero-point fluctuations of modes longer in wavelength than $2d$ between the plates.

Result: higher (vacuum) energy density outside the plates than inside, leading to a force that tries to squish the plates together.

Quantum effects: Casimir force

This Casimir force is very strongly distance dependent; the exact functional form depends on the precise geometry of the electrodes.

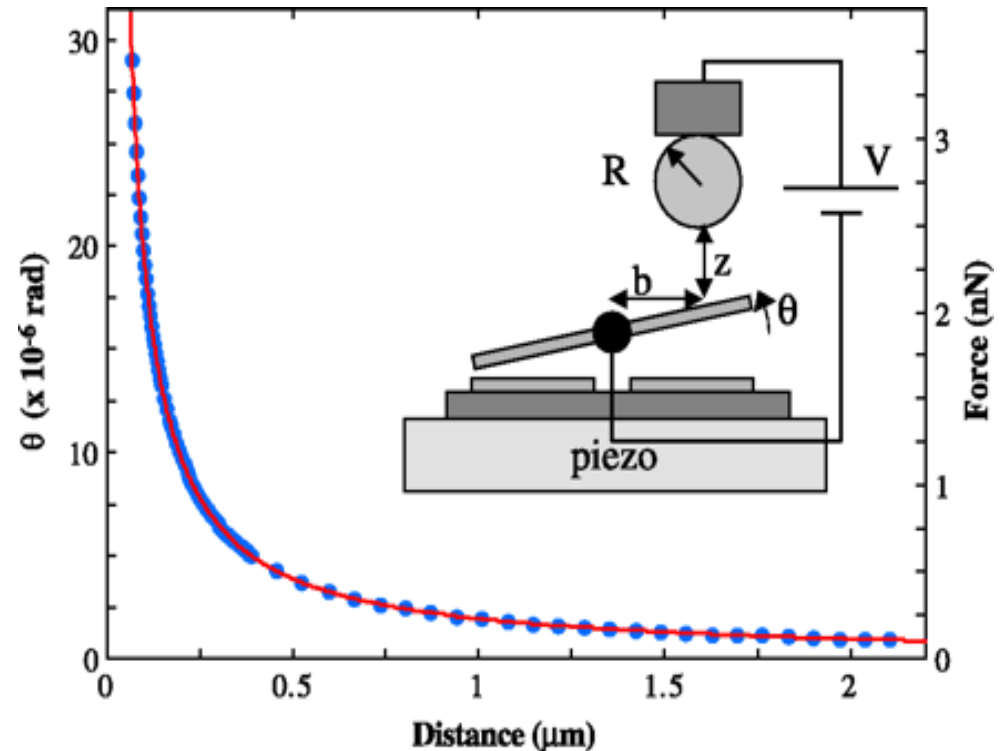
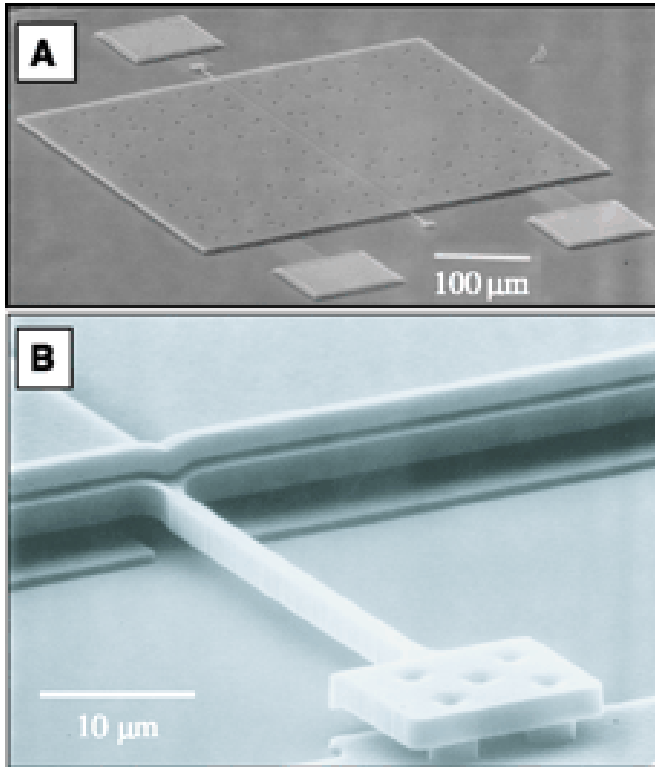
- Force still exists even for realistic conductors and dielectrics.
- Closely related (but not precisely identical?) to the Van der Waals interaction.

between plates $F_c = -\frac{\pi^2 \hbar c}{240} \frac{1}{d^4}$

between sphere and plate $F_c = -\frac{\pi^3 \hbar c}{360} R \frac{1}{d^3}$

Quantum effects: Casimir force

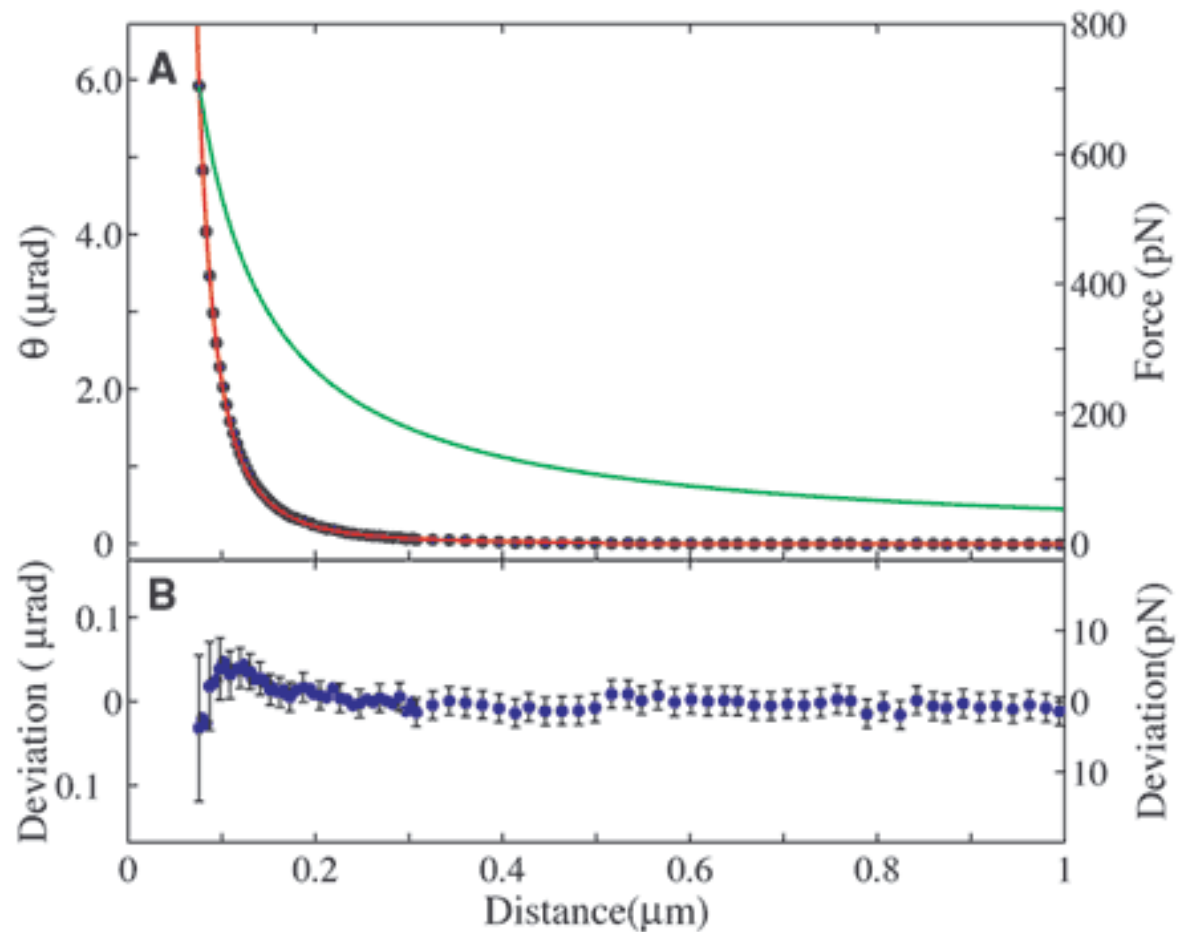
Chan *et al.*, Science **291**, 1941 (2001)



- Made torsional paddle, calibrated force vs. displacement response by electrostatic torque.
- Then carefully nulled out electrostatics (incl. work fn. difference!), and measured force vs. separation between sphere and paddle.

Quantum effects: Casimir force

Chan *et al.*, Science **291**, 1941 (2001)



- Agreement with theory, to within precision of their knowledge of conductivity of Au and poly-Si.
- [Quantum electrodynamics](#) can have significant effects in nanoscale devices!

True quantum mechanics?

Gaidarzhy *et al.*, PRL **94**, 030402 (2005)

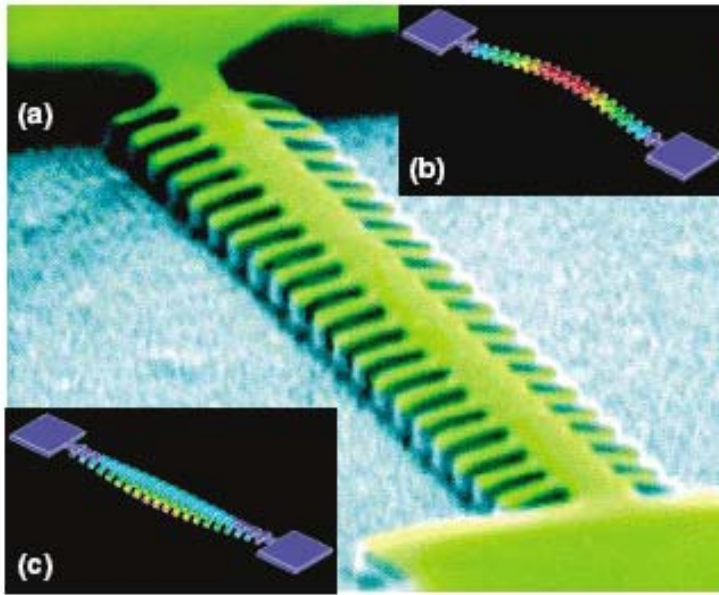


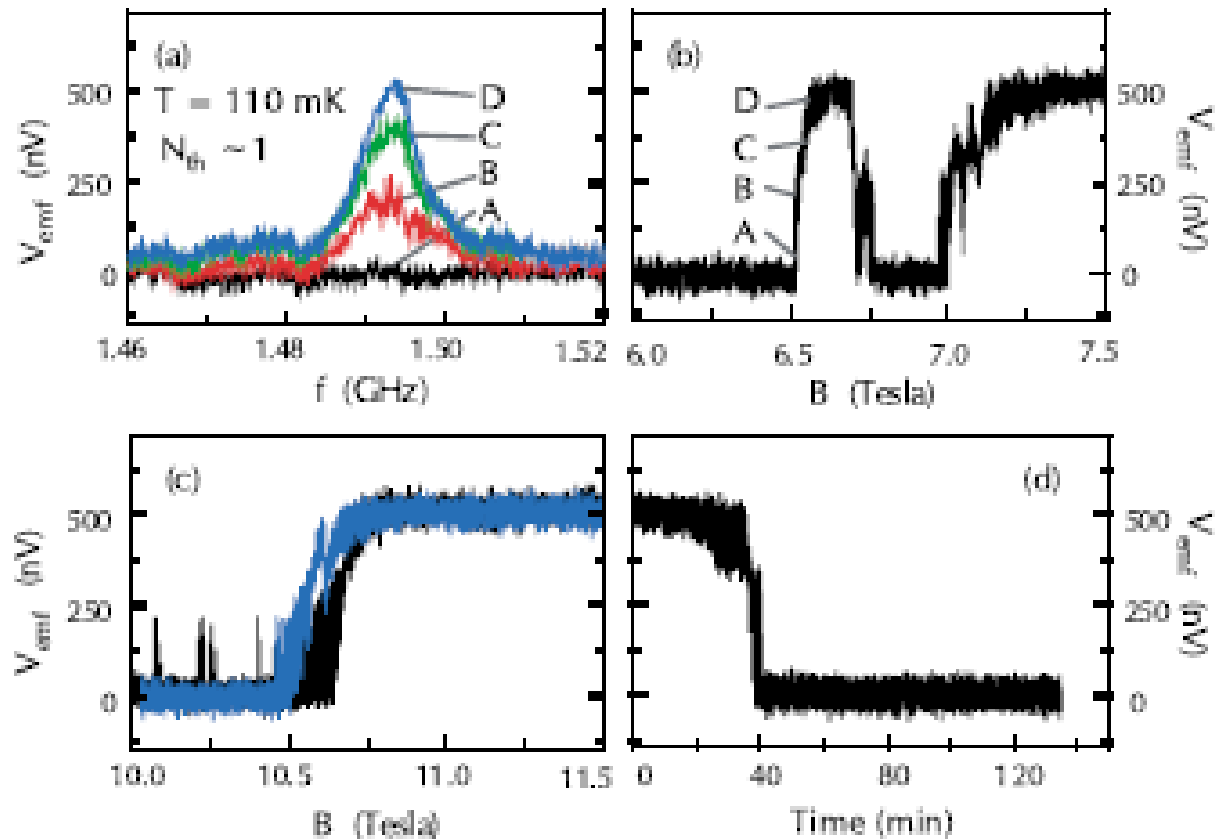
FIG. 1 (color). (a) Scanning electron micrograph of the suspended antenna oscillator. It consists of a central Si beam, $10.7 \mu\text{m}$ long and 400 nm wide, as well as two arrays of 500 nm long and 200 nm wide paddles on both sides. The total thickness of the structure is 245 nm , comprised of the device layer of silicon (185 nm) and the thermally evaporated gold electrode (60 nm), colorized in yellow. (b) Modal simulation of the antenna structure, showing the low frequency ($f \approx 10 \text{ MHz}$) fundamental resonance mode. (c) In the high order collective mode, the paddles vibrate at their own natural frequency ($f \geq 1 \text{ GHz}$), and the induced in-phase strain drives the central beam, which acts as an amplifier of the paddle motion.

BU group argues that a collective mode of this complicated oscillator has a frequency of 1.49 GHz , and amplitude large enough to detect magnetomotively.

At that frequency, thermal population of the 1st excited oscillator state should be around 1.

True quantum mechanics?

Gaidarzhy *et al.*, PRL **94**, 030402 (2005)



Discrete transitions between different oscillatory behaviors (detectable signal vs. no signal). Is this discrete quantum behavior?

True quantum mechanics?

Schwab *et al.*, PRL **95**, 248901 (2005)

Comment on “Evidence for Quantized Displacement in Macroscopic Nanomechanical Oscillators”

Some major objections raised:

- Continuously measuring oscillator displacement can't be used like this to see the quantized energy occupancy.
- This is a driven oscillator; thermal occupancy of the ground state is irrelevant.
- The Q implies an energy occupancy lifetime of ~ 10 ns, not hours.
- The collective dynamics shouldn't amplify amplitudes of motion passively.

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True quantum mechanics?

Gaidarzhy *et al.*, PRL **95**, 248902 (2005)

Gaidarzhy *et al.* Reply:

Authors' responses:

- Disagree that this is a continuous measurement, or that such a measurement is necessarily bad.
- *No real response to drive criticism*, though they rebut other concerns about noise from electronics.
- Say they never claimed to be measuring the relaxation time.
- Collective mode does indeed have big displacement, and signal is strongly affected by geometry of oscillator anyway.

A. Gaidarzhy, G. Zolfagharkhani, R. L. Badzey, and
P. Mohanty
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Read the papers – make up
your own mind!

Tribology

Study of friction and lubrication.

“Bastard child” of mechanical engineering, surface science, and materials science.

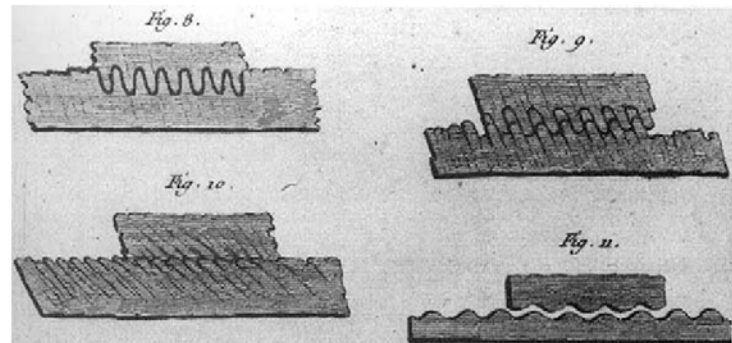
- What do we usually mean by “friction”? -- classical laws
- What is the underlying microscopic physics?
- Is there new physics to see at the nm scale here?

Amonton's laws: classical friction (*c.* 1700)

- (Tangential) Frictional force is directly proportional to the *normal* force at an interface.
- This frictional force is, for identical normal forces, *independent* of the area of contact at the interface (!).
- (Coulomb's other law) While there is a difference between static and sliding friction, once sliding has begun the coefficient of sliding friction is *independent* of the relative velocity at the interface.

Failed attempts to understand this microscopically:

Coulomb's idea that rough surfaces play a role....



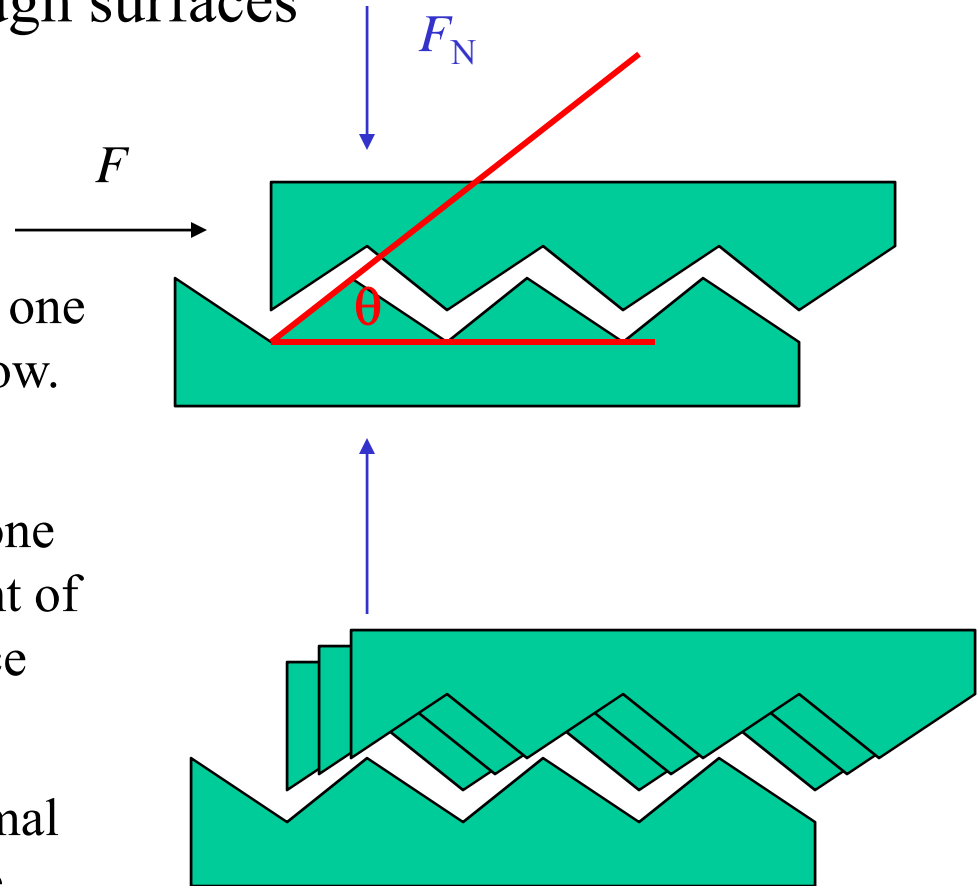
Classical friction and rough surfaces

Coulomb's static friction
basic idea:

Just consider trying to slide one
facet up another facet for now.

If the height of one of these
bumps was d , then clearly one
needs to do a certain amount of
work to slide the upper piece
past the lower piece.

Problem with this: the normal
force then *does* work on the
way down the other side.



- Everything in this picture is conservative - can't ever get dissipation this way.

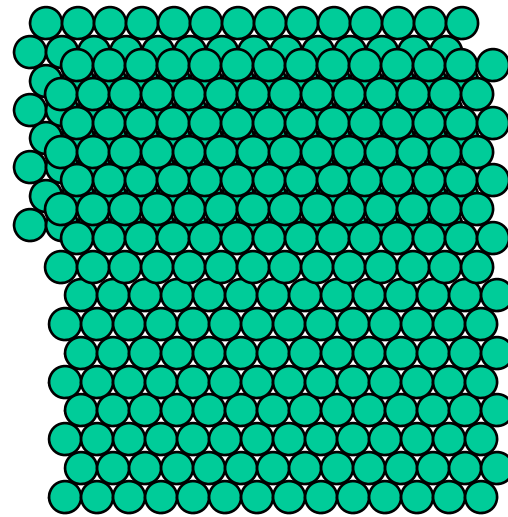
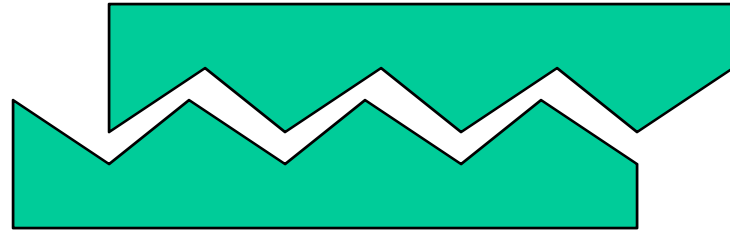
Classical friction and rough surfaces

Another problem: this picture predicts that smooth, clean surfaces should be essentially frictionless.

In fact, two smooth, polished pieces of metal can *cold-weld* when placed in contact!

The reason for this should be obvious; in the absence of surface contamination, it's energetically favorable to satisfy all the bonding at what used to be the interface.

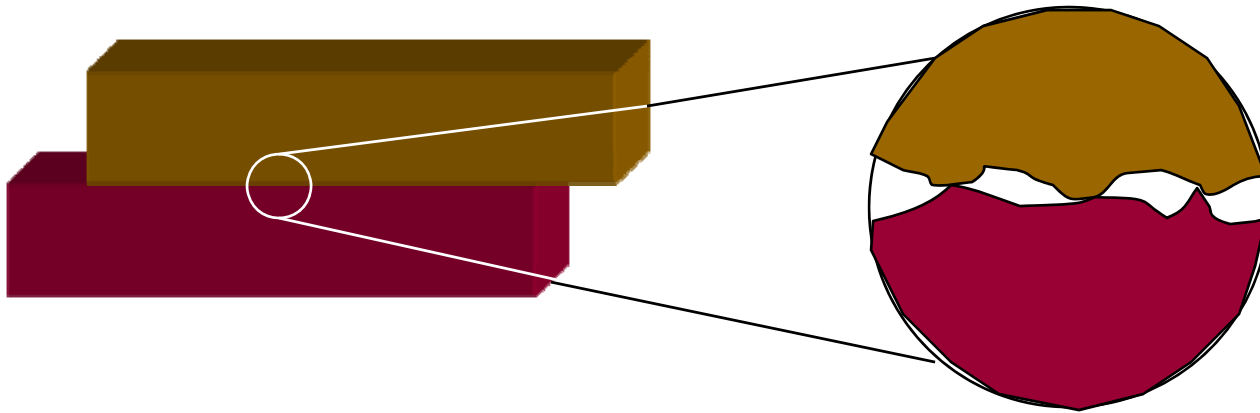
This is a clue toward modern investigations of nanotribology....



What is the true contact area?

In the 1950s, a group at Cambridge advanced the idea that the actual contact area between surfaces:

- is much smaller than the apparent contact area
- depends on the normal force between the surfaces.



Idea here is that friction comes about by shearing away the true contacts through (irreversible) plastic deformation.

Small contact model

If true contact area is A , and shear strength of the junctions in question is τ_{\max} , then the friction force is just given by

$$F_f = A \tau_{\max}$$

Suppose the true contact area is proportional to the normal force. The idea would be that the little contacts squish down into larger contacts as the normal force increases.

If this is so, then the contact pressure P should be constant, and the friction coefficient

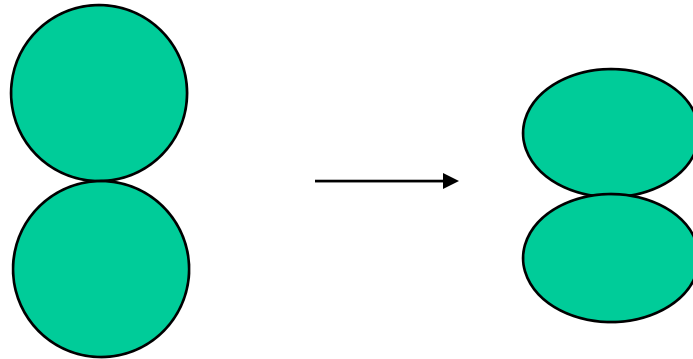
$$\mu \equiv \frac{F_f}{N} = \frac{A \tau_{\max}}{N} = \frac{\tau_{\max}}{P}$$

One must then examine microscopic models to see if $A \sim N$ is really reasonable, and perform experiments to see if it seems to be true.

Note that molecular adhesion, neglected here, is assumed to become important in the limit that P approaches zero.

Small contact model

For perfect elastic deformation and two spherical surfaces,



one can do the calculation and find $A \sim N^{2/3}$.

For plastic deformation, one finds $A \sim N$ as desired.

Furthermore, it was shown in the 1960s that, for a statistical distribution of spherical contacts (“multiasperity model”), one finds that the ensemble ends up with $A \sim N$ as the number of contacts gets large.

Small contact model

One big problem: what is the largest reasonable friction coefficient one can get from this model?

For big normal forces, the largest reasonable pressure, well into the plastic deformation regime, is something like $3\sigma_{\max}$, three times the yield strength of the material.

Similarly, τ_{\max} , the maximum shear strength, is on the order of $\sigma_{\max}/2$ for most materials in the continuum limit.

So,

$$\mu_{\max} = \frac{\tau_{\max}}{P_{\max}} \approx \frac{\sigma_{\max} / 2}{3\sigma_{\max}} \approx \frac{1}{6}$$

Unfortunately, much larger values of μ are routinely measured, even in systems with no evidence of irreversible damage.

Modern techniques

Tribology renaissance with the availability of ultrahigh vacuum, atomically smooth surfaces, and sensitive force measurements.

- Quartz crystal microbalance

Quartz crystal resonator can be used to monitor the deposition of sub-monolayer amounts of adsorbates.

Mass loading of adsorbates changes natural frequency of resonator; stick-slip motion broadens the resonance.

Can have quartz crystals with atomically flat and smooth surfaces; can precoat with Au and anneal in UHV, for example, to get Au (111) as determined by electron diffraction.

Note: no friction between adsorbate and surface = no mechanical loading.

Quartz crystal microbalance

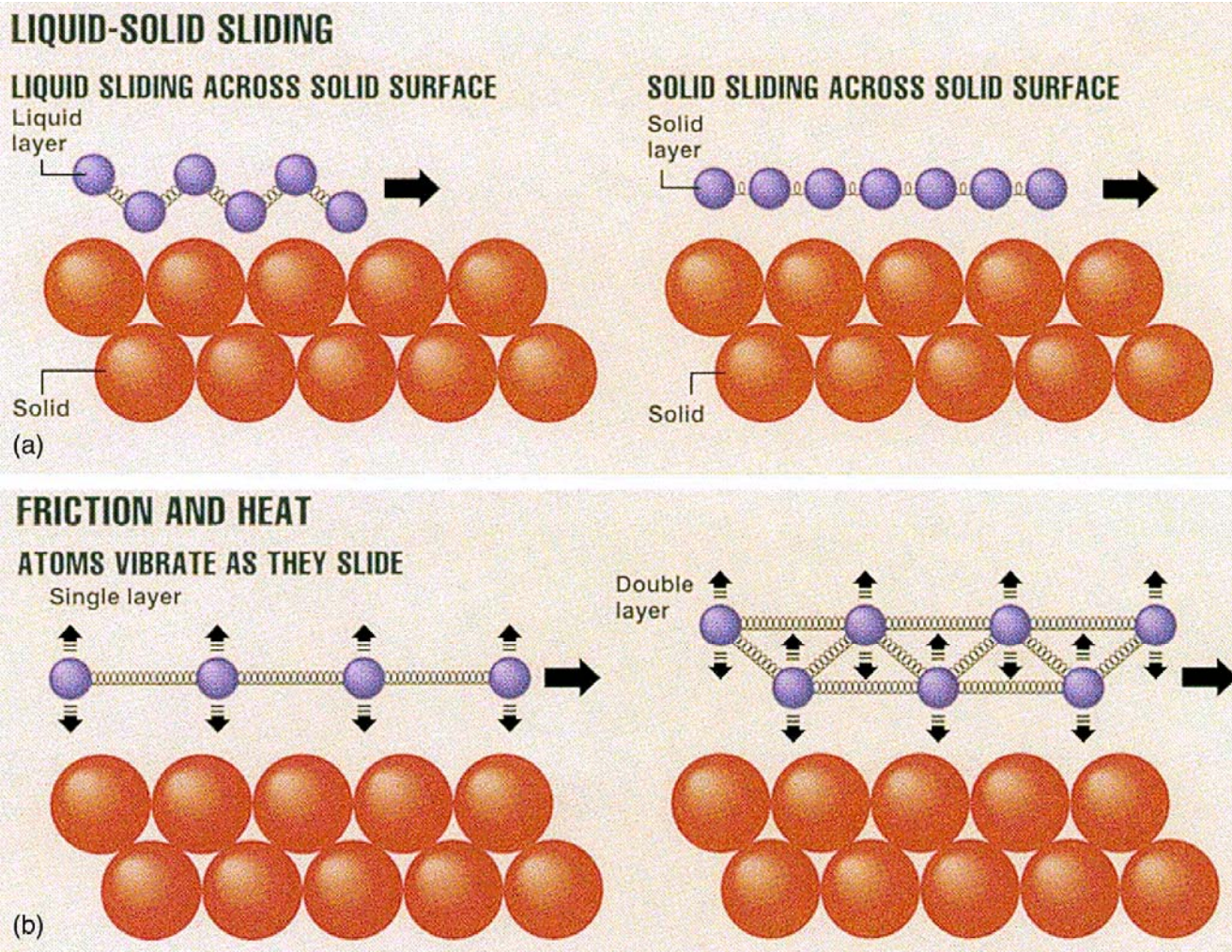
Typical experiment (1980s, early 90s): calibrate adsorption of noble gas (krypton, xenon) on Au(111) through a number of surface scattering techniques (know coverage of surface).

Then observe friction effects as a function of conditions (coverage, surface roughness, temperature).

Important results from this work:

- Could see phase transitions (solid-liquid) in the adsorbed monolayers.
- Frictional interactions well-described by assuming microscopic irreversibility comes about via *phonon emission*.
- Example of this evidence: friction is higher in a solid *bilayer* than in a solid *monolayer*....

Microscopically irreversible processes



Electronic effects?

Idea of phonon emission was that strain builds up between adsorbate and surface until it becomes energetically favorable to launch a lattice vibration into one of the two.

These phonons eventually thermalize, and this is where irreversibility comes in. The work being done against friction really is showing up as heat, even without damage to the surfaces.

What about electronic effects? If one of the surfaces is a metal, can't the (gapless) electrons also be an energy sink (and therefore a source of irreversibility)?

Electronic effects?

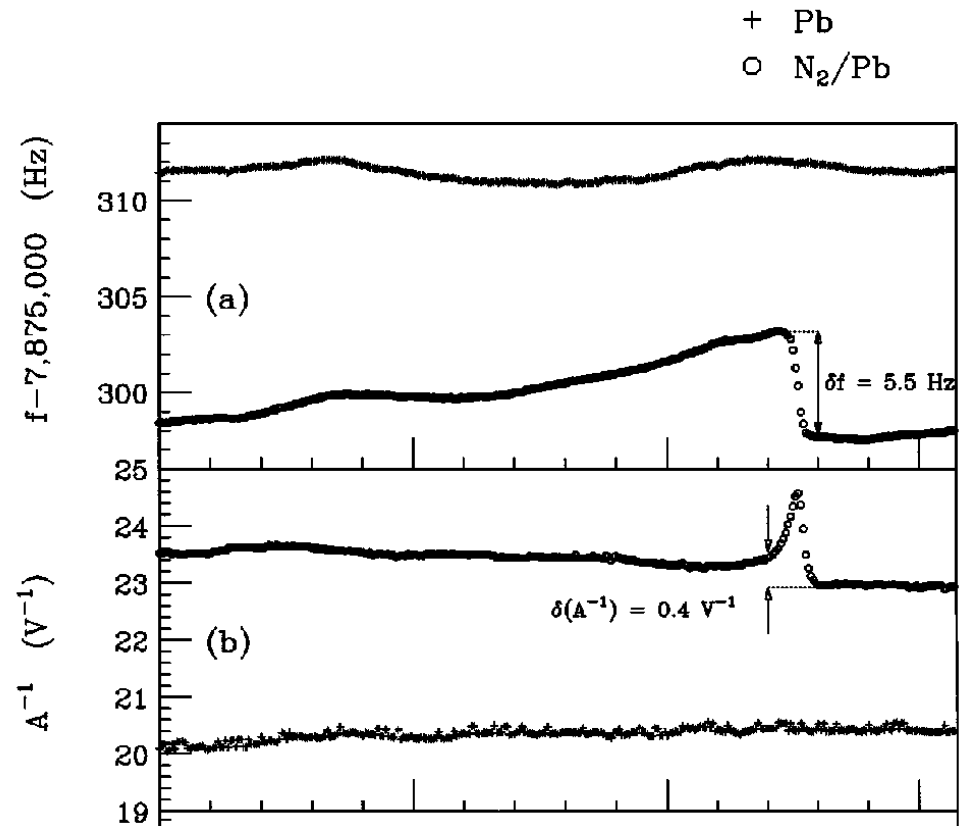
Dayo *et al.*, PRL 80, 1689 (1998)

Can perform experiment on superconducting Pb film, using adsorbed N₂.

Dayo *et al.* saw a sudden decrease in frictional effects when the lead went superconducting.

Possible reason:

- Electronic dissipation goes away and eliminates one source of effective friction.



Note that this work remains somewhat controversial - attempts to duplicate the result have not been successful.... Lead is notoriously finicky, too.

Ultraclean surfaces + chemistry

It's clear that to really get at the underlying physics requires ultrahigh vacuum and exceedingly clean (at least over the contact area) surfaces.

Turns out that most of the attributes we associate with friction are apparently due to the sub-monolayer of adsorbed junk on most surfaces!

What happens in the ultraclean limit?

Perhaps unsurprisingly, chemistry and exact commensurability of surfaces is crucially important.

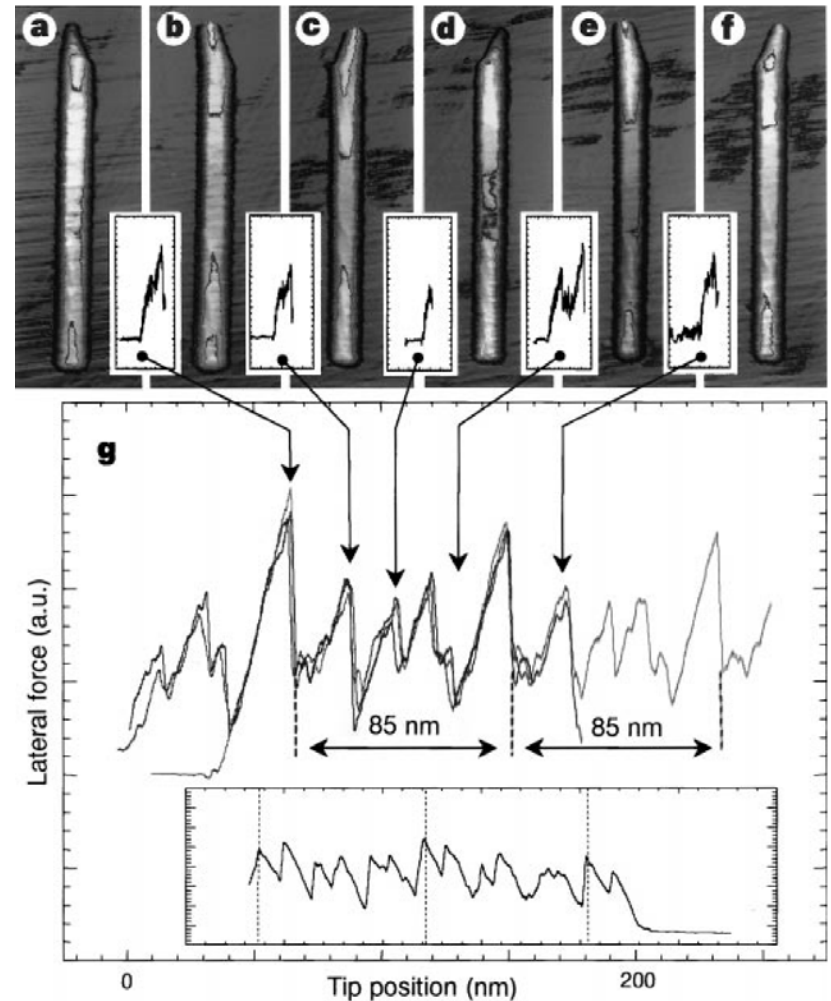
Ultraclean surfaces + chemistry

Falvo *et al.*, Nature **397** 236 (1999)

Rolling a multiwalled carbon nanotube across an atomically flat, clean, graphite surface.

Result: force needed to roll tube looks complicated as a function of roll angle, but is completely reproducible.

Force resisting the motion is determined by the van der Waals interaction and the details of exactly how the carbon atoms in the tube line up with those in the graphite.



Ultraclean surfaces + chemistry

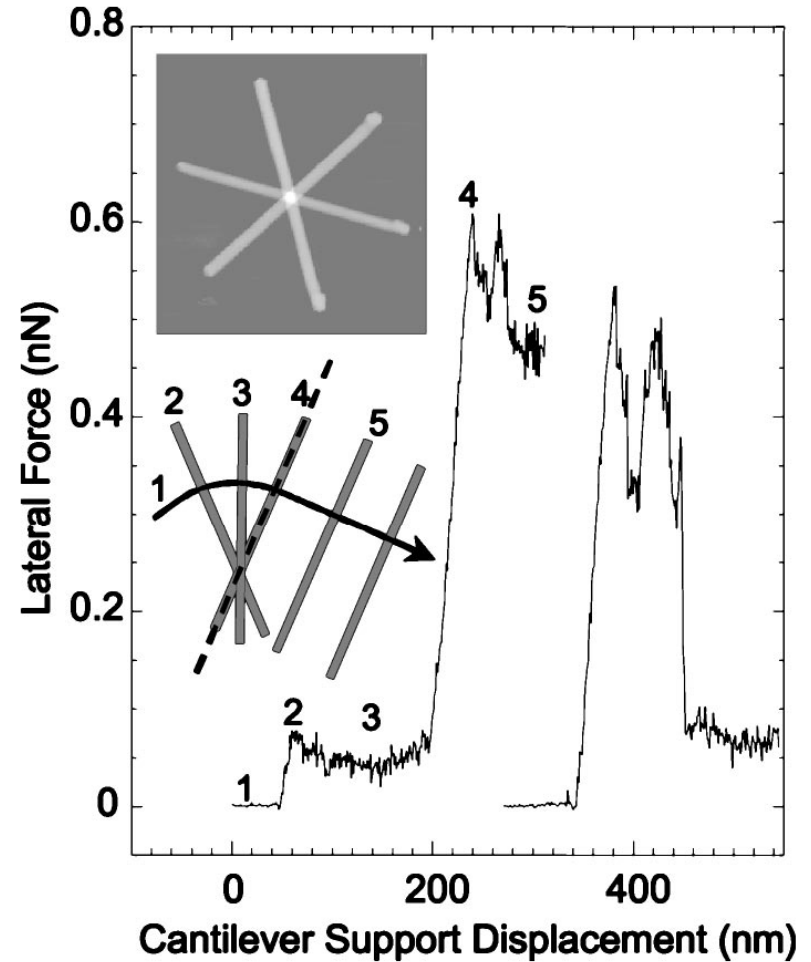
Falvo *et al.*, PRB **62** 10665 (2000)

Even more convincing:

Again, tube on graphite.

When trying to revolve tube on surface, investigators found that for a particular rotation of the tube, there were three specific directions where the stiction force was very large.

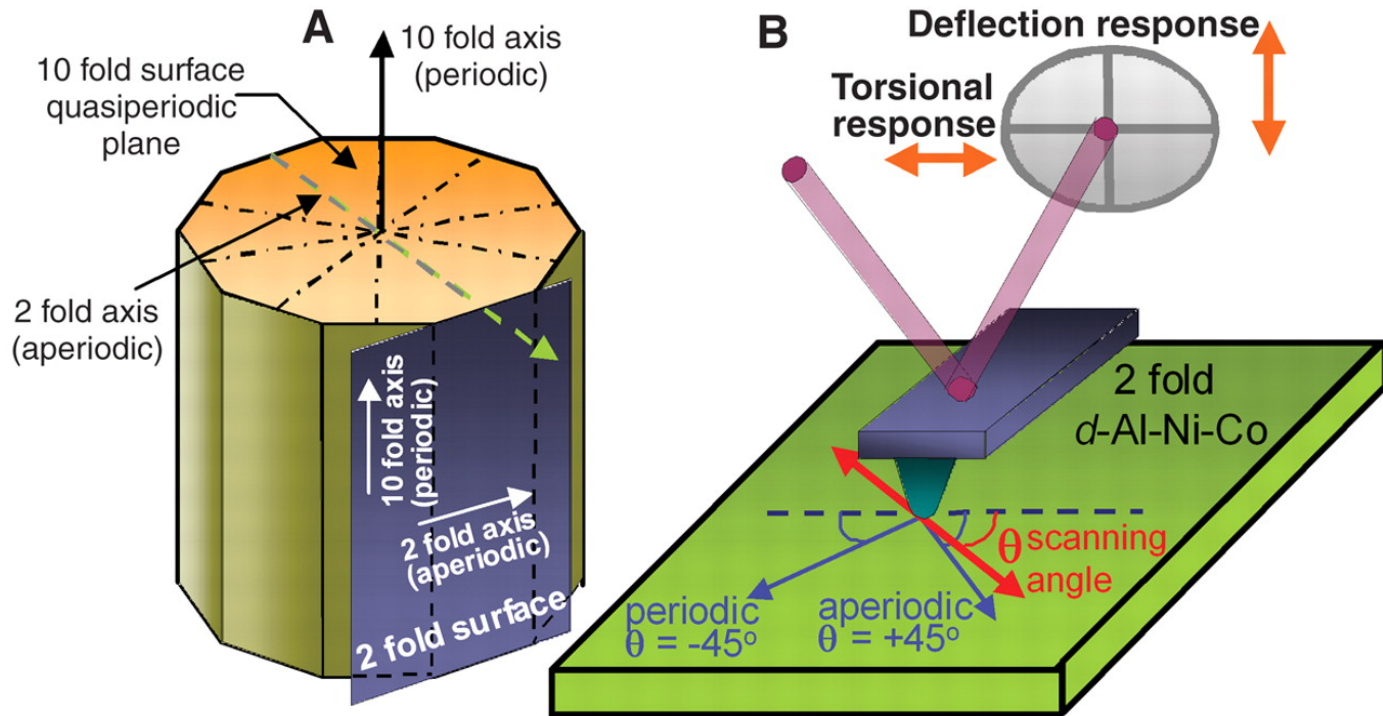
Correspond with commensurability of the tube atoms with underlying lattice!



Ultraclean surfaces + chemistry

A unique class of materials to further test these ideas: *quasicrystals*

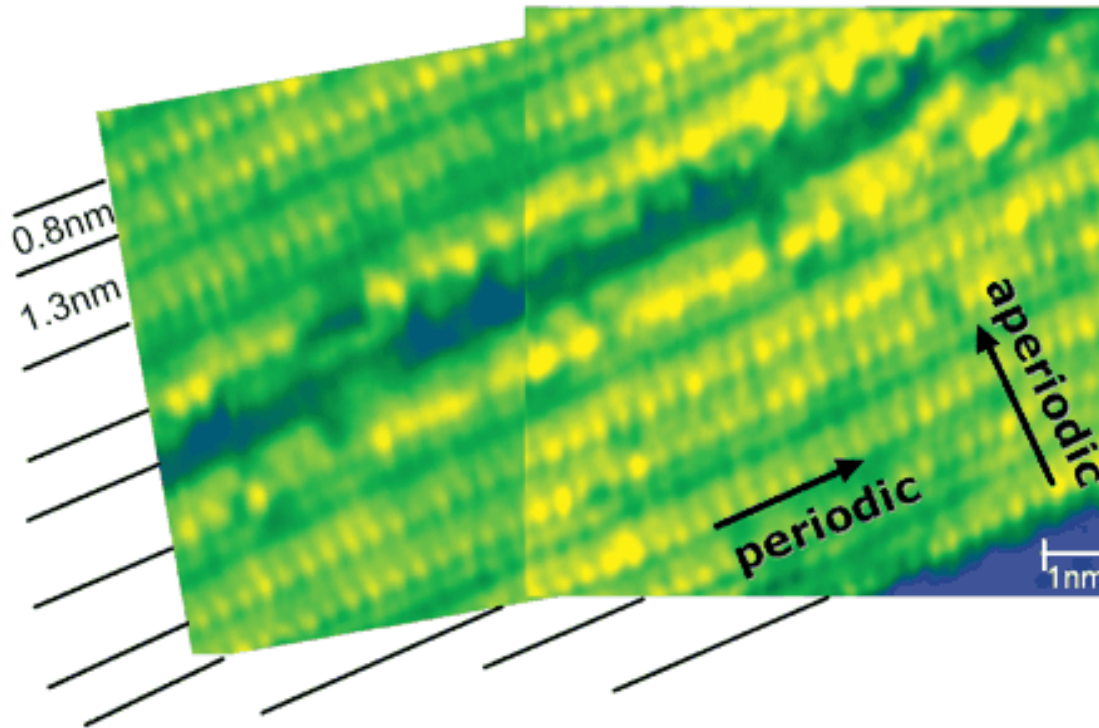
- Periodic along certain directions
- Aperiodic along other directions



Ultraclean surfaces + chemistry

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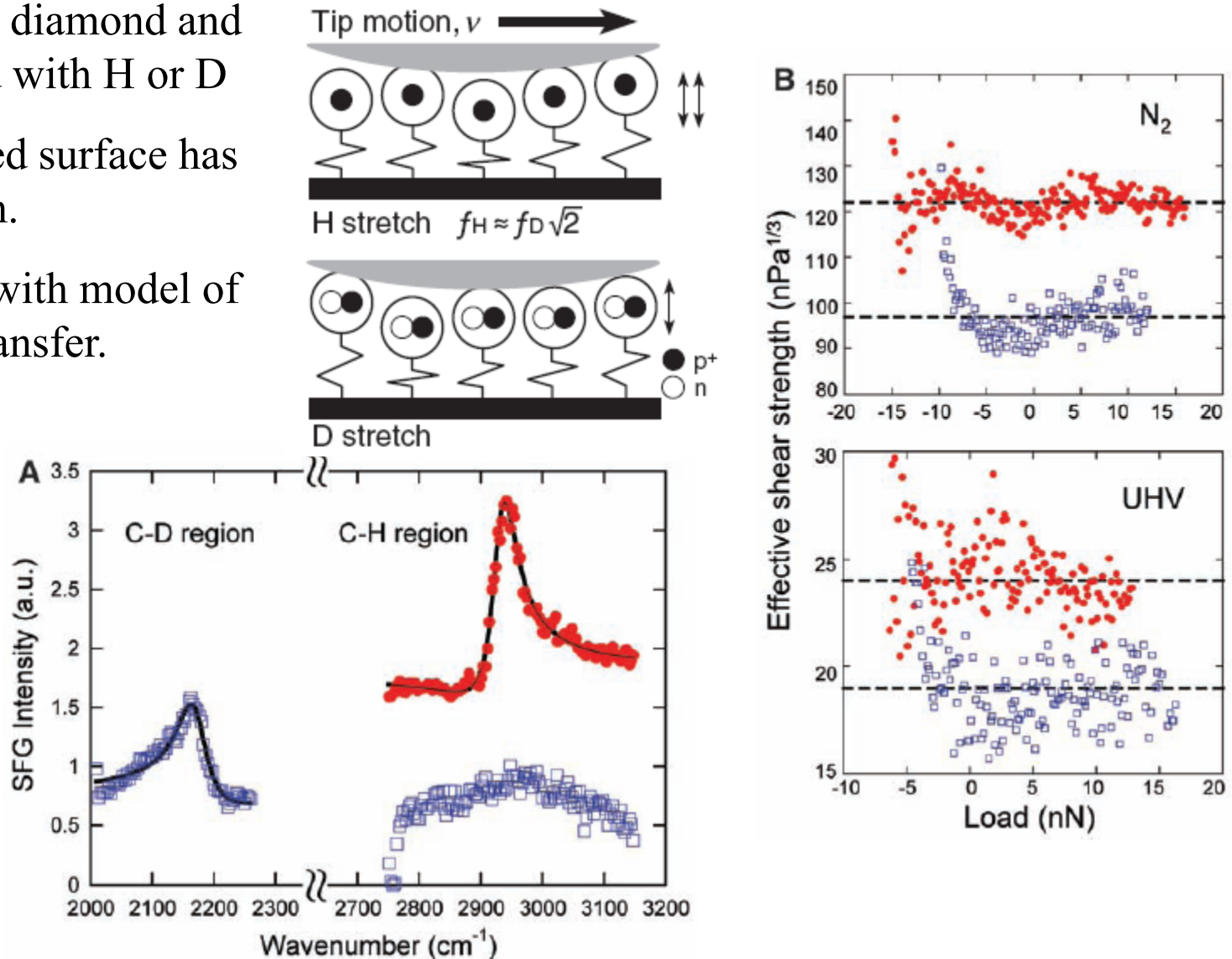


Ultraclean surfaces + chemistry

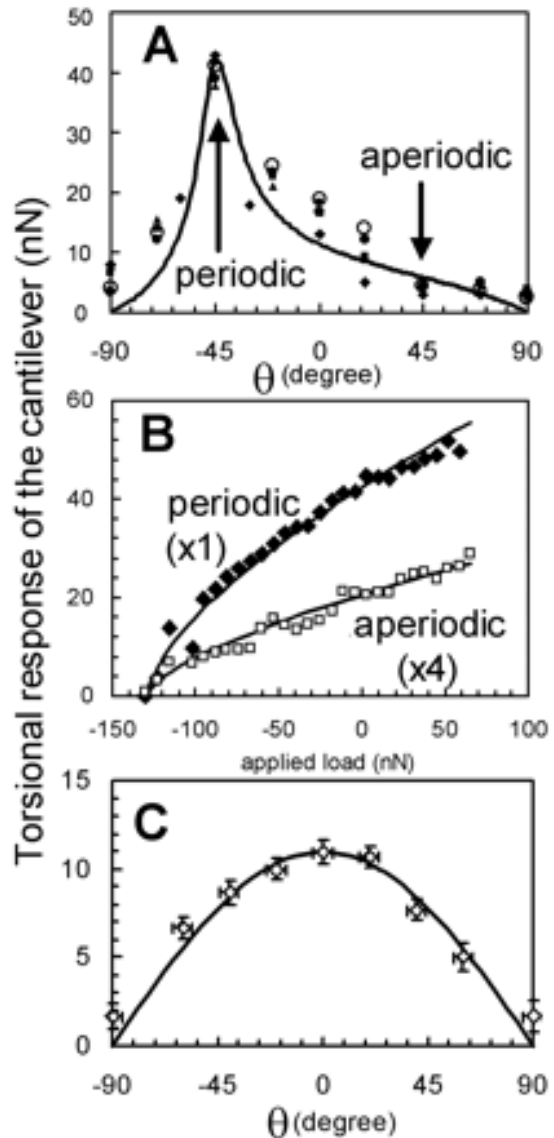
Cannara *et al.*, Science **318**, 780 (2007)

Single-crystal diamond and Si, terminated with H or D

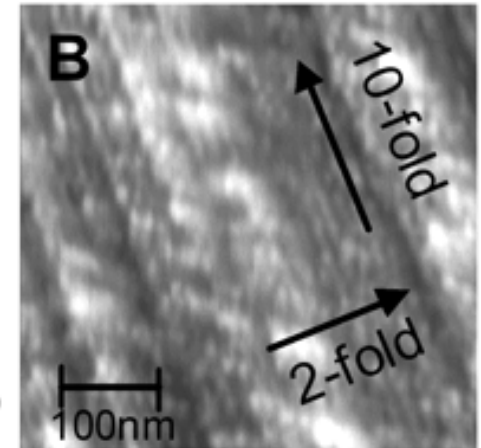
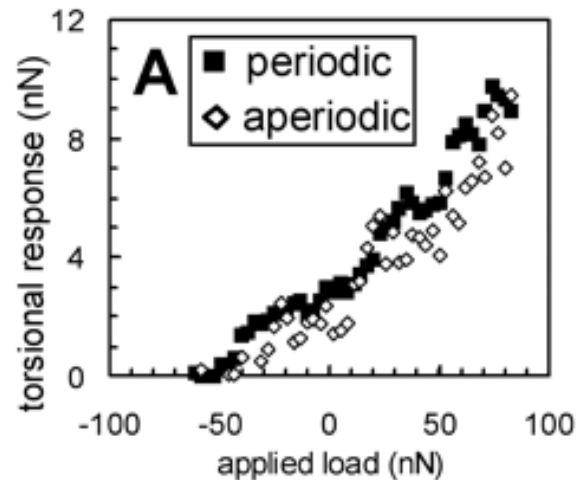
- H-terminated surface has higher friction.
- Consistent with model of vib. energy transfer.



Ultraclean surfaces + chemistry



Oxidation kills the anisotropy in the frictional force by messing up the surface.



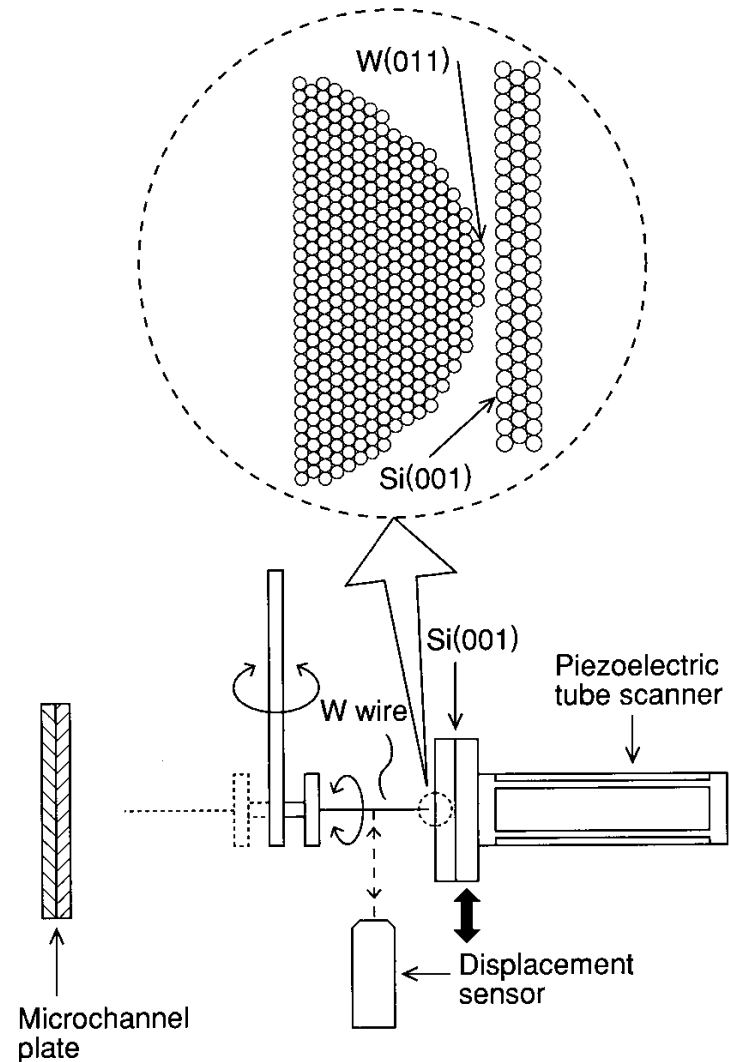
Superlubricity

Ultimate limit of these ideas: what happens if two surfaces are exceedingly clean, and there is no underlying commensurability between the two lattices?

Superlubricity: Hirano et al., PRL 78 1448 (1997).

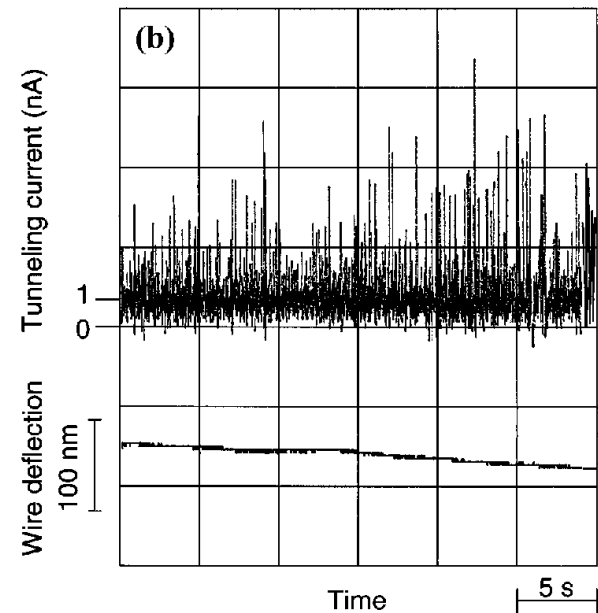
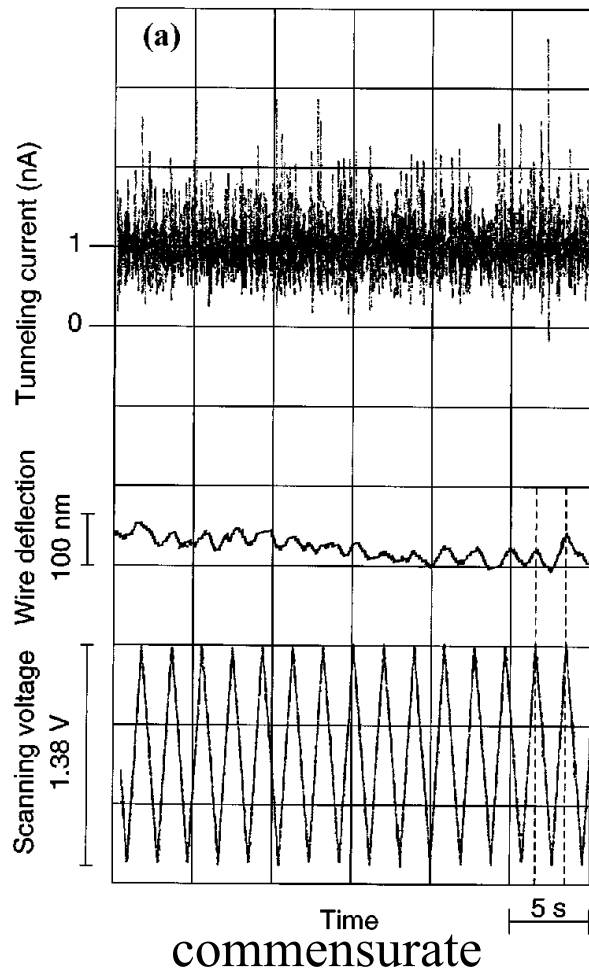
Use specially prepared tungsten (011) STM tip, and single crystal Si (001) surface.

Optically sensed wire lateral deflection to measure friction force.



Superlubricity

By varying substrate orientation, can perform friction measurement with either commensurate or incommensurate surfaces!



incommensurate

Summary:

- Origins of friction are quite subtle and complicated.
- Impressive progress has been possible recently because of the development of a number of tools and capabilities that are nano-related.
- Really at the atomic scale, the detailed chemistry of surfaces and the inelastic interactions between atoms determine the origins of dissipation.