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:

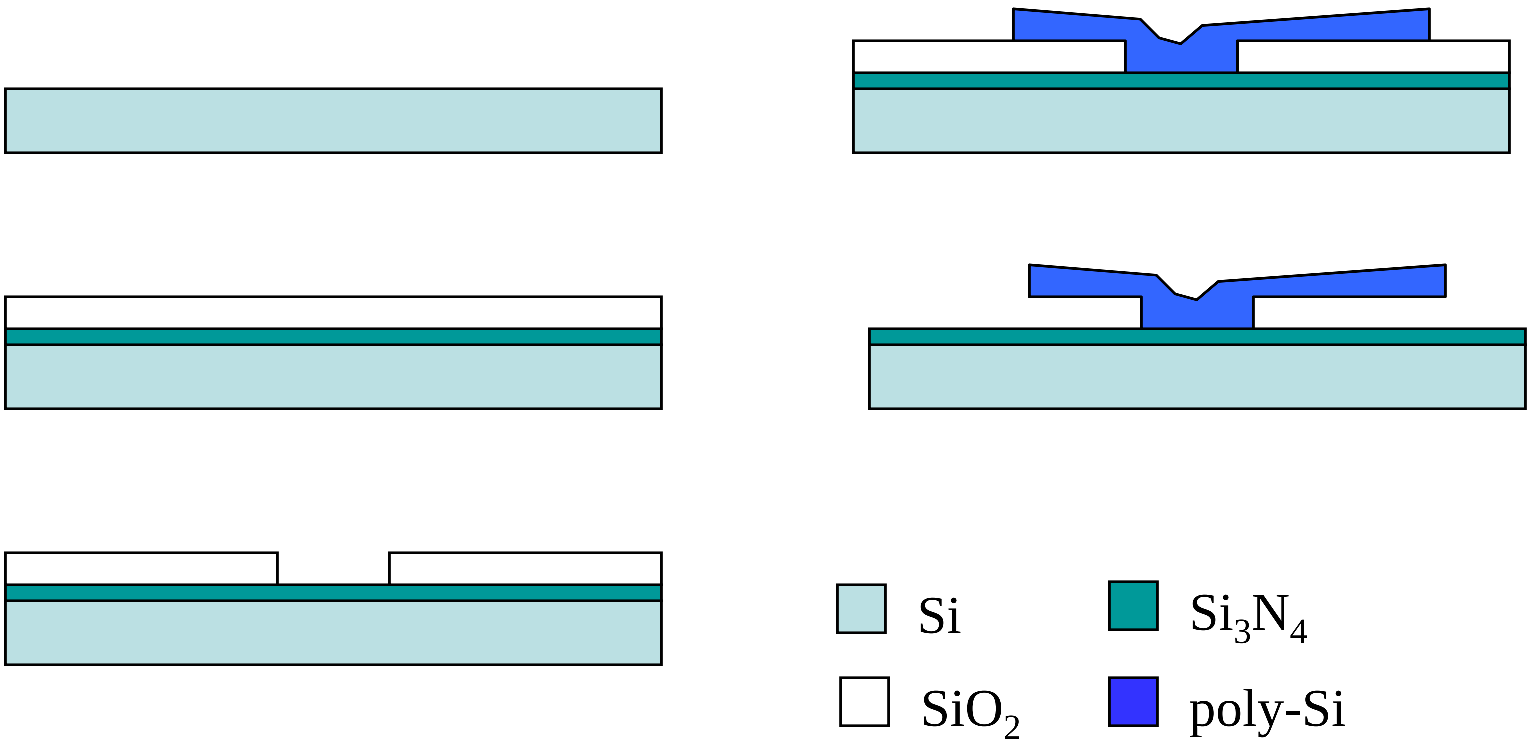
- Fabrication
- Enabling ideas + obstacles
- Applications

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:



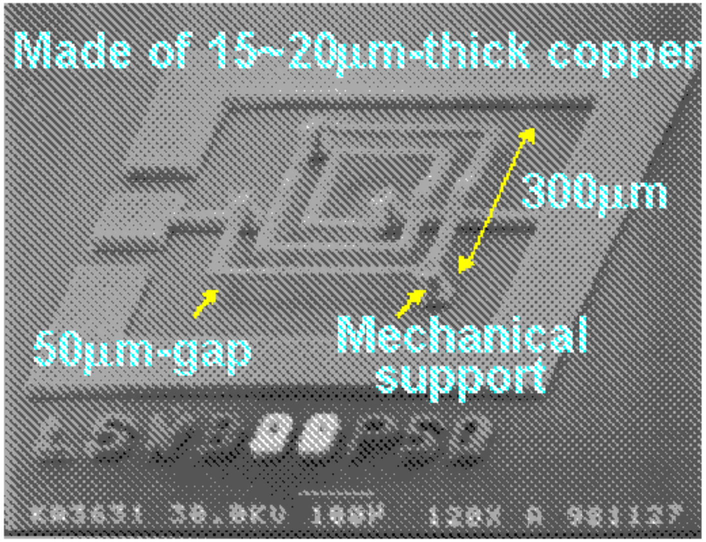
MEMS and NEMS fabrication

Additive processes

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

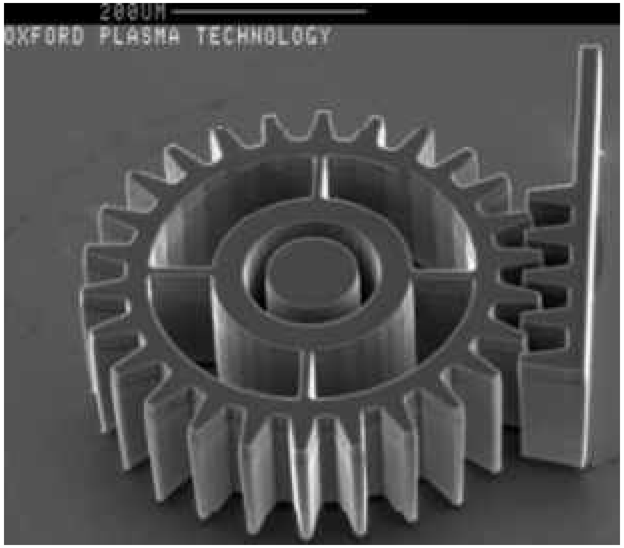
Pattern definition

- Photolithography
- Electron beam lithography



Wu, UCLA

MEMS and NEMS fabrication



Oxford Plasma Tech.

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!

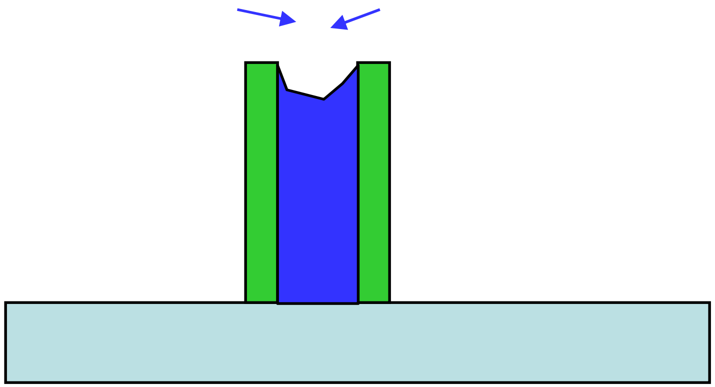
- Reactive Ion Etching (RIE), Inductively Coupled Plasma (ICP)-RIE

  Highly directional, chemically selective, can be slow.

  Vertical sidewalls, little or no undercut.

Supercritical drying

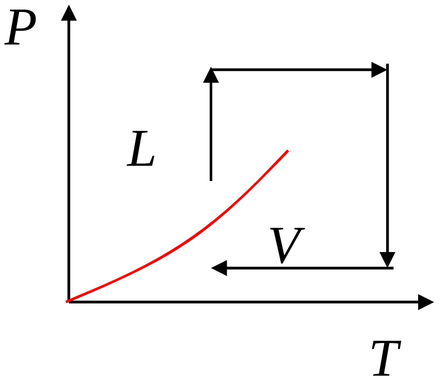
Surface tension forces can be large enough to be destructive, for nanoscale structures:



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

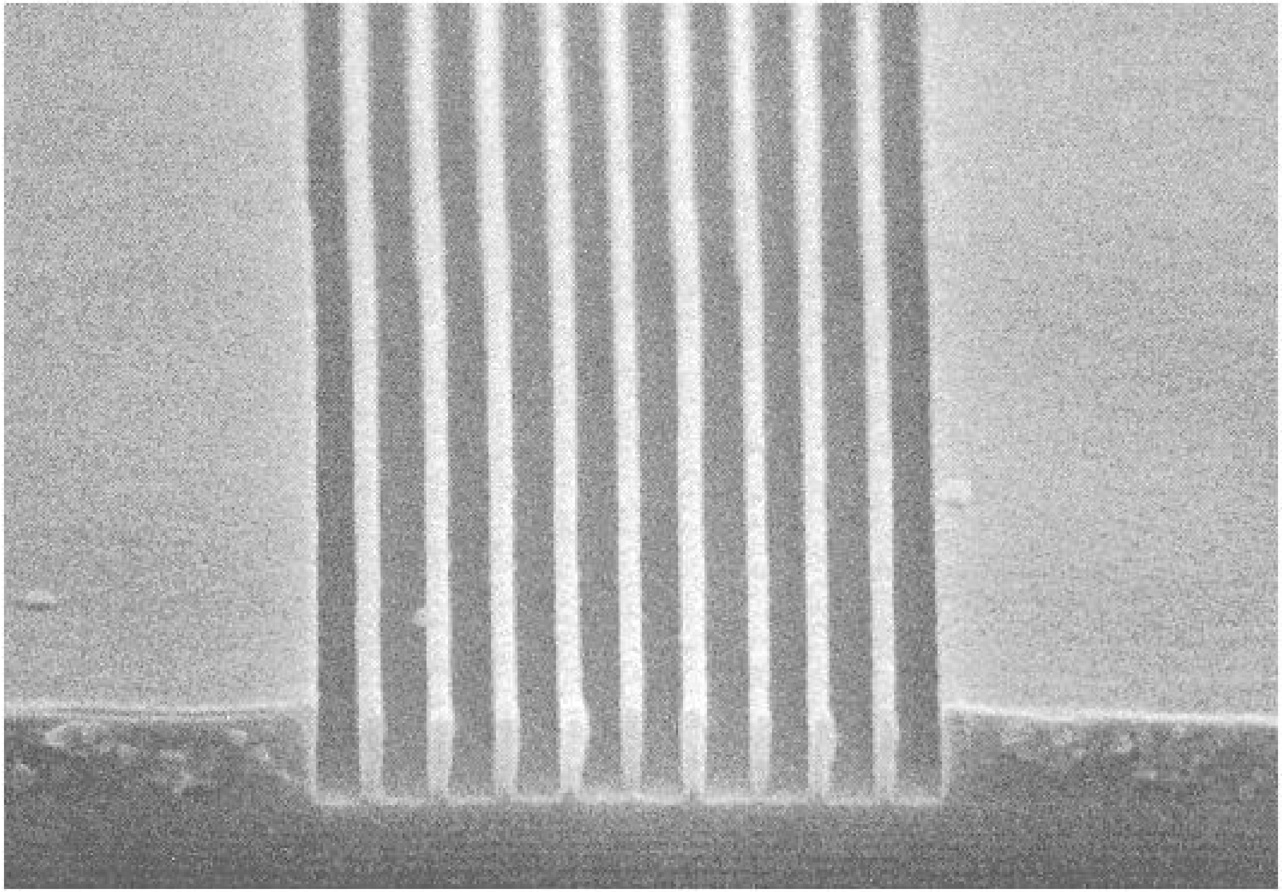
For photoresist ribs, the surface tension force can easily bend over and collapse the polymer.

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



Supercritical drying

Supercritical drying



H. Namatsu, NTT

Driving mechanisms

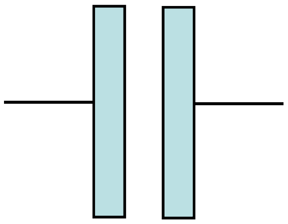
Several different means of driving MEMS devices:

- 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.



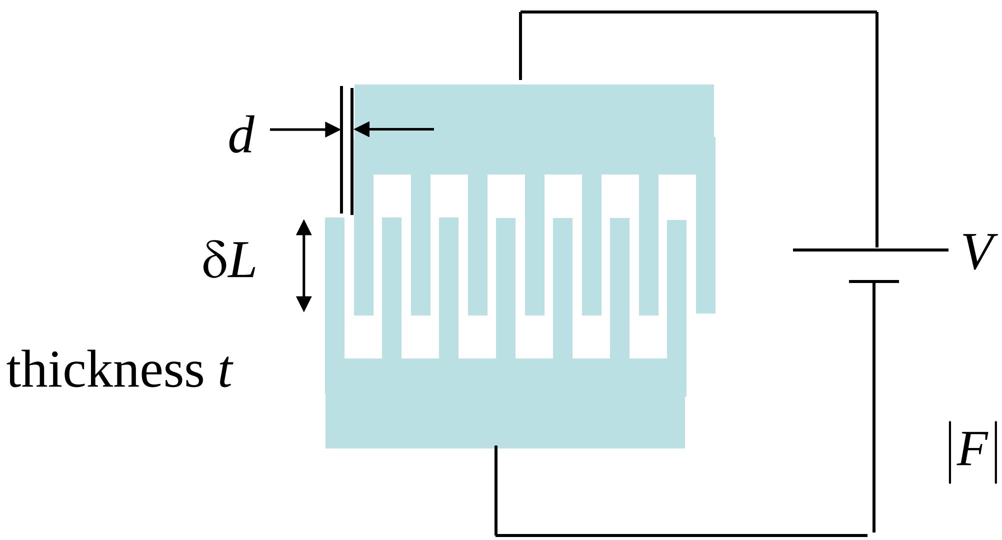
At given voltage, $F \propto C(V_{dc} + V_0 \exp(-i\omega t))^2$

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

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.



$$C \approx \frac{2N\varepsilon_0 Lt}{d}$$

$$\delta C \approx \frac{2N\varepsilon_0 t}{d}\delta L$$

$$|F| = |-\nabla U| = \frac{1}{2}\left[\frac{\partial C}{\partial z}\right]V^2 = \frac{N\varepsilon_0 t}{d}V^2$$

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

Driving mechanisms

- Magnetostatically

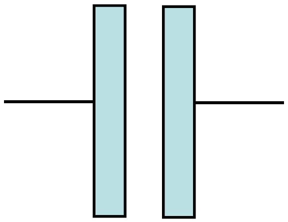
  Attach a small piece of ferromagnet to a (soon-to-be) antinode of the resonator. Apply a time-varying magnetic field gradient from nearby, leading to a dipole-field gradient force.

- 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.

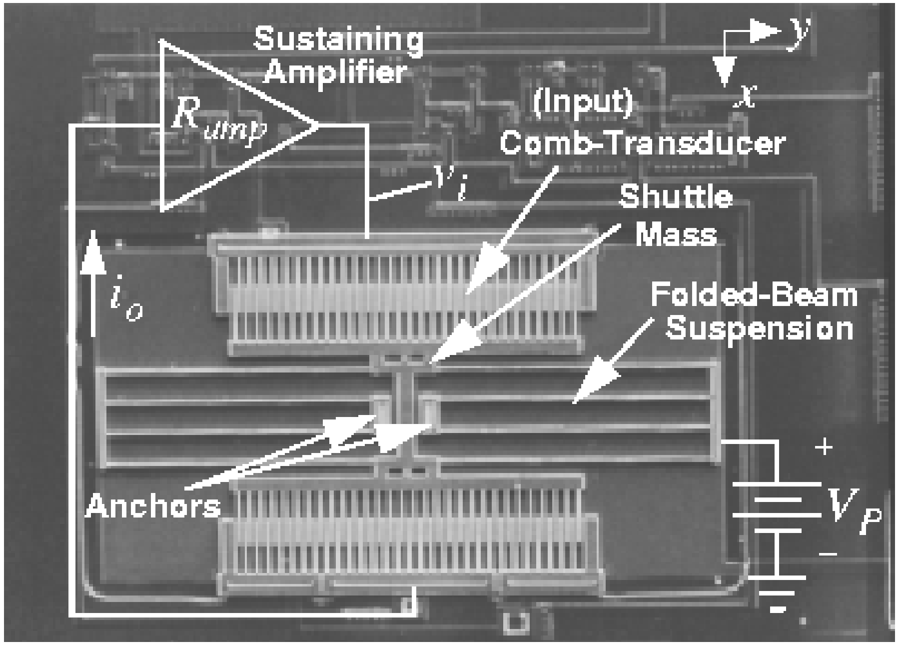
Sensing mechanisms

Nguyen, Proc. IEEE, 1997

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

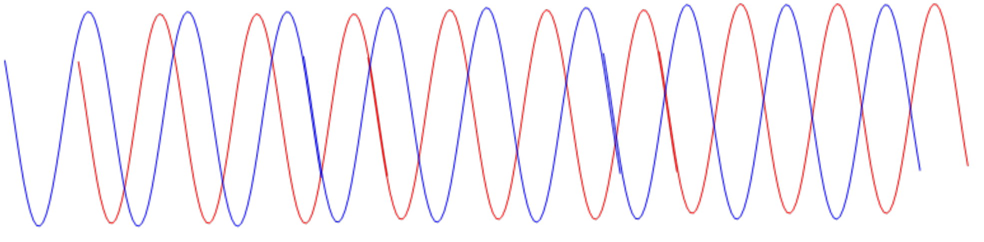
Changing the capacitance leads to a changing current:

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



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 π/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 ~ 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

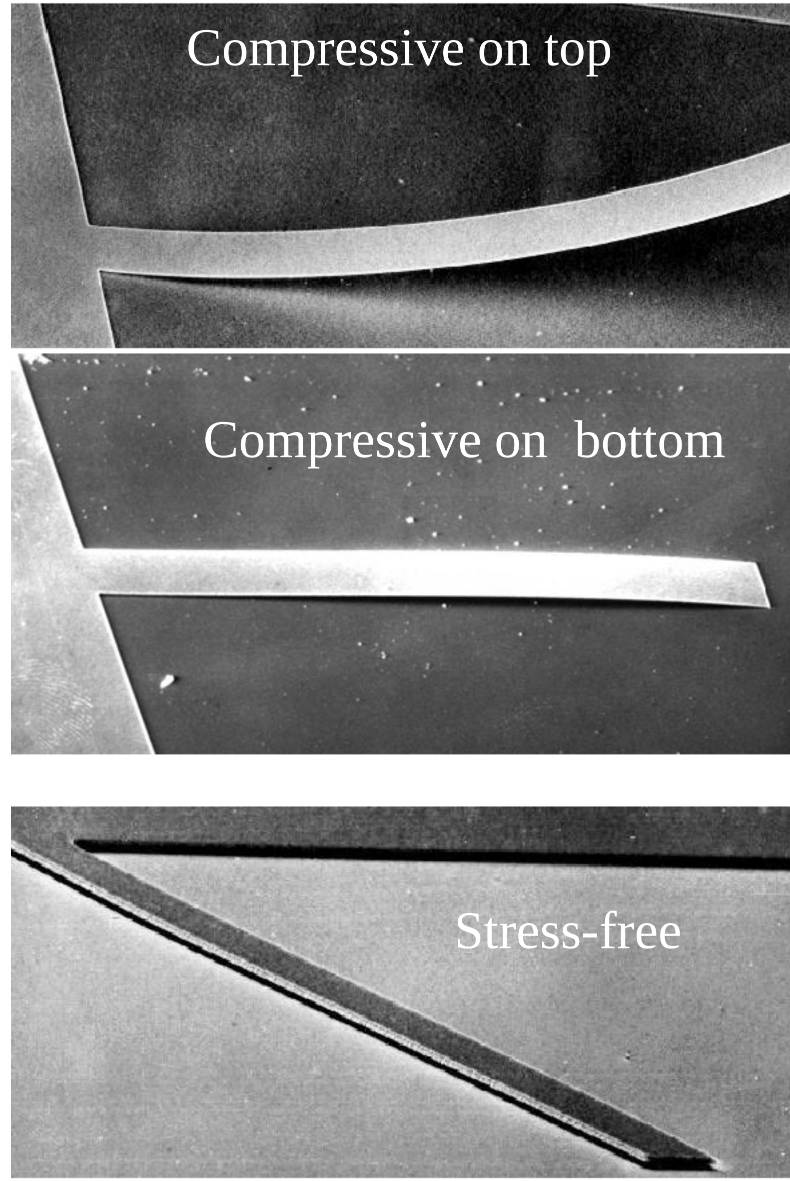
Tunneling current is an exponentially sensitive transduction method, but requires great stability and very small separations to be useful.

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.



Pister, Berkeley

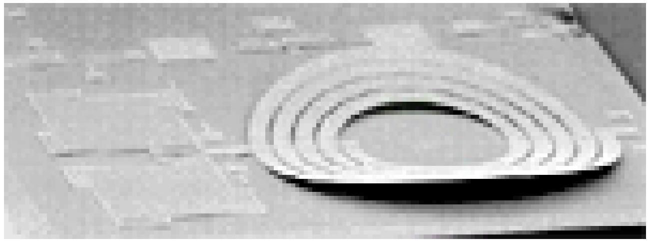
Internal film stresses

Stresses can be engineered deliberately into metal films.

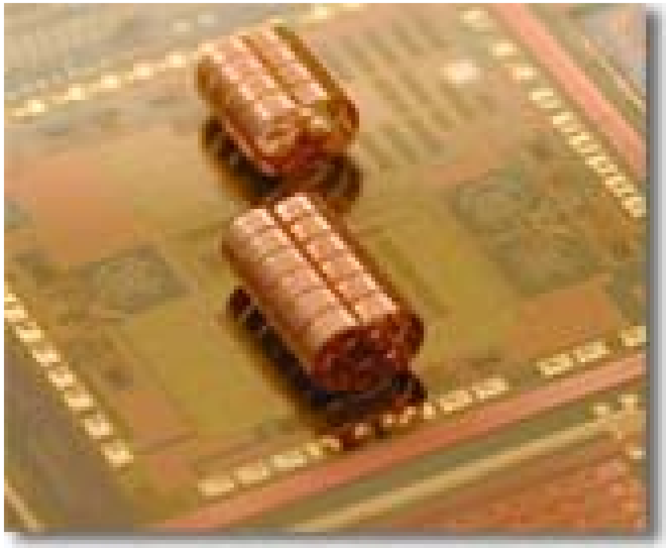
For example, *Q* of *LC* resonators on chips can be much higher if the inductor is far from the doped substrate.

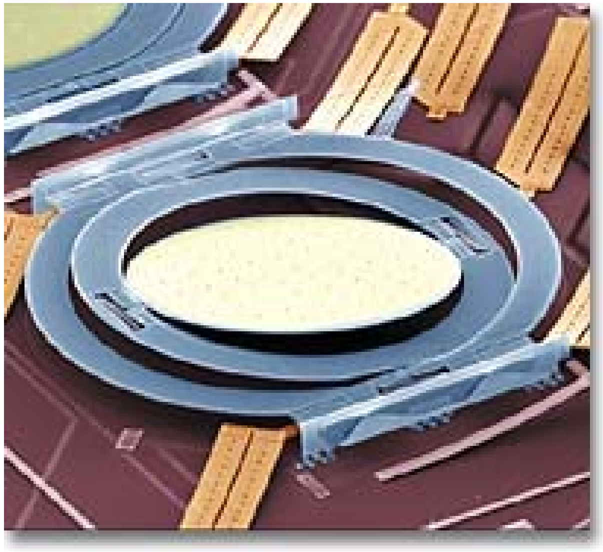
Solution: upon release, metal curls up away from wafer.

Lucent



Xerox



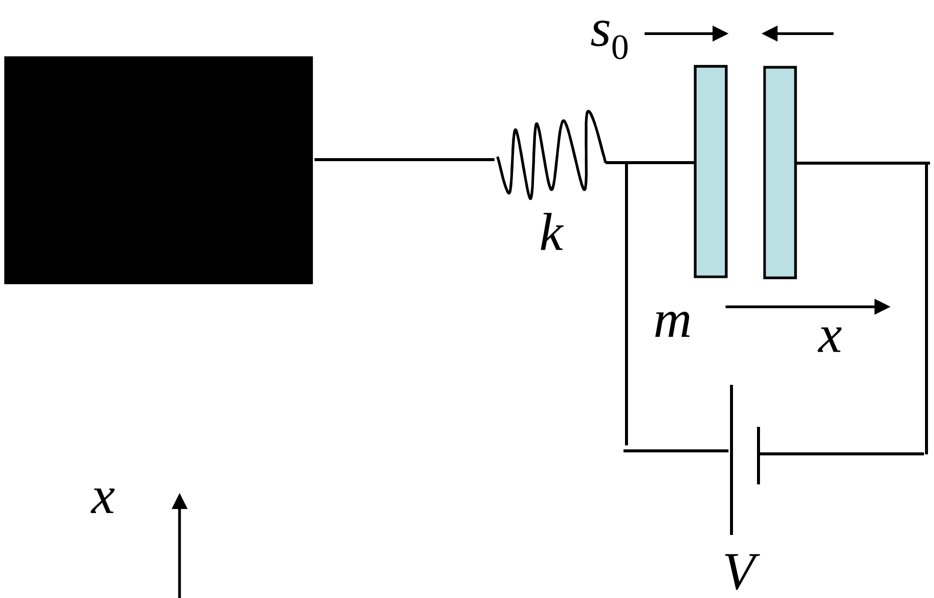


Lucent

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

Electrostatic instability

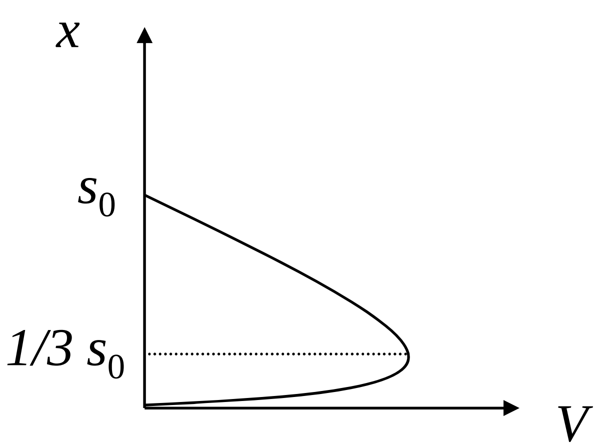
Also called “pull-in” or “snap-down” instability.



$$F = \frac{1}{2}\frac{\varepsilon_0 A V^2}{(s_0 - x)^2} = kx$$

$$V = \sqrt{\frac{2kx}{\varepsilon_0 A}}(s_0 - x)$$

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



$$V^* = \sqrt{\frac{8ks_0^3}{27\varepsilon_0 A}}$$

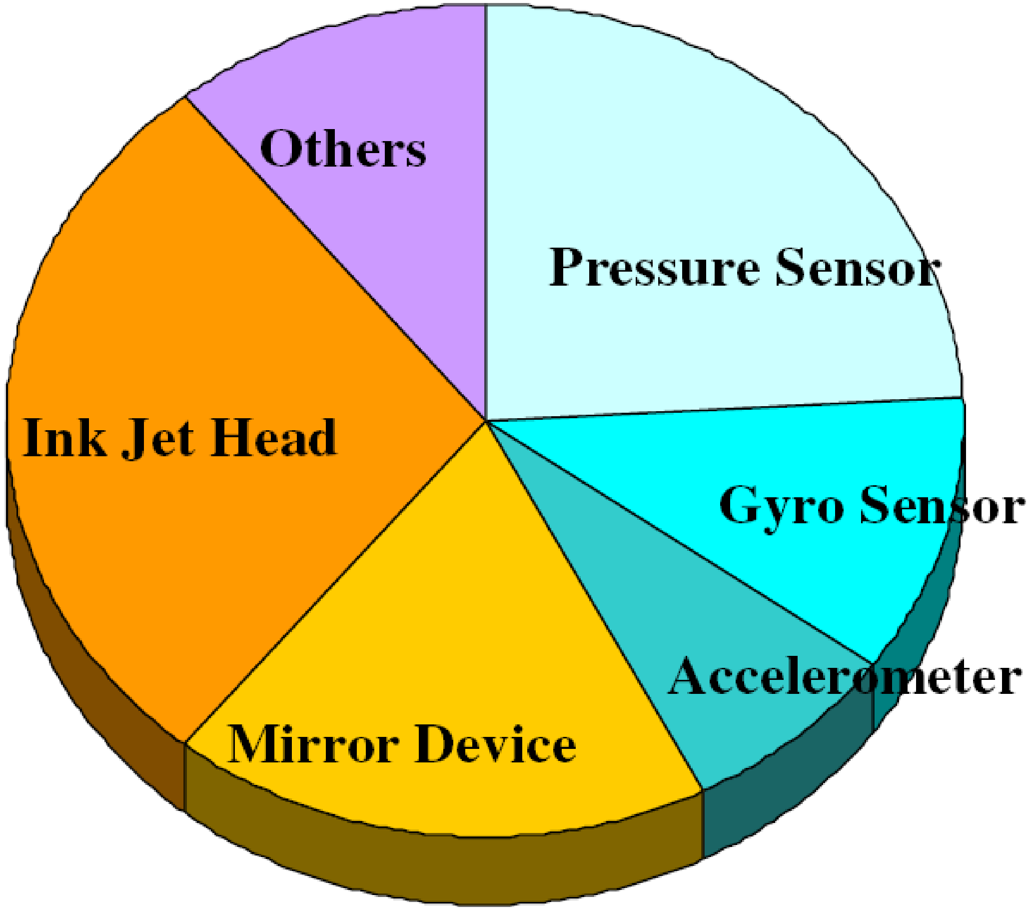
Electrostatic instability

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.

Tanaka, Microelect. Eng. **84**, 1341 (2007).

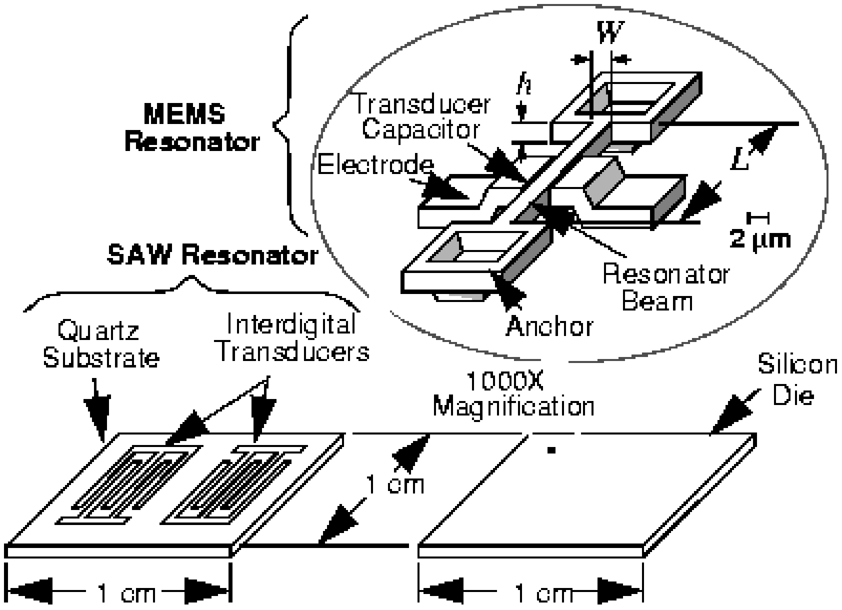
Filters

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.



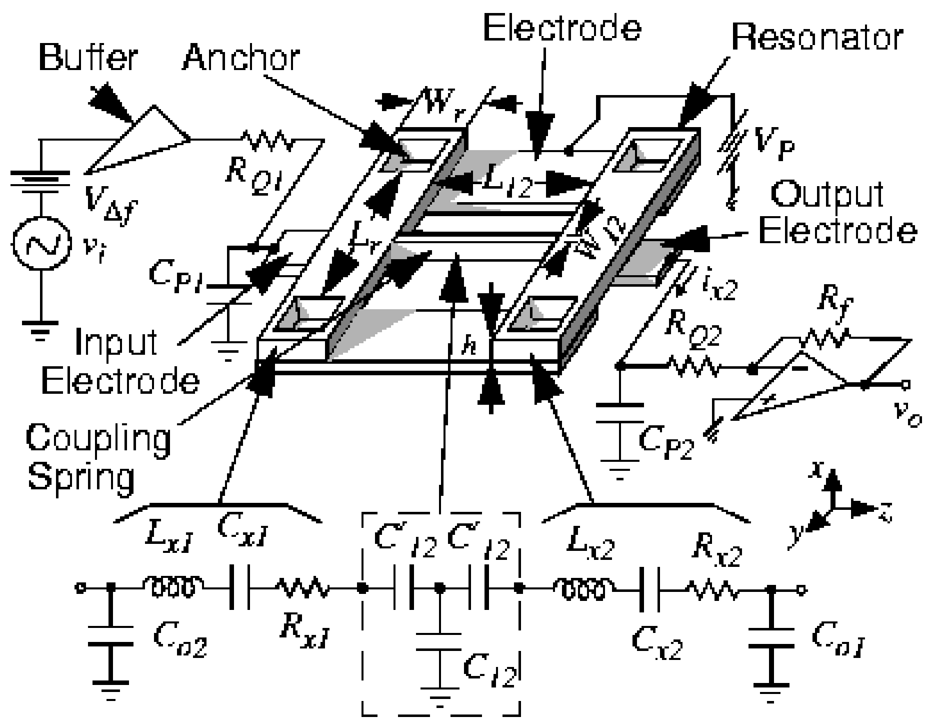
Advantages of MEMS or NEMS filters over competing technologies:

- 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.

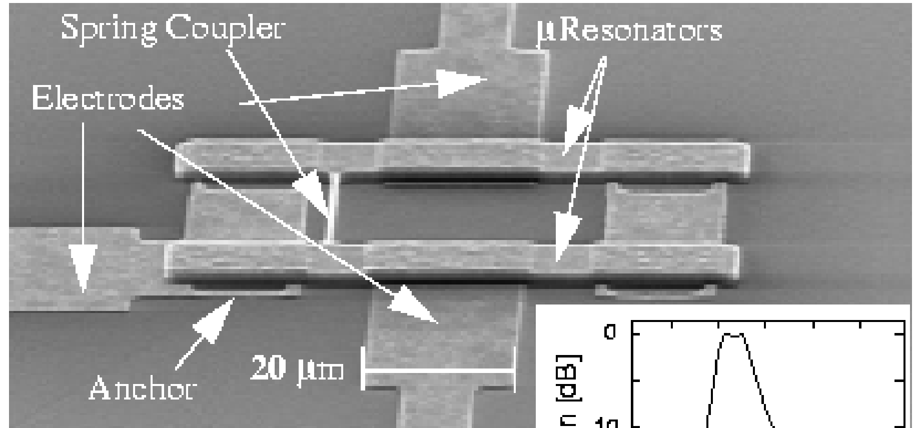
- Bandpass center defined by individual resonators.
- Bandwidth set by strength of coupling.

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.



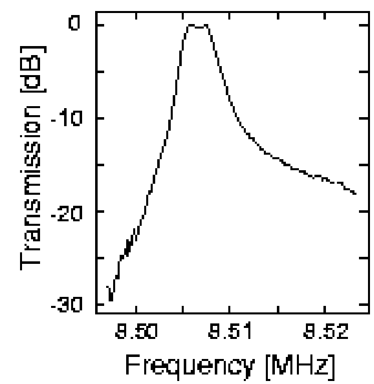


Fig. 4: **SEM** of a spring-coupled **HF** bandpass μmechanical filter and its measured frequency response spectrum.

Applications of these gadgets: wireless technology.

Accelerometers

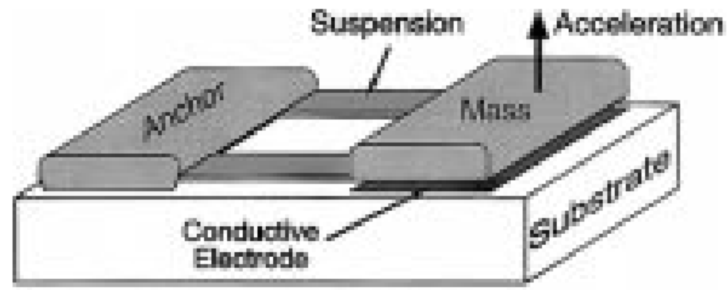
Yazdi *et al.*, IEEE 1998

Inertial sensors are a broad class of MEMS products.

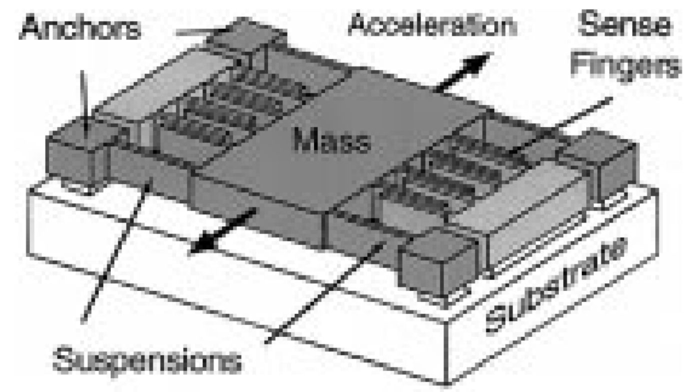
Basic idea: have a test mass suspended or held laterally by micromachined springs.

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

Sense displacements using the methods outlined above.



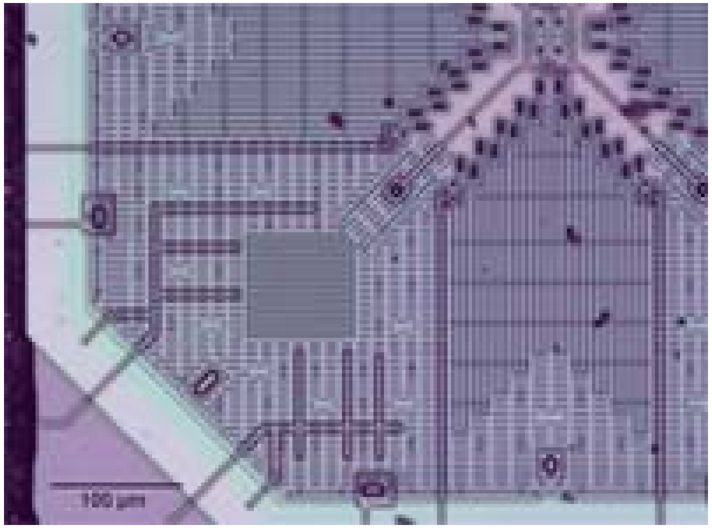
(a)

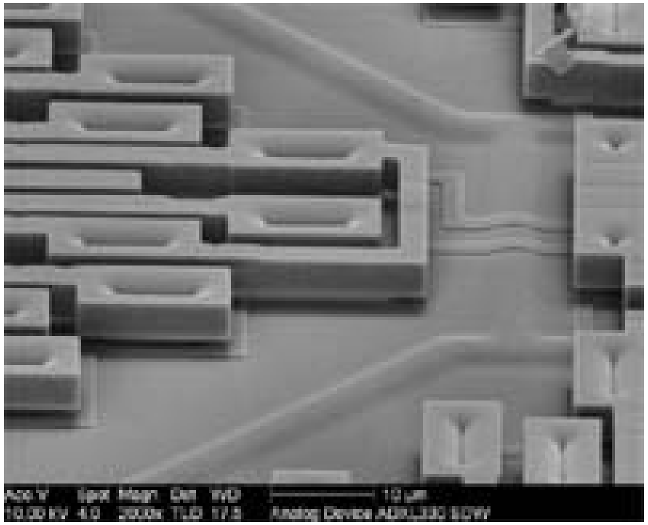


Disadvantage of MEMS: test masses (and thus inertial forces) tend to be small.

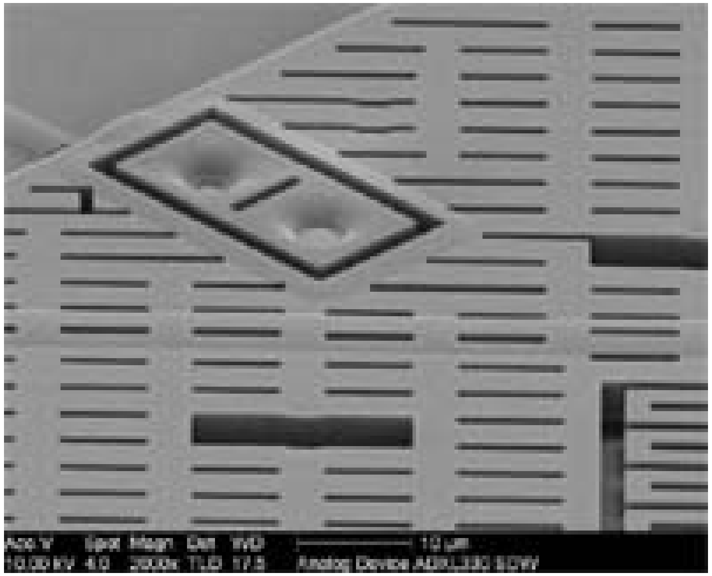
Advantages: high precision displacement sensing, cheap manufacture, high reproducibility.

Accelerometers



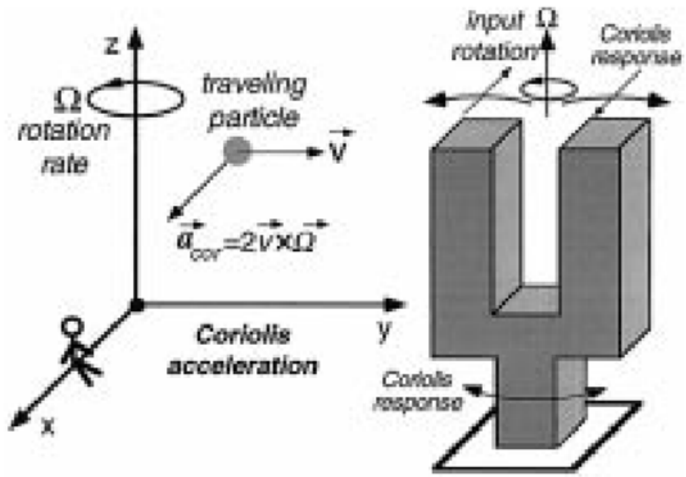


Analog Devices **ADXL330**



Gyroscopes

Yazdi *et al.*, IEEE 1998



(a) (b)

Table 2 Performance Requirements for Different Classes of Gyroscopes

Parameter	*Rate Grade*	*Tactical Grade*	*Inertial Grade*
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

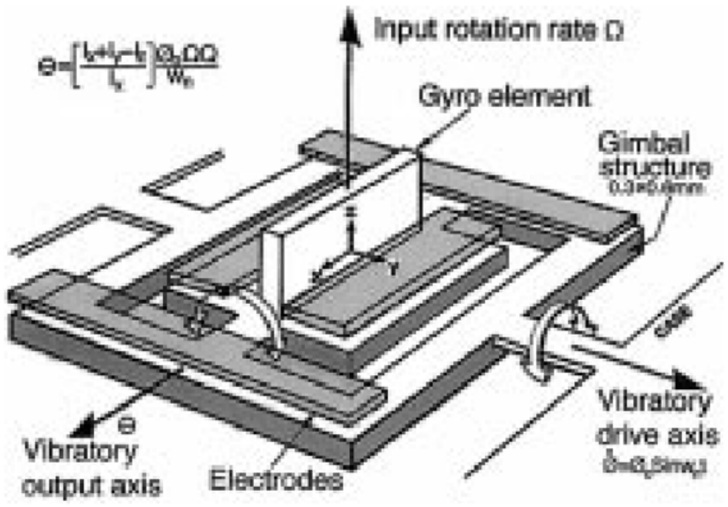


Fig. 10. Draper's first silicon micromachined double-gimbal vibratory gyroscope (1991) [100].

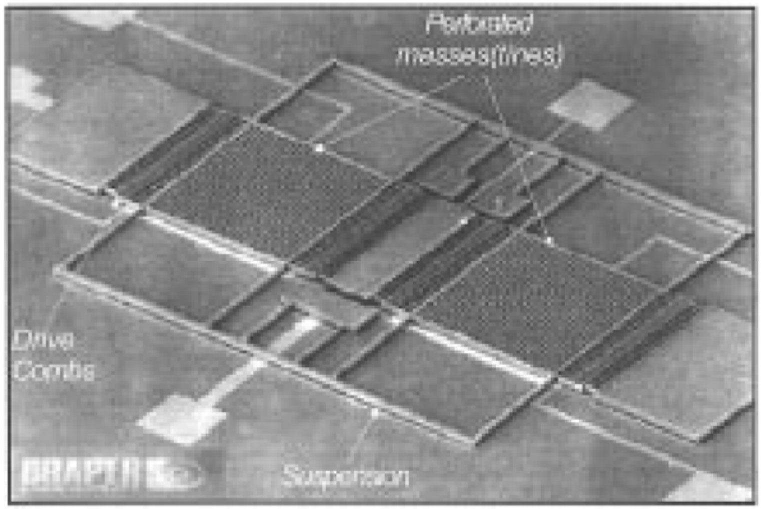


Fig. 11. SEM view of Draper's single-crystal silicon-on-glass tuning-fork gyroscope [103].

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

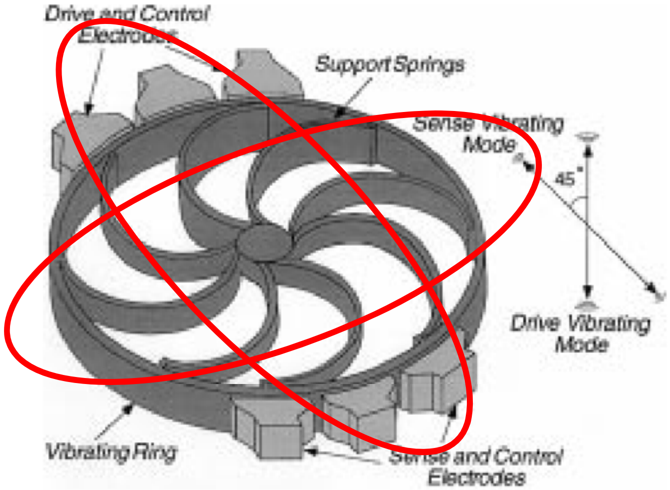


Fig. 15. Structure of a vibrating ring gyroscope.

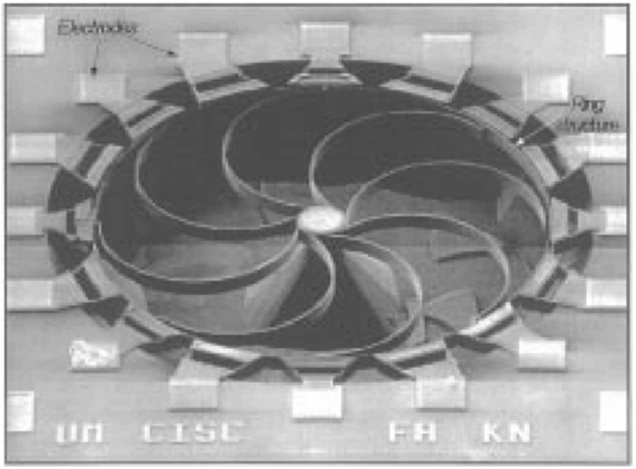


Fig. 16. SEM view of a PRG [123]. The polysilicon ring is 1 mm in diameter, 3 μm wide, and 35 μm tall.

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

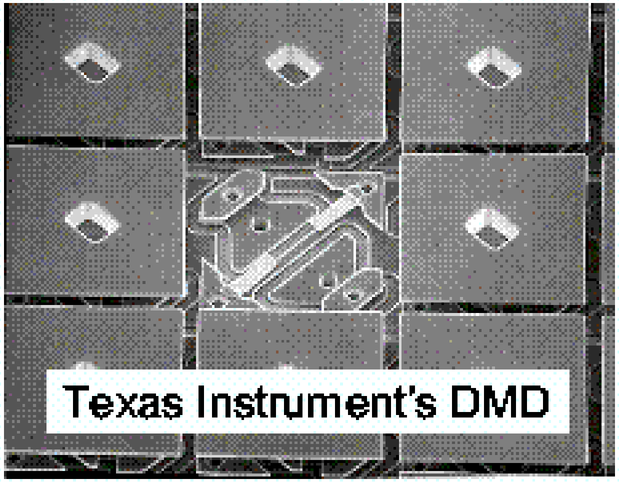
Beyond inertial sensing, there is potentially a huge (eventual) market for optical MEMS.

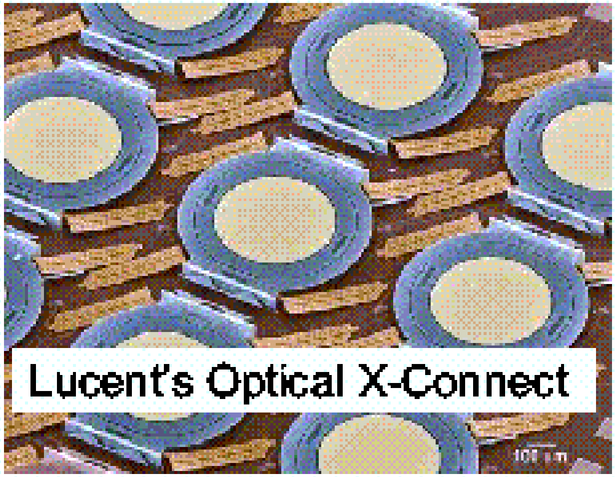
For example, one can do optical switching by having micromachined mirrors that may be moved by electrostatic actuation.

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

Downsides:

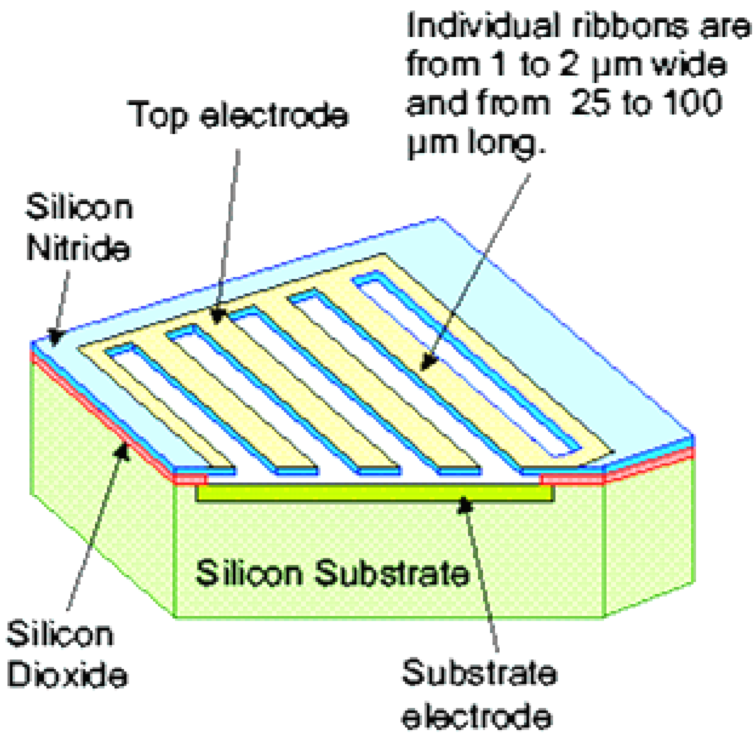
Alignment; high operating voltages; packaging and reliability

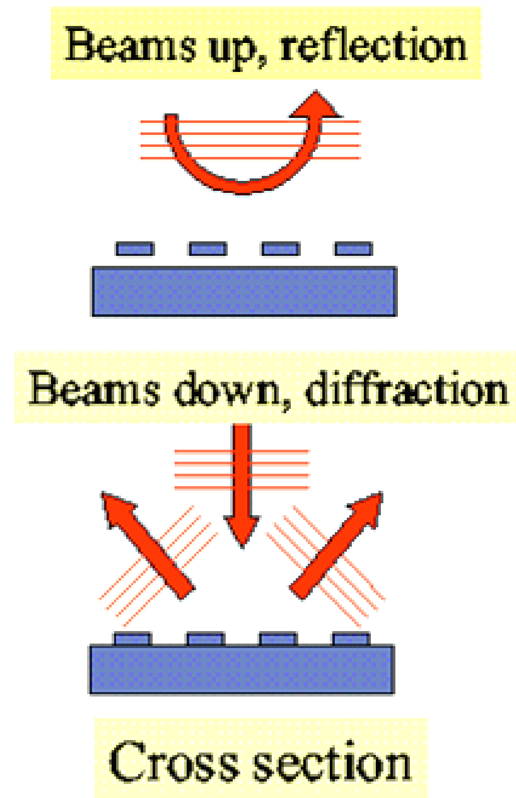




Optical switching – diffraction gratings

Ho, Stanford

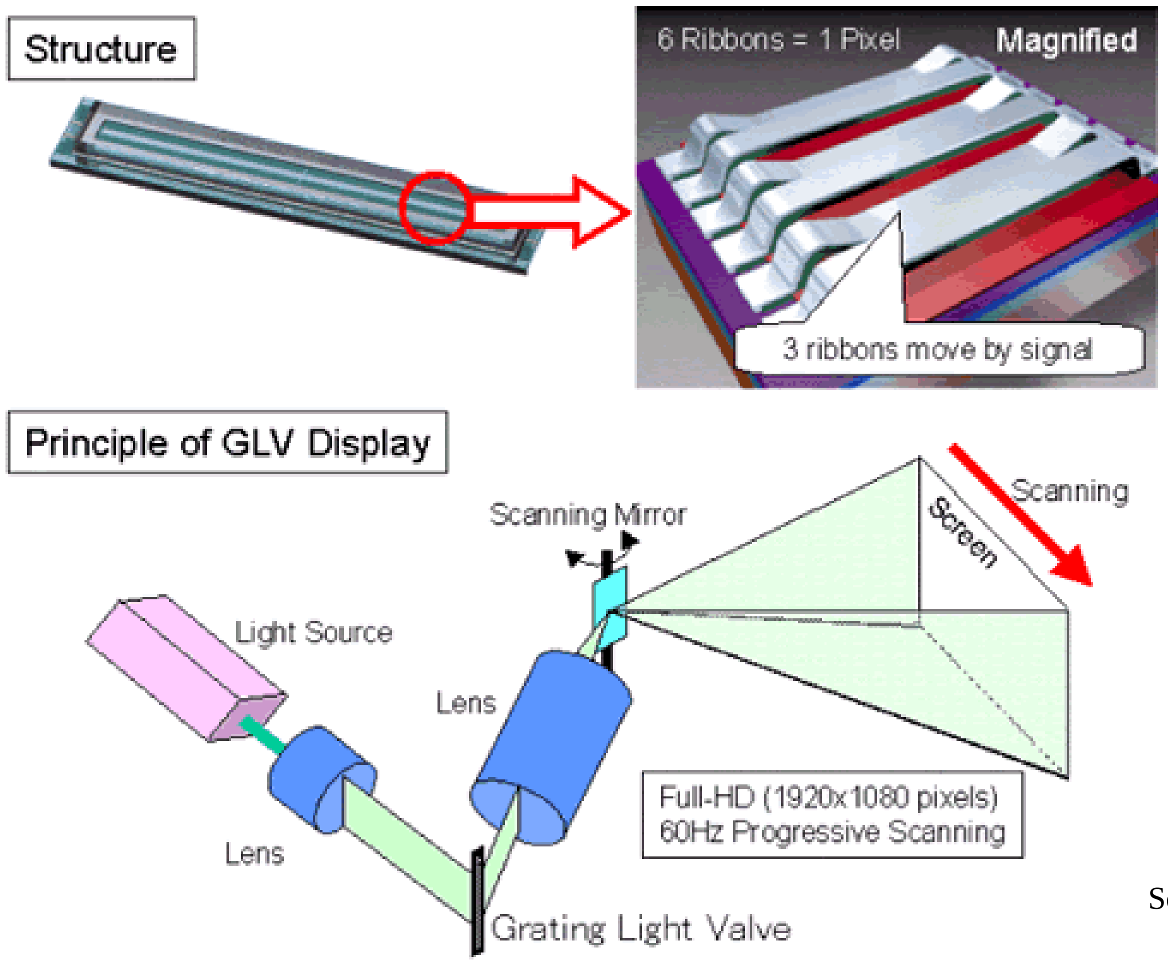




“Grating light valve” (Silicon Light Machines).

Used in optical switching, displays, projectors….

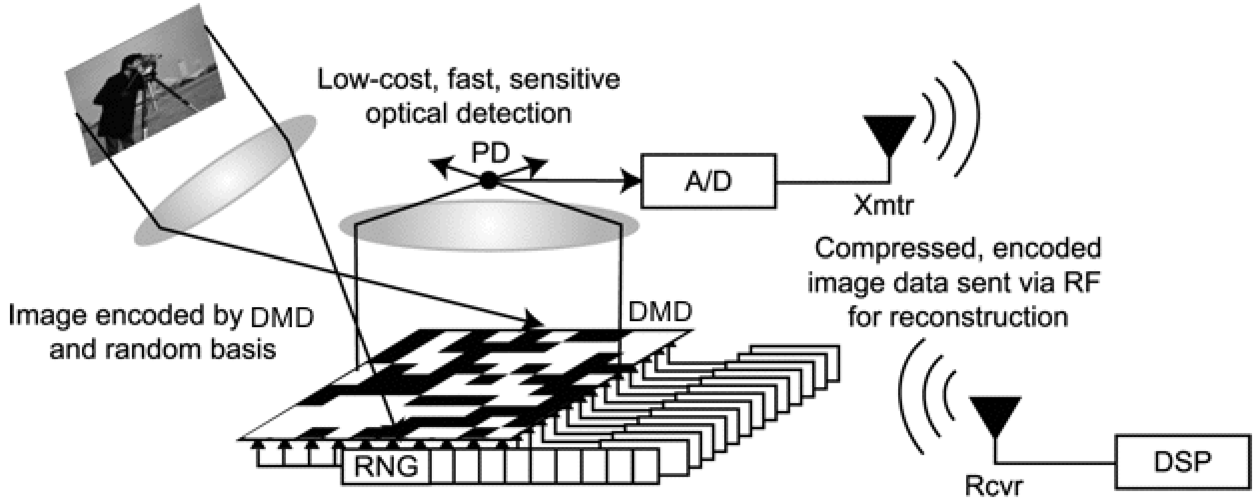
Grating light valve

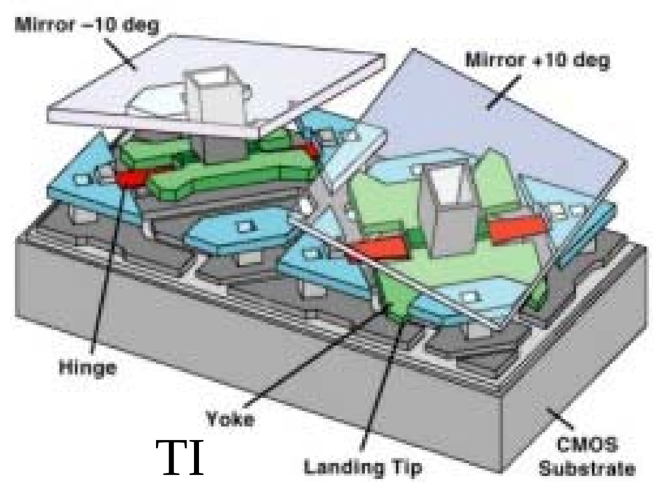


Sony

For projection high definition video….

Single-pixel camera

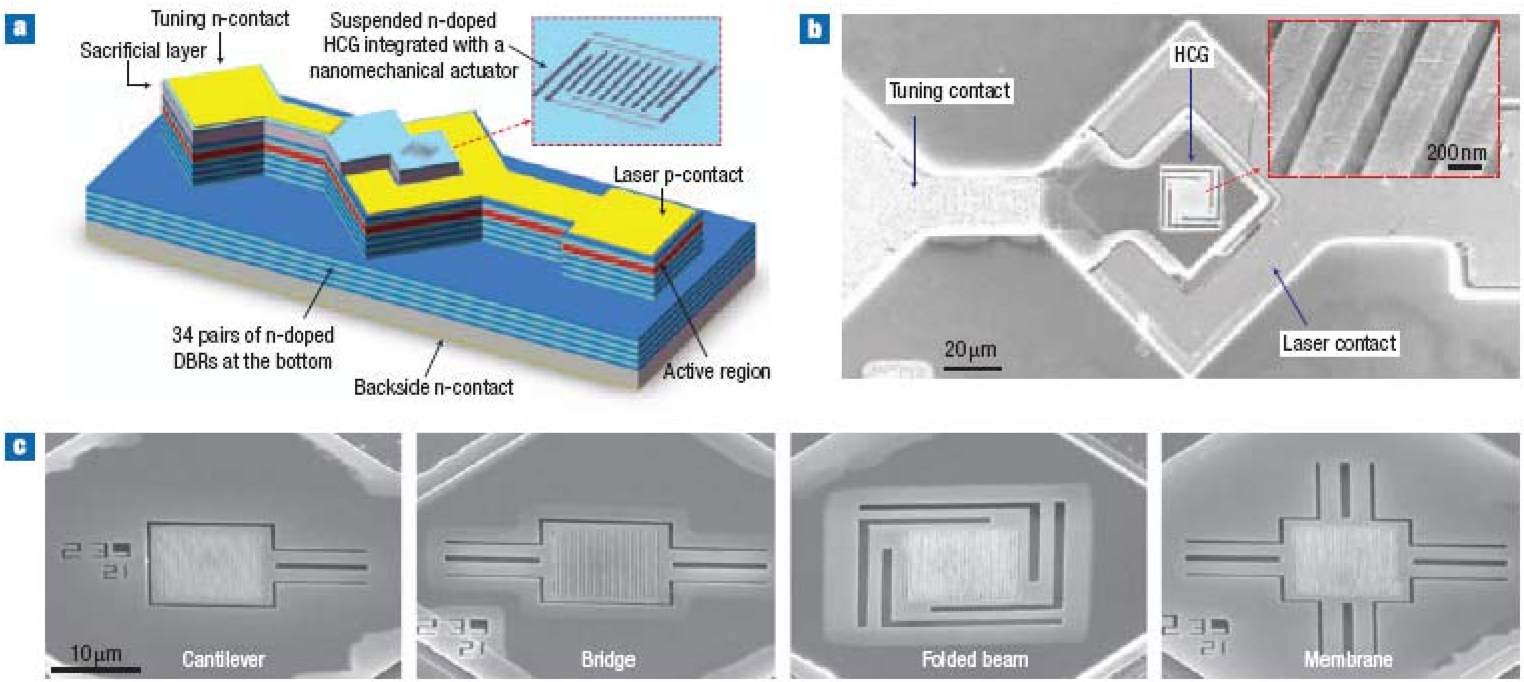




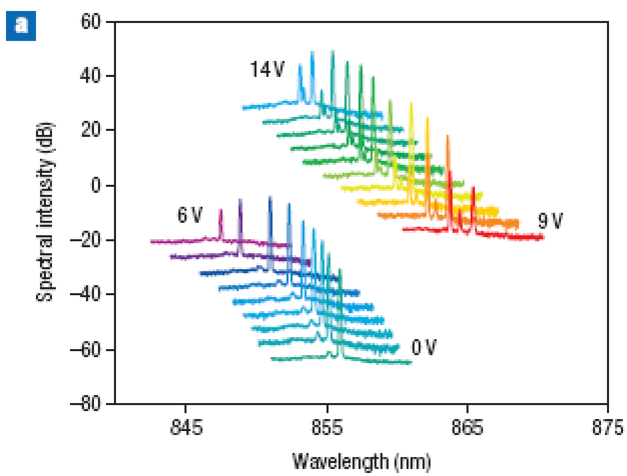
TI

MEMS-tuned laser

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

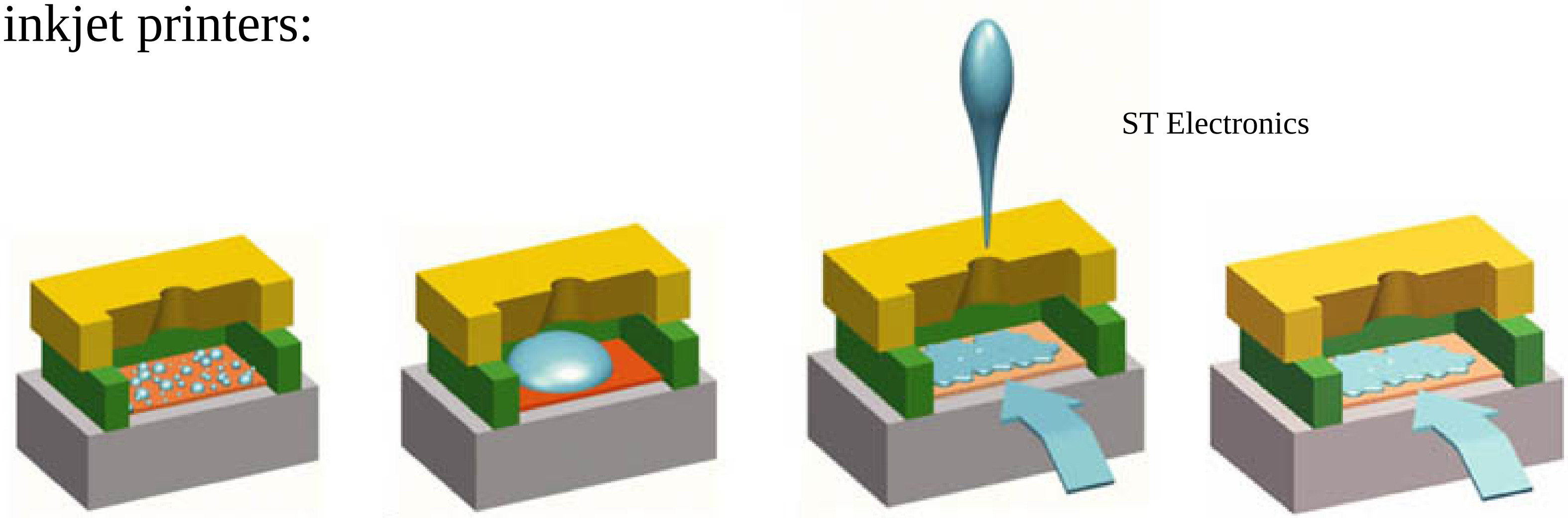


- High-contrast grating as top mirror
- MEMS actuator moves suspended top mirror, altering cavity shape.
- Different lasing modes tuned in and out of threshold by bias voltage.



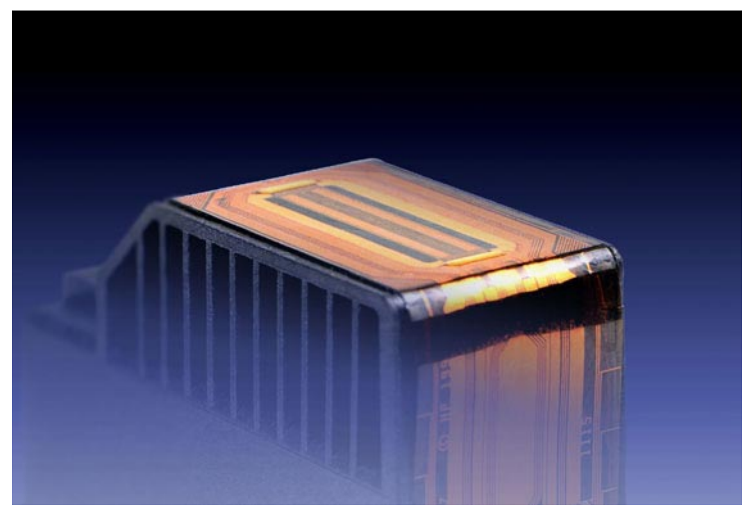
Inkjet printers

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



ST Electronics

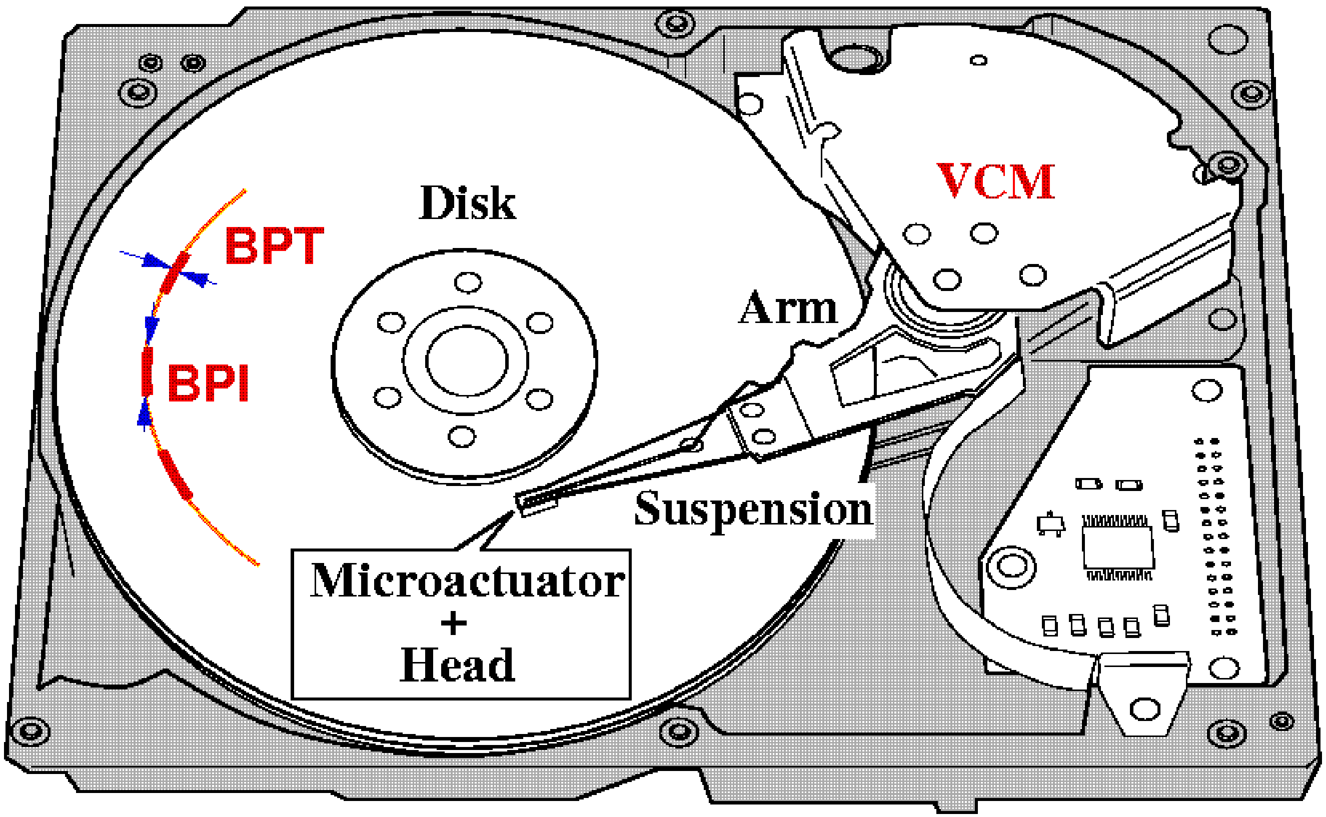
True 2400 dpi printing = 10 micron droplets ~ few micron nozzles.



Data storage

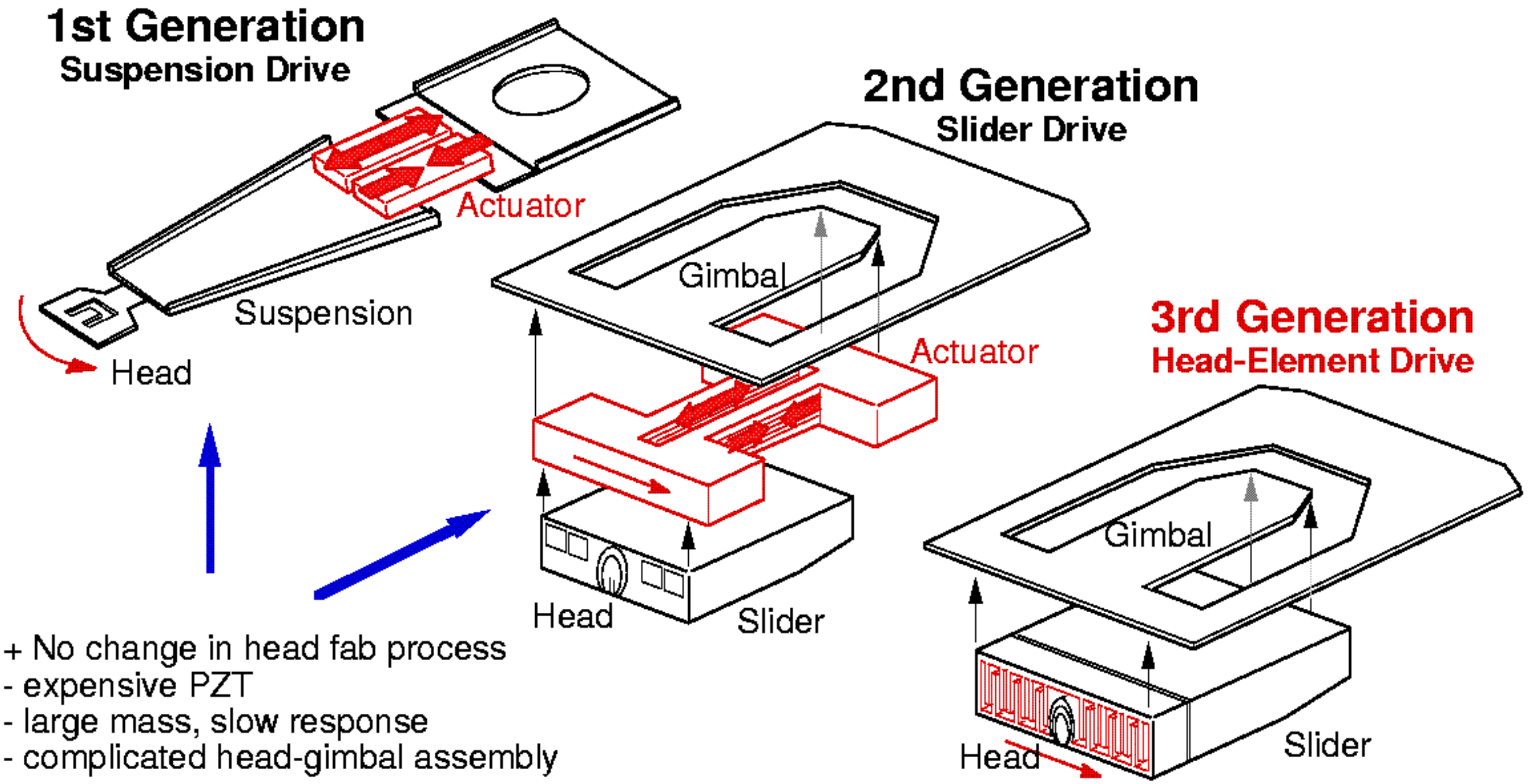
MEMS already play an active role in the data storage industry:

- Positioning hardware for hard drive read/write heads



University of Tokyo

Data storage - Hard drives



+ No change in head fab process
- expensive PZT
- large mass, slow response
- complicated head-gimbal assembly

- Large Change in head fab process
+ no expensive PZT
+ full integration
+ no assembly

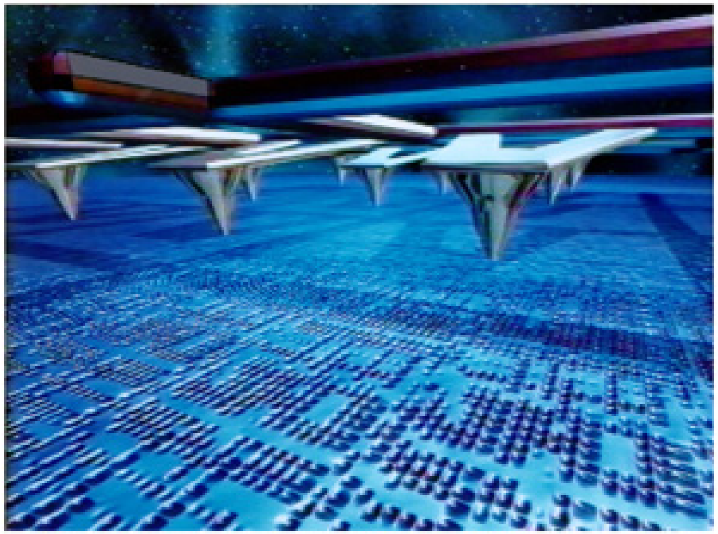
University of Tokyo/Hitachi

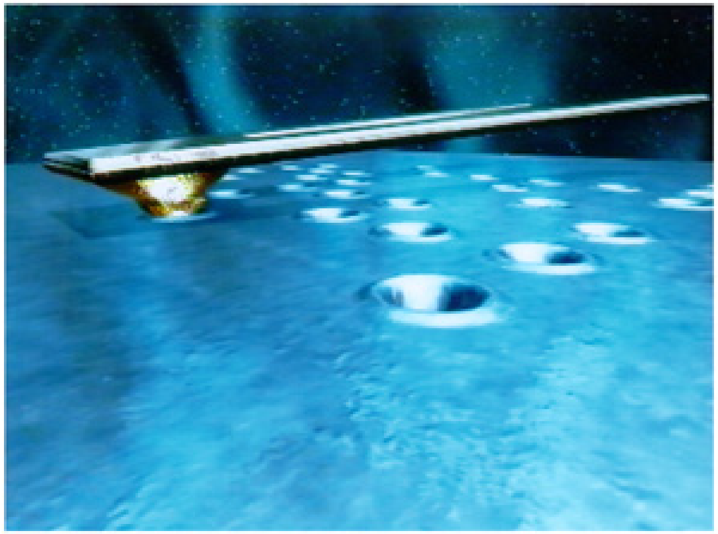
Data storage

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.



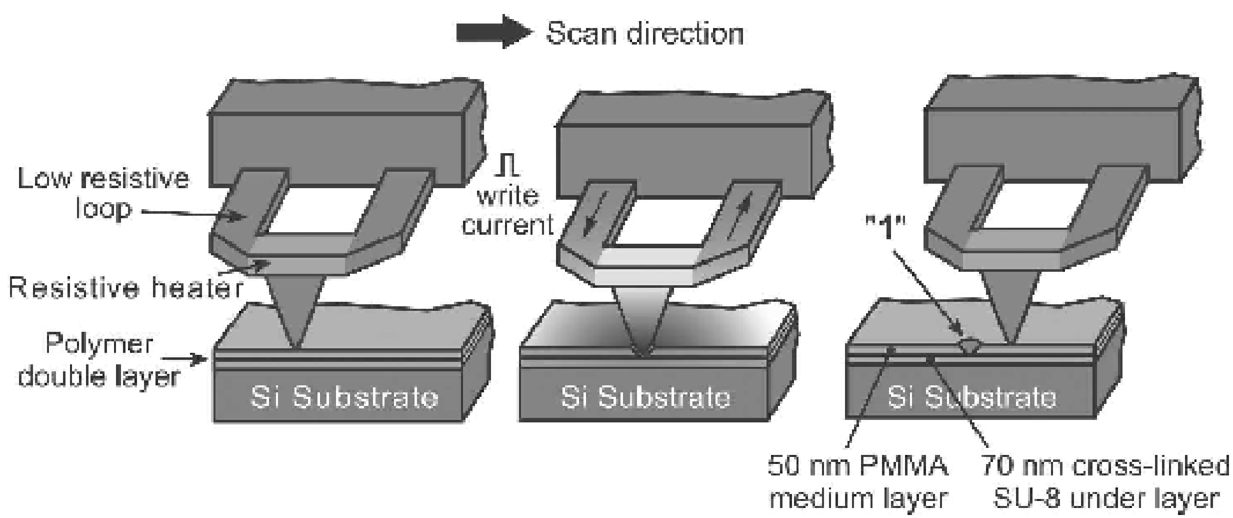


Data storage: Millipede

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.

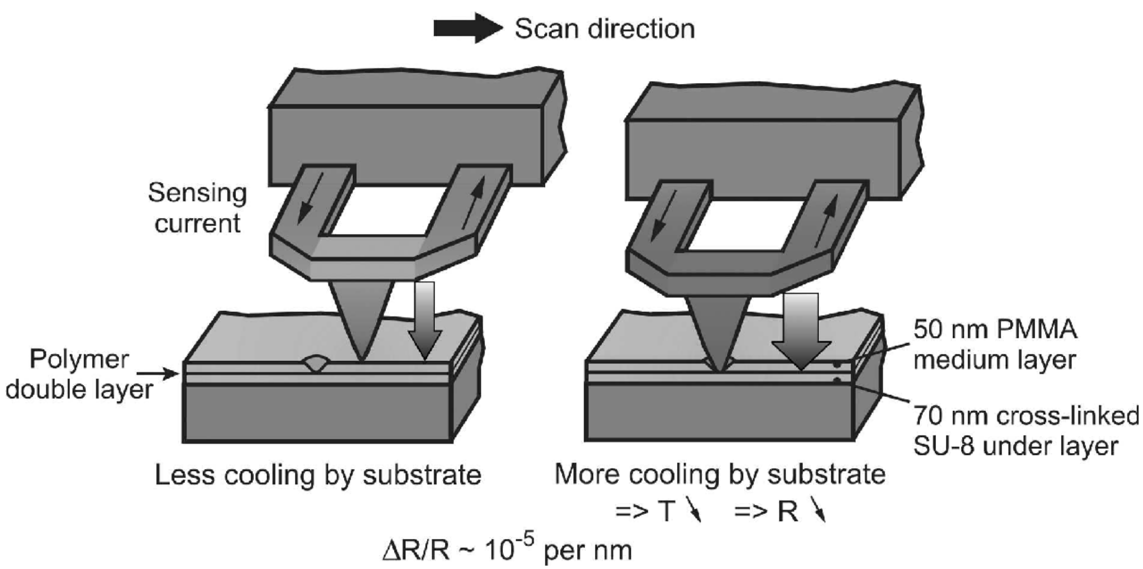


IBM

Data storage: Millipede

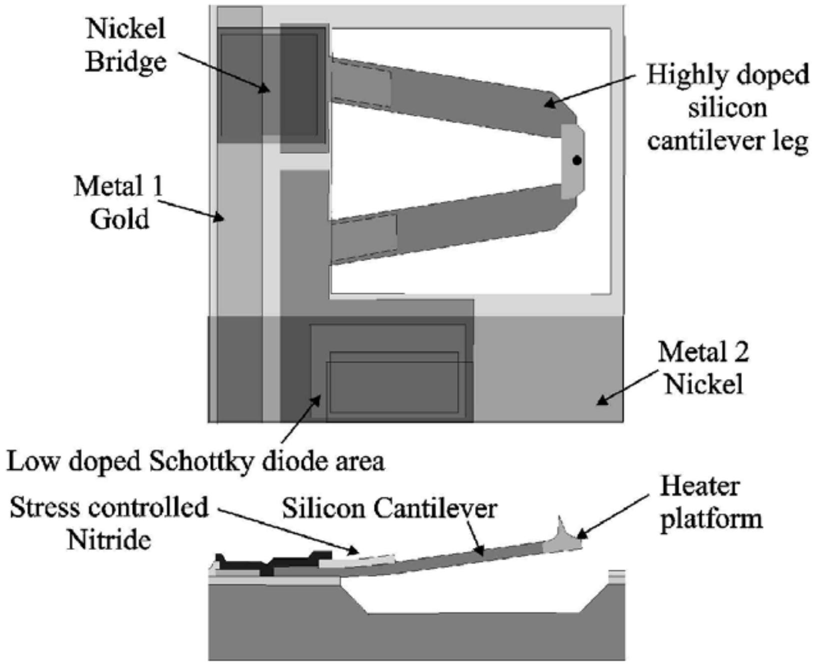
Read process is similar: cantilever *T* sensed by resistance measurement. Allow cantilever to self-heat (lower than T_g of PMMA) at fixed heater power.

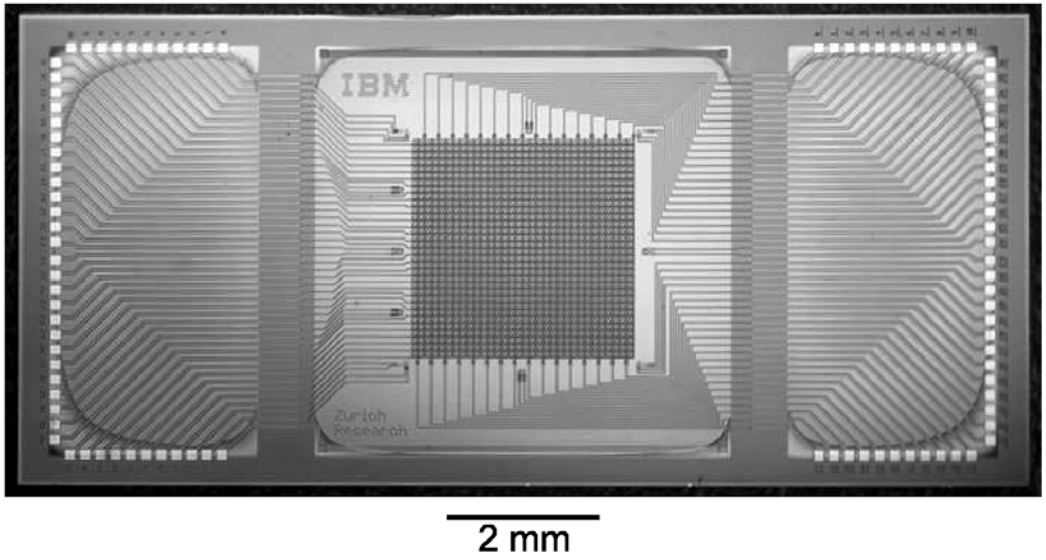
When tip is in a pit ("1"), the tip becomes better thermally coupled to the substrate: *T* falls, *R* falls, and bit can be sensed.



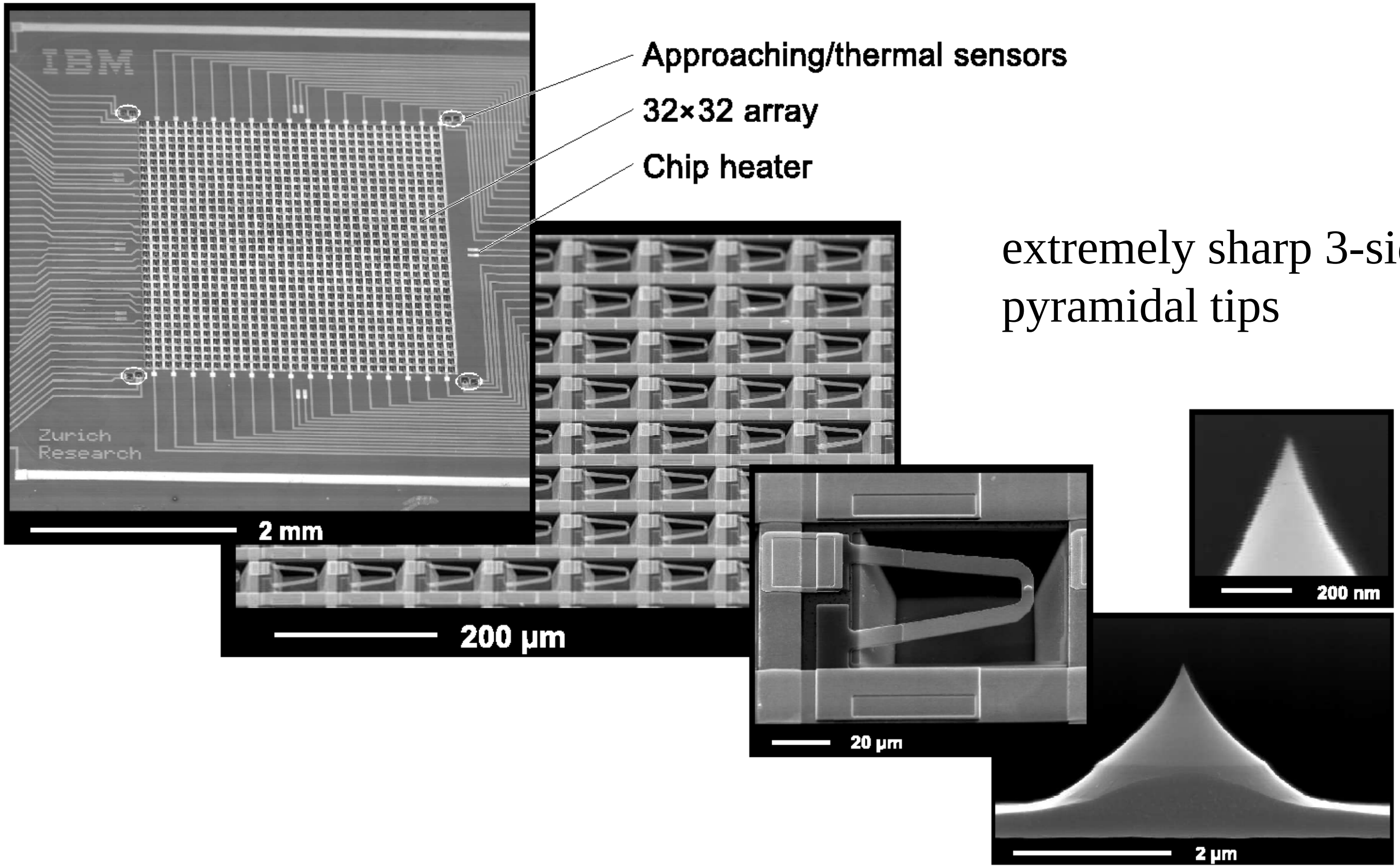
Data storage: Millipede

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





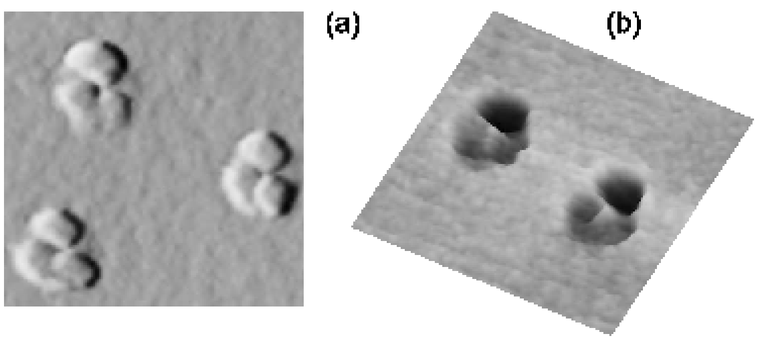
Data storage: Millipede

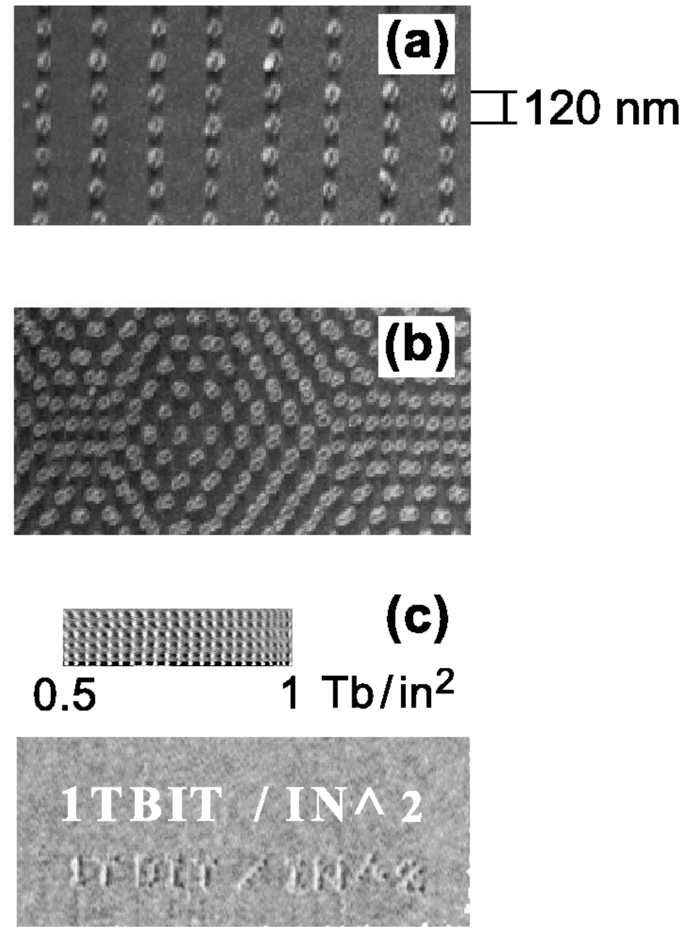


extremely sharp 3-sided pyramidal tips

Data storage: Millipede

When tweaked, can get 1 TB/in^2 densities, better than the best magnetic media.





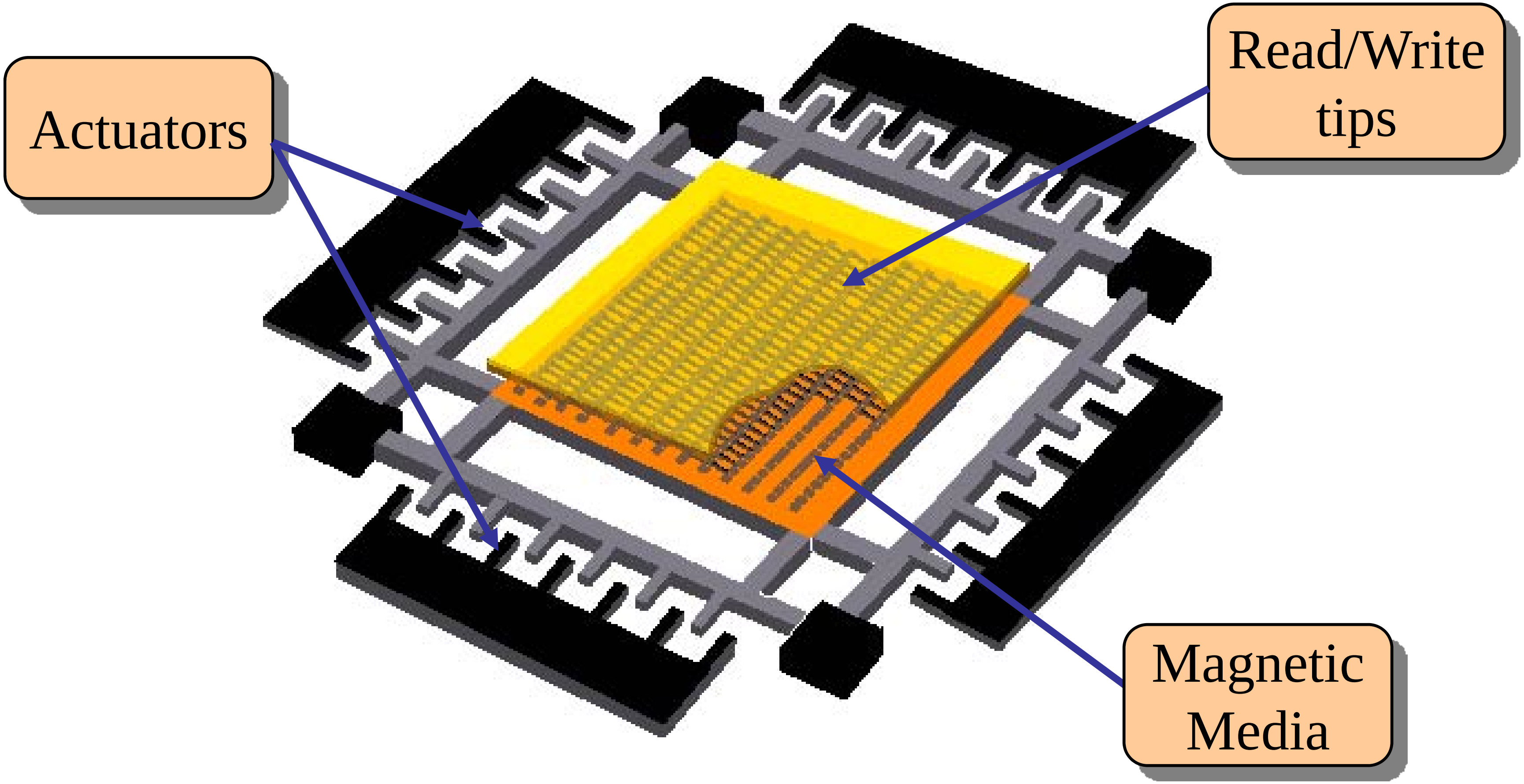
Data storage: “Disk on a chip”

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

- David Nagle, Greg, Ganger, Steve Schlosser, and John Griffin

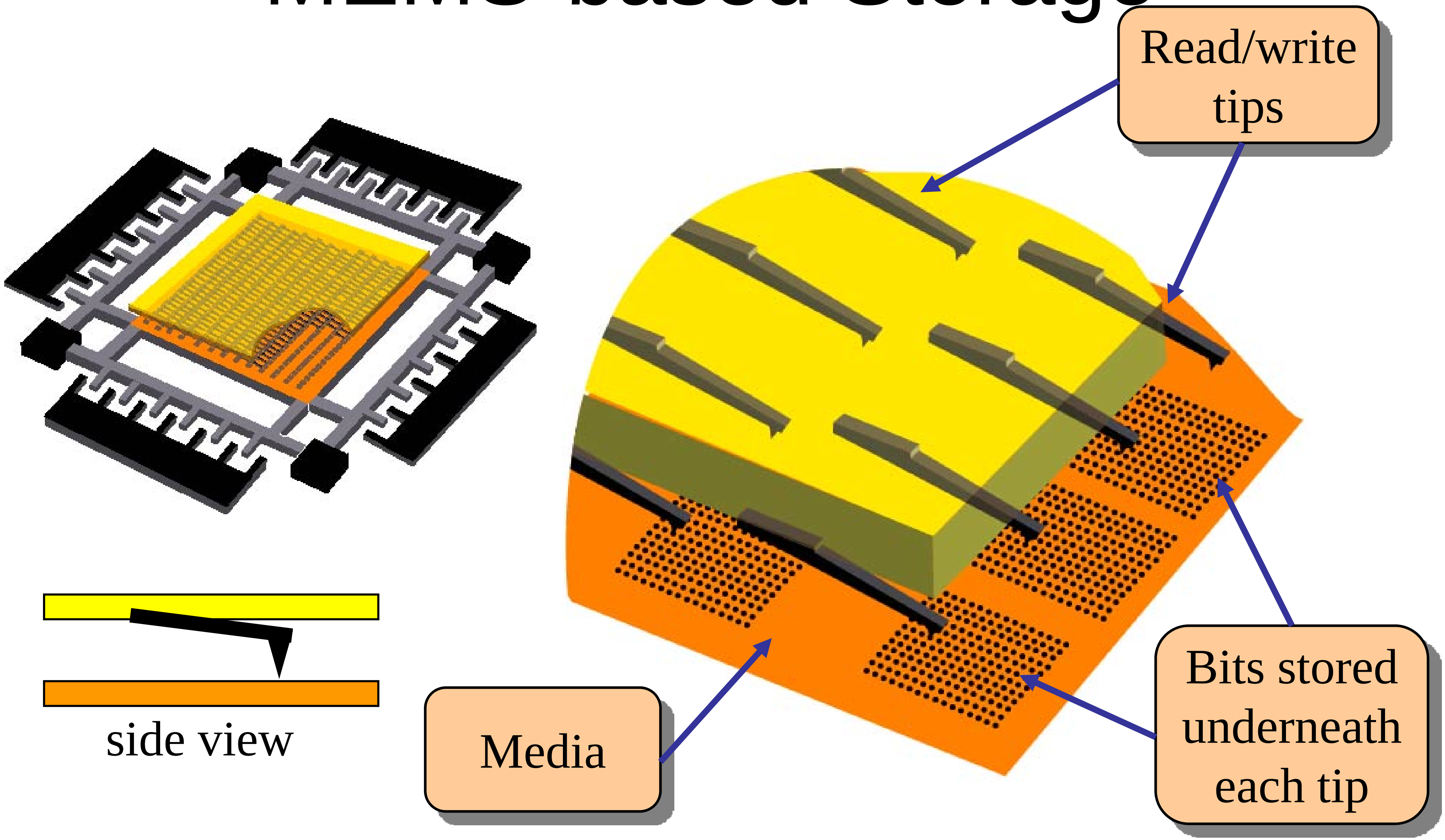
- http://www.chips.ece.cmu.edu/

Data storage: “disk on a chip”



Nagel, Ganger, Schlosser, Griffin http://www.chips.ece.cmu.edu/

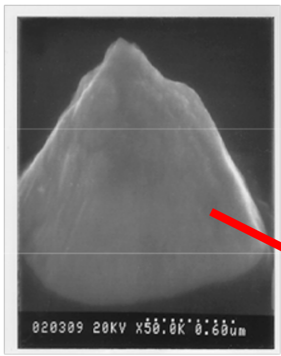
MEMS-based Storage



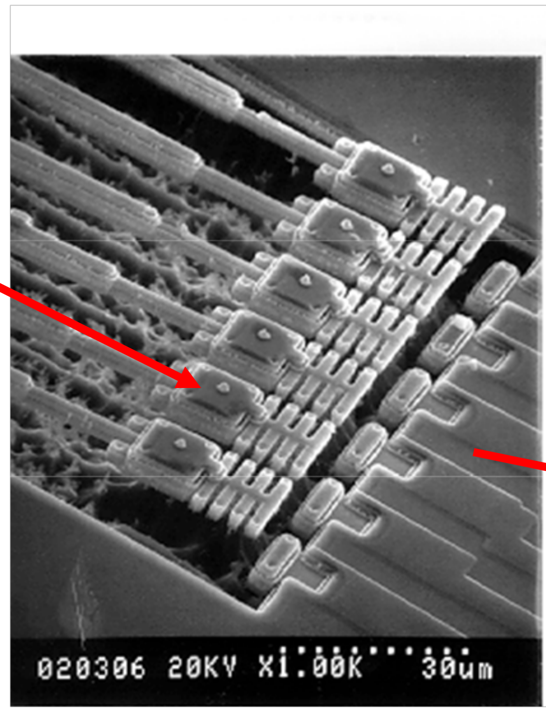
Nagel, Ganger, Schlosser, Griffin http://www.chips.ece.cmu.edu/

MEMS-based Storage

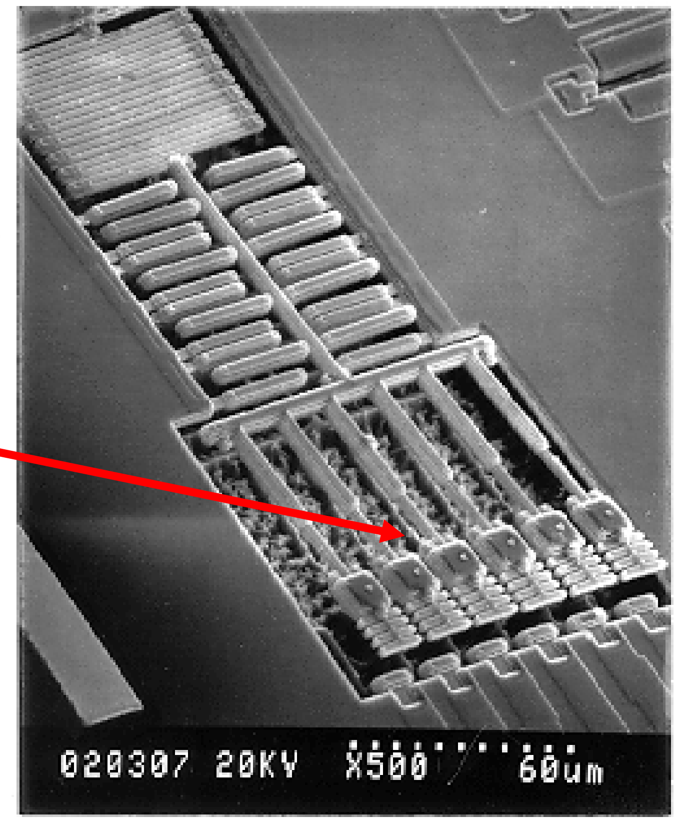
- Read/write probe tips



1 µm
probe tip



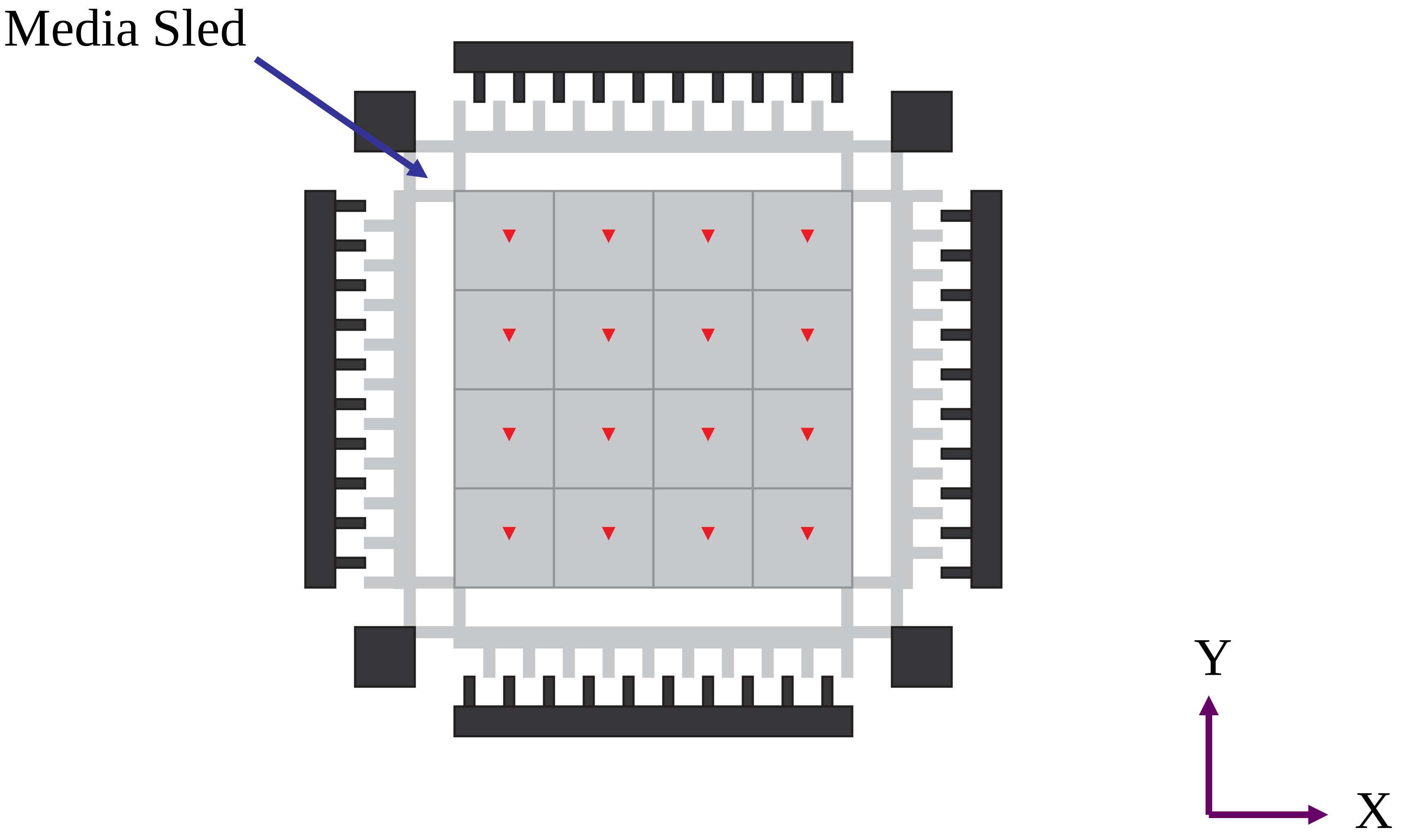
group of six tips



100 µm

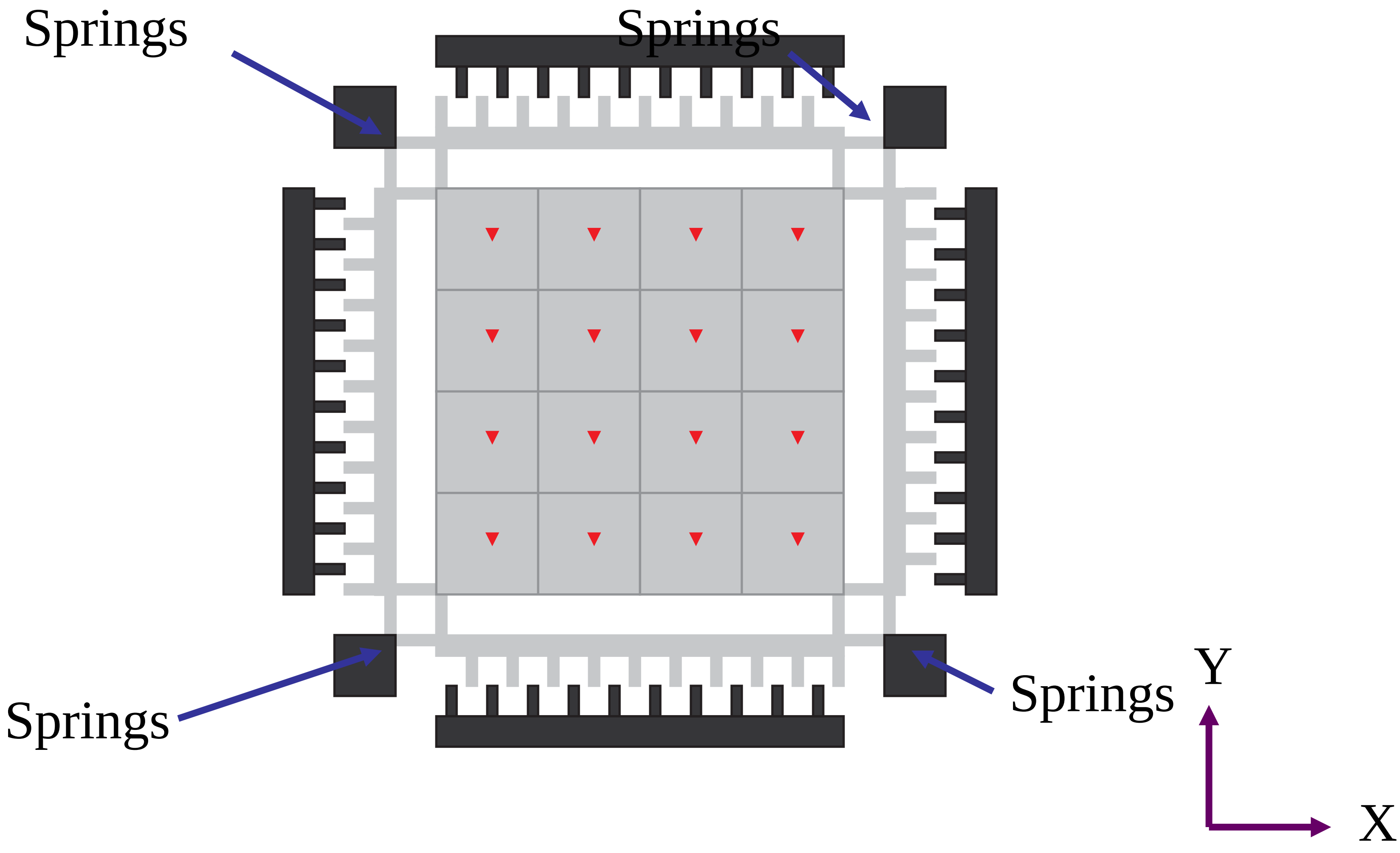
Nagel, Ganger, Schlosser, Griffin http://www.chips.ece.cmu.edu/

MEMS-based Storage



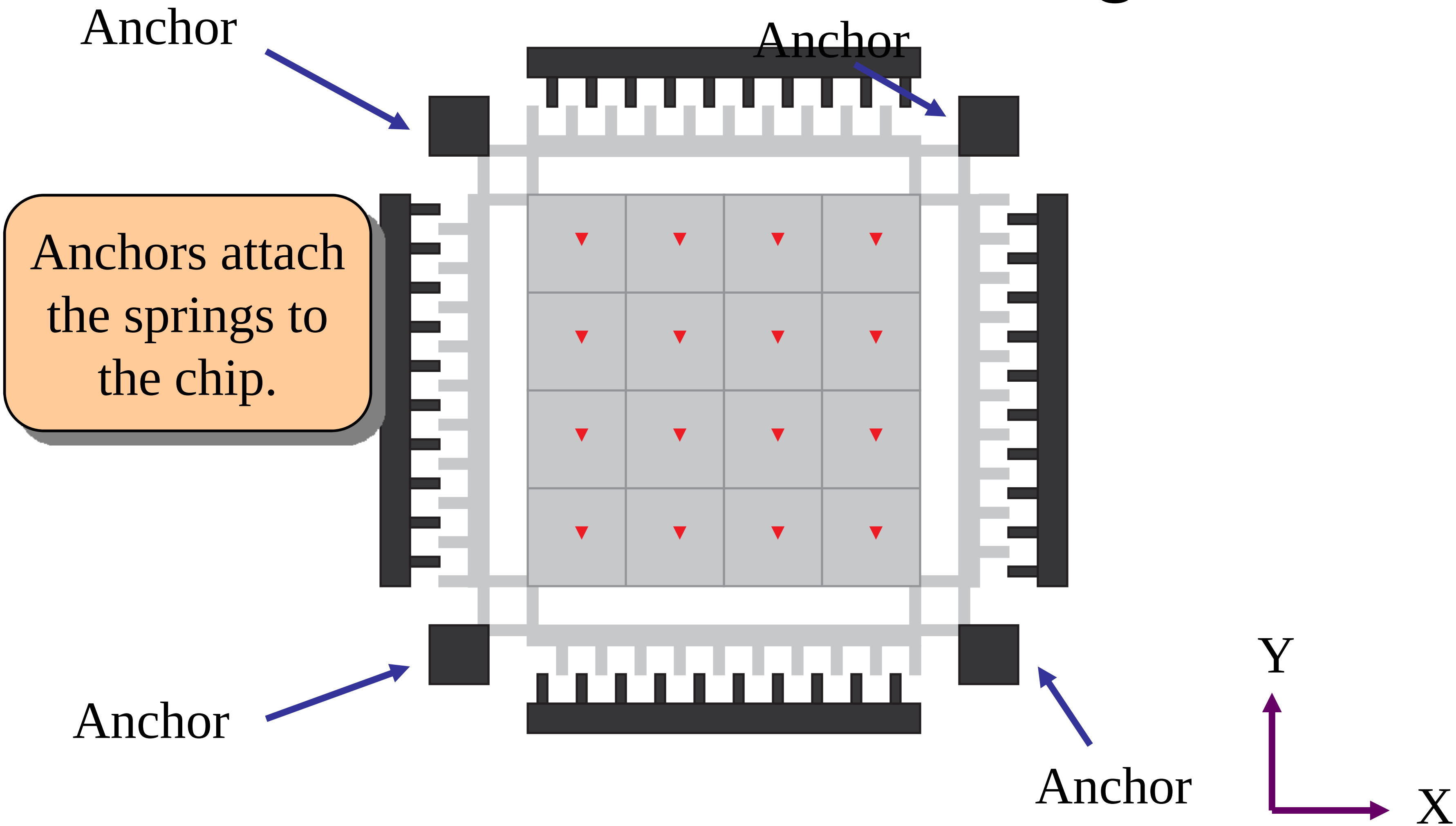
Nagel, Ganger, Schlosser, Griffin http://www.chips.ece.cmu.edu/

MEMS-based Storage



Nagel, Ganger, Schlosser, Griffin http://www.chips.ece.cmu.edu/

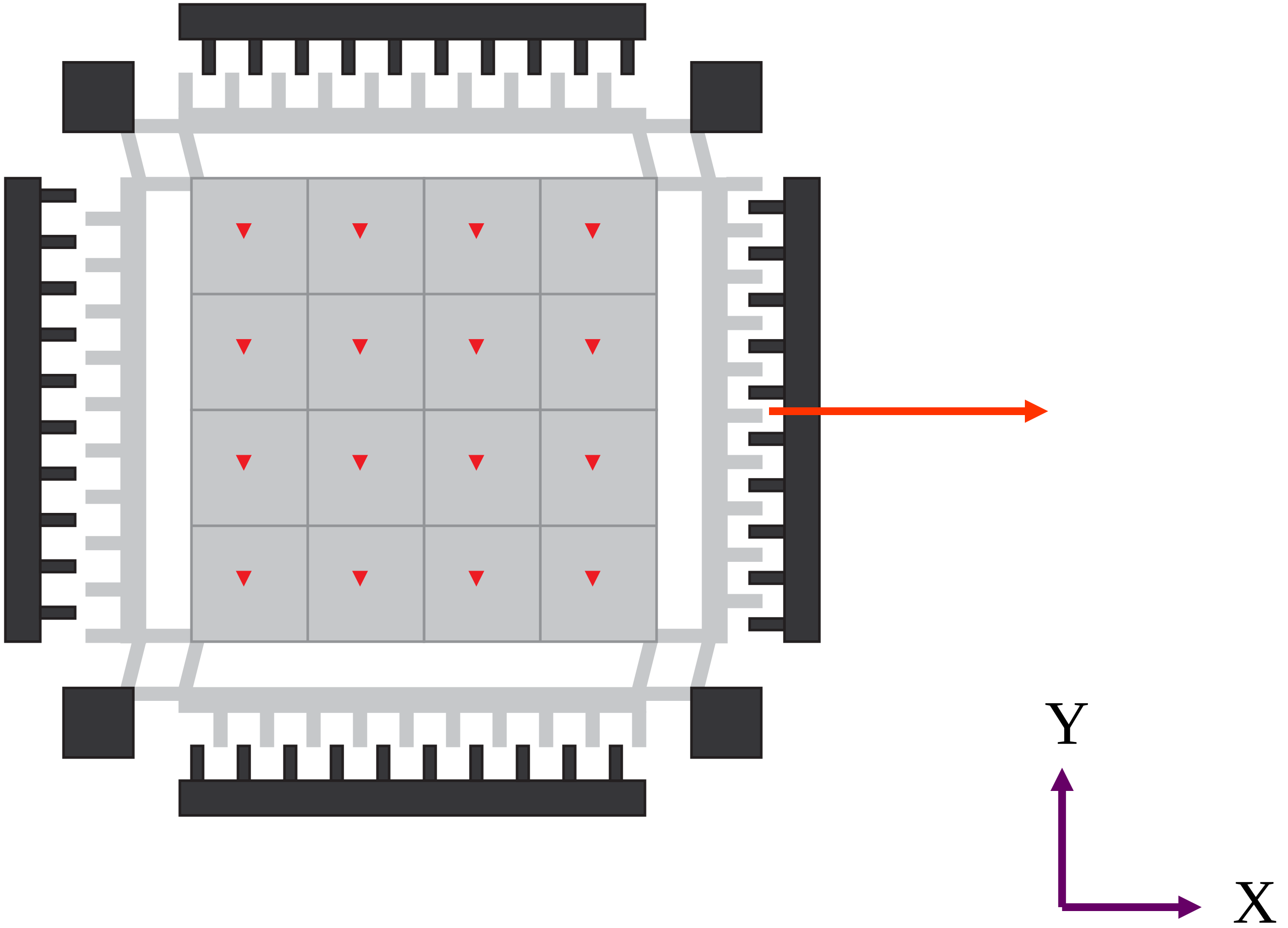
MEMS-based Storage



Nagel, Ganger, Schlosser, Griffin http://www.chips.ece.cmu.edu/

MEMS-based Storage

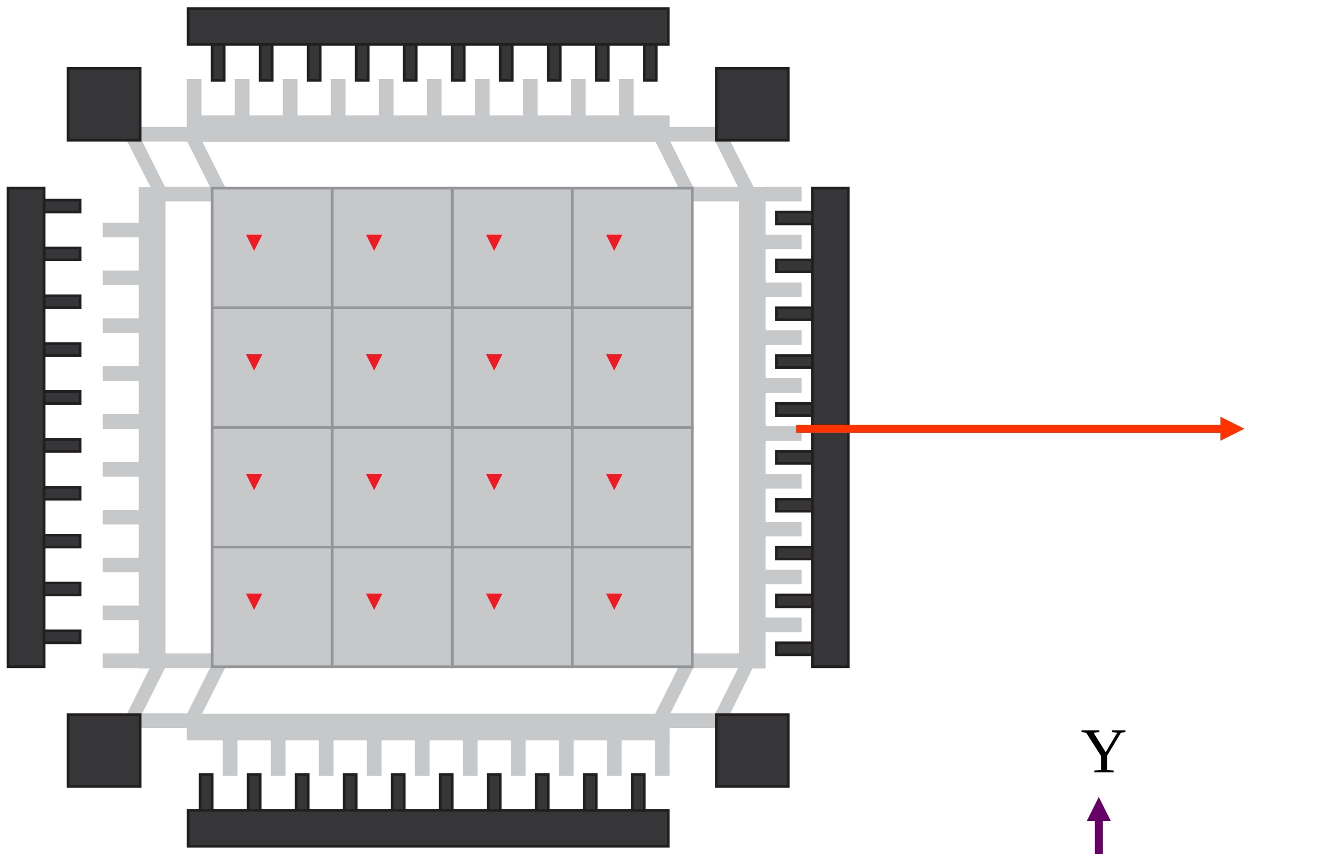
Sled is free to move



Nagel, Ganger, Schlosser, Griffin http://www.chips.ece.cmu.edu/

MEMS-based Storage

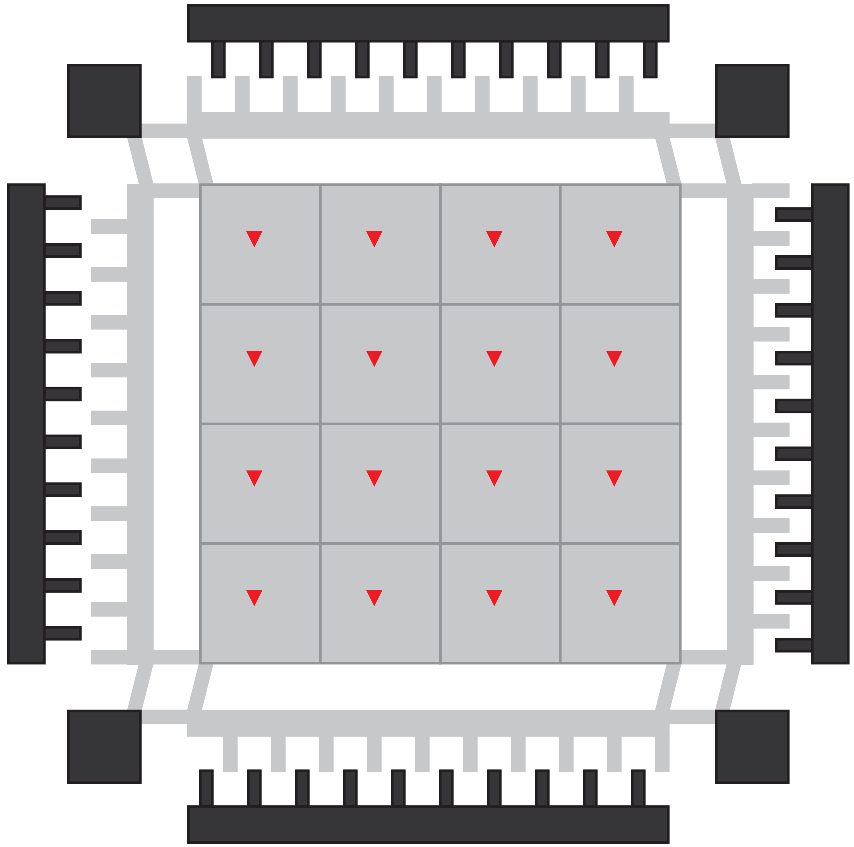
Sled is free to move

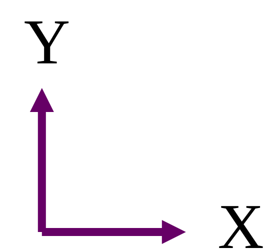


Nagel, Ganger, Schlosser, Griffin http://www.chips.ece.cmu.edu/

MEMS-based Storage

Springs pull sled toward center

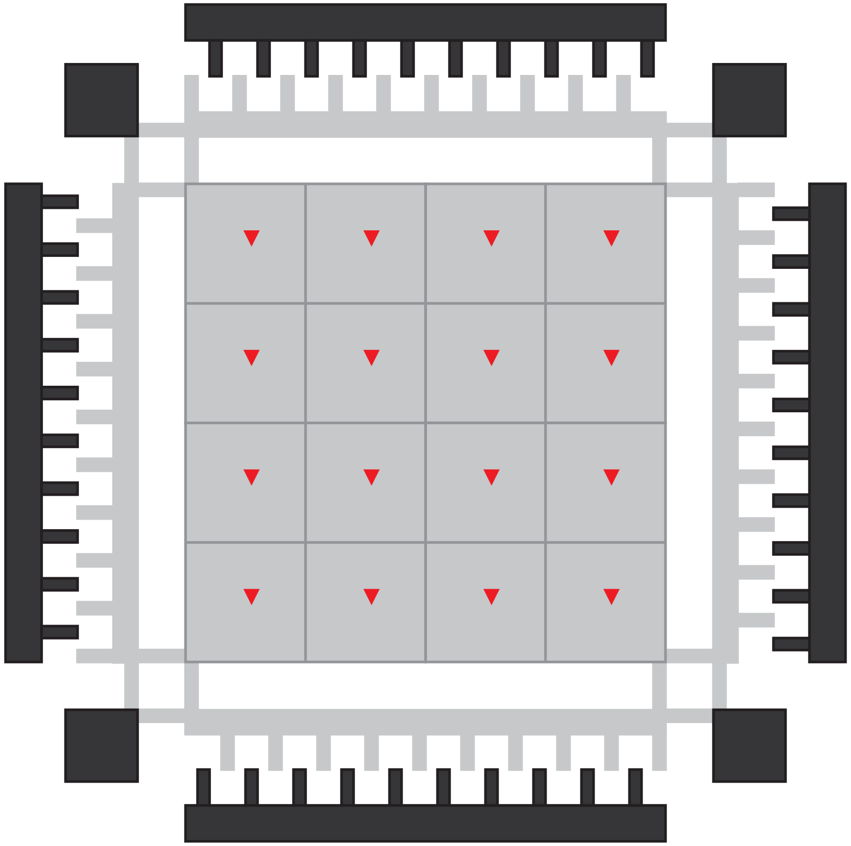


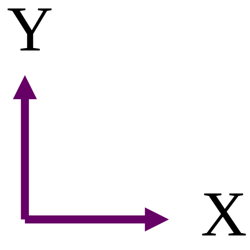


Nagel, Ganger, Schlosser, Griffin http://www.chips.ece.cmu.edu/

MEMS-based Storage

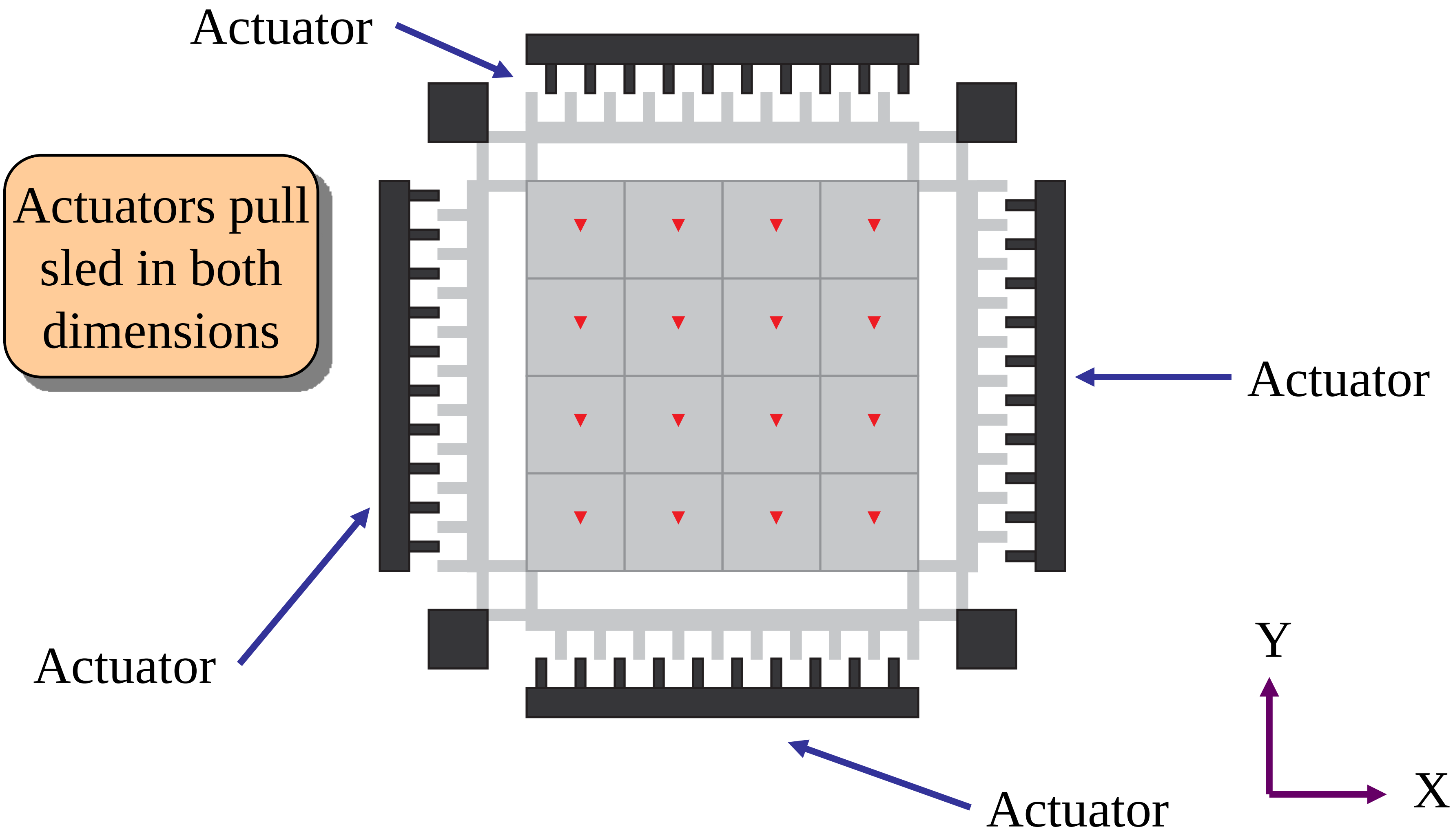
Springs pull sled toward center





Nagel, Ganger, Schlosser, Griffin http://www.chips.ece.cmu.edu/

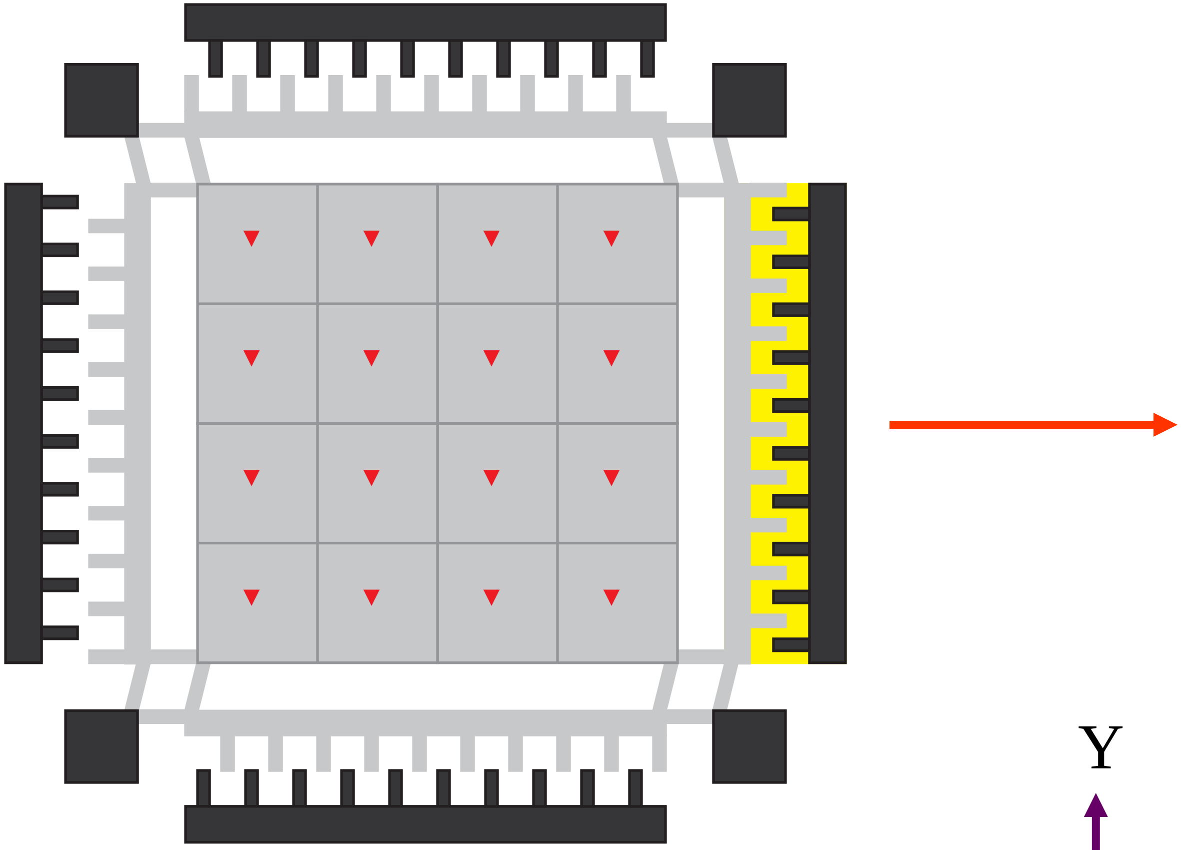
MEMS-based Storage

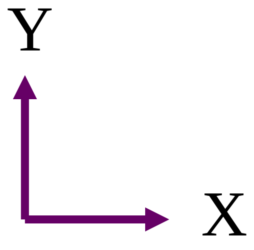


Nagel, Ganger, Schlosser, Griffin http://www.chips.ece.cmu.edu/

MEMS-based Storage

Actuators pull sled in both dimensions

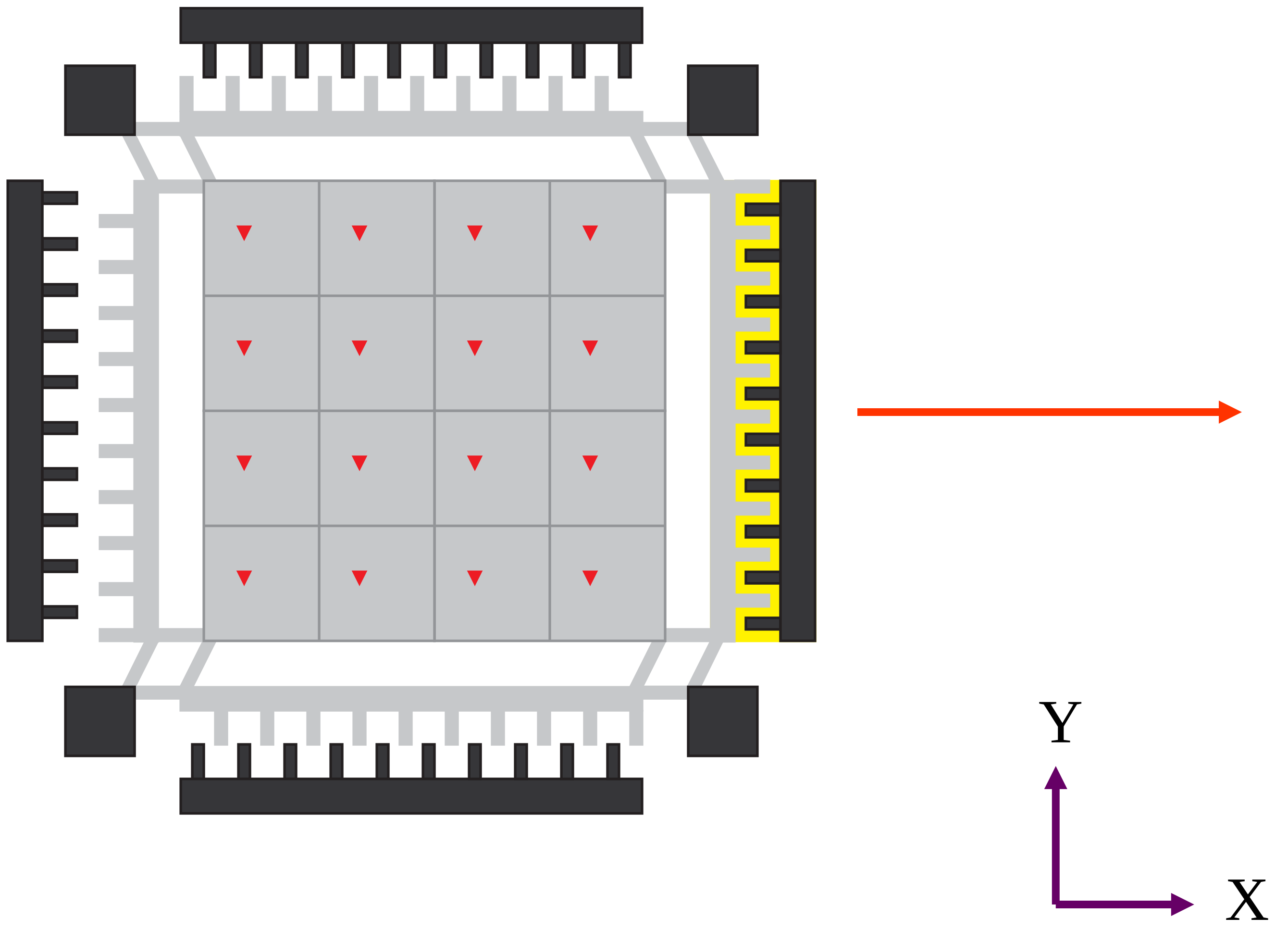




Nagel, Ganger, Schlosser, Griffin http://www.chips.ece.cmu.edu/

MEMS-based Storage

Actuators pull sled in both dimensions



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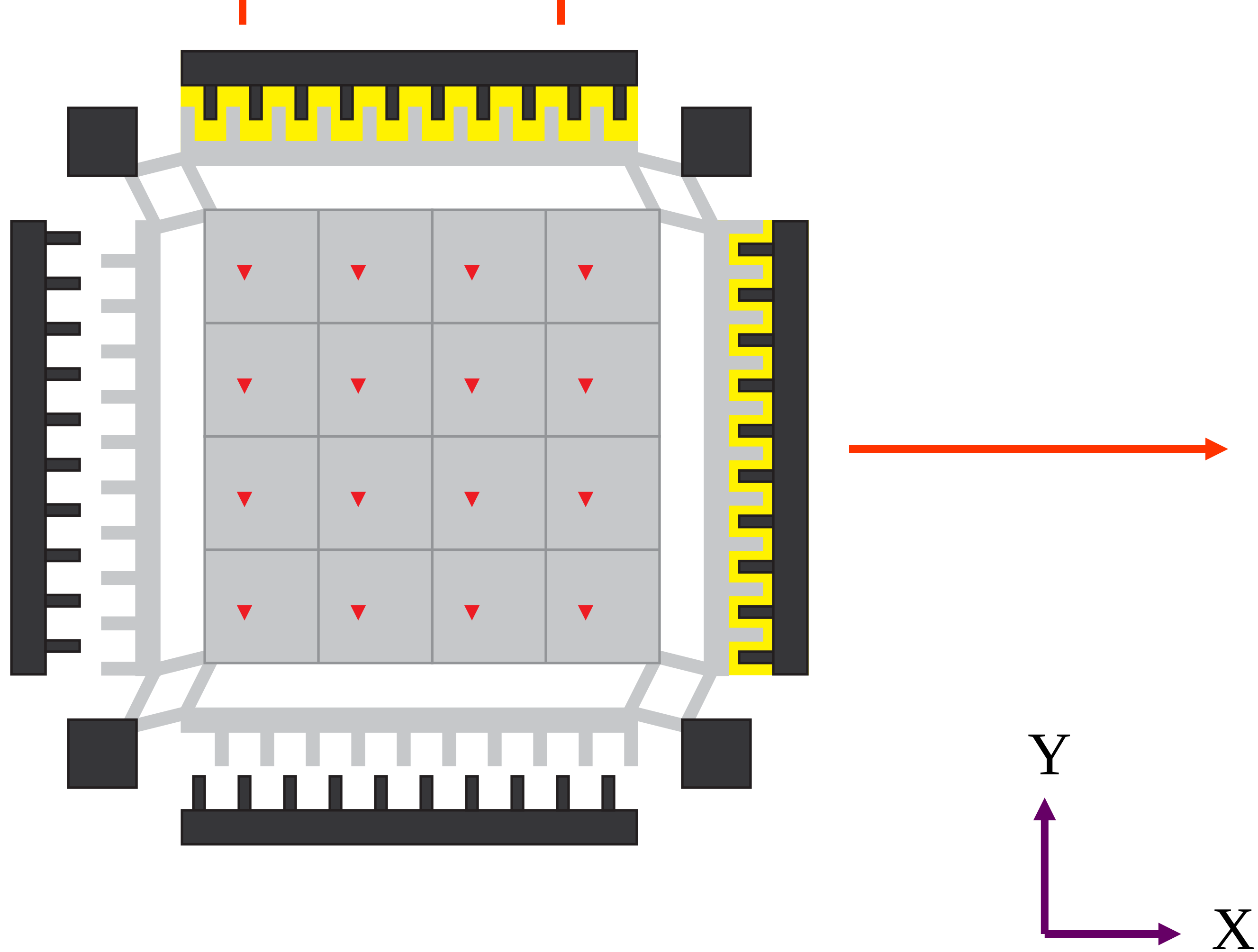
MEMS-based Storage

Actuators pull sled in both dimensions



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MEMS-based Storage

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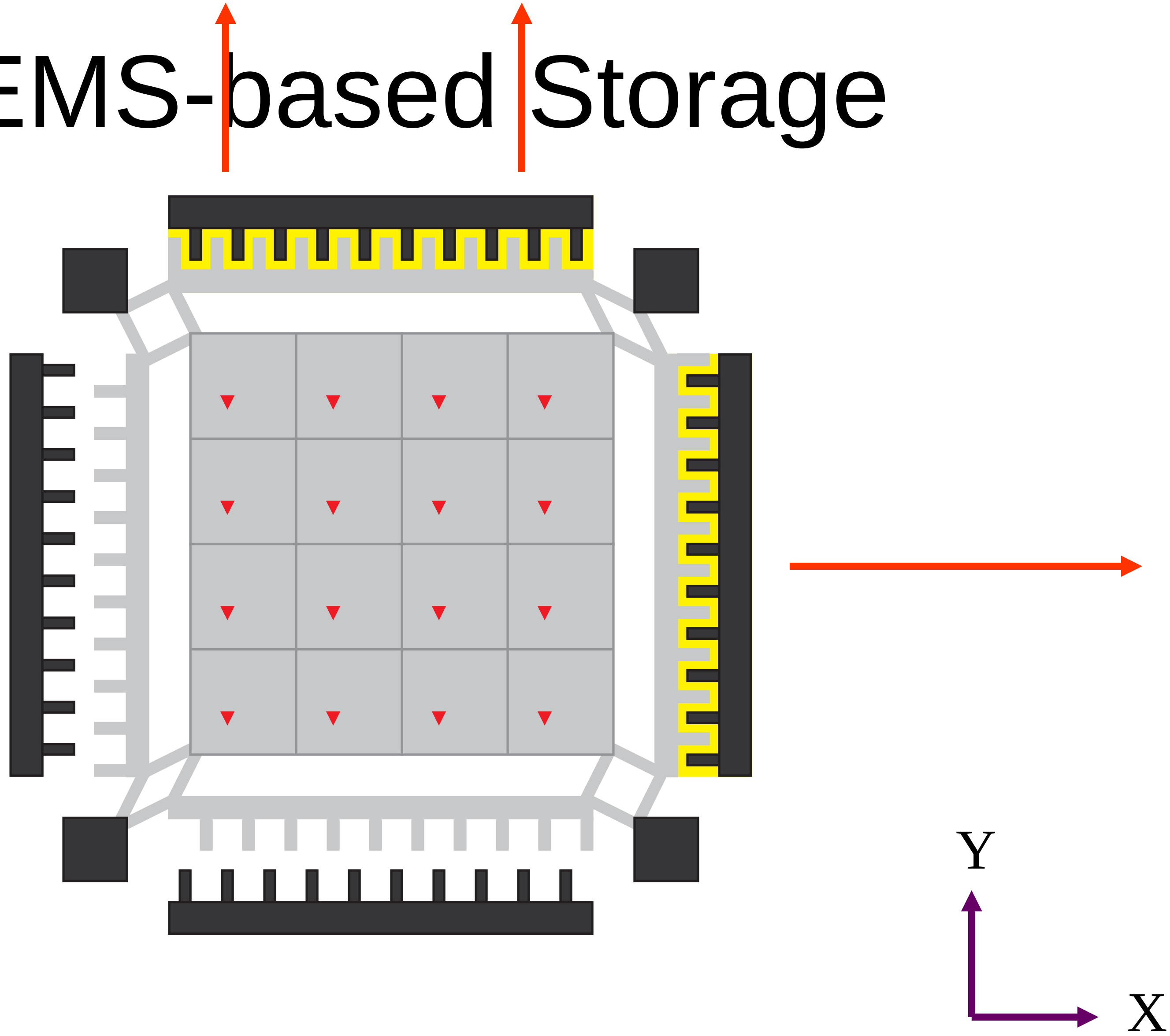

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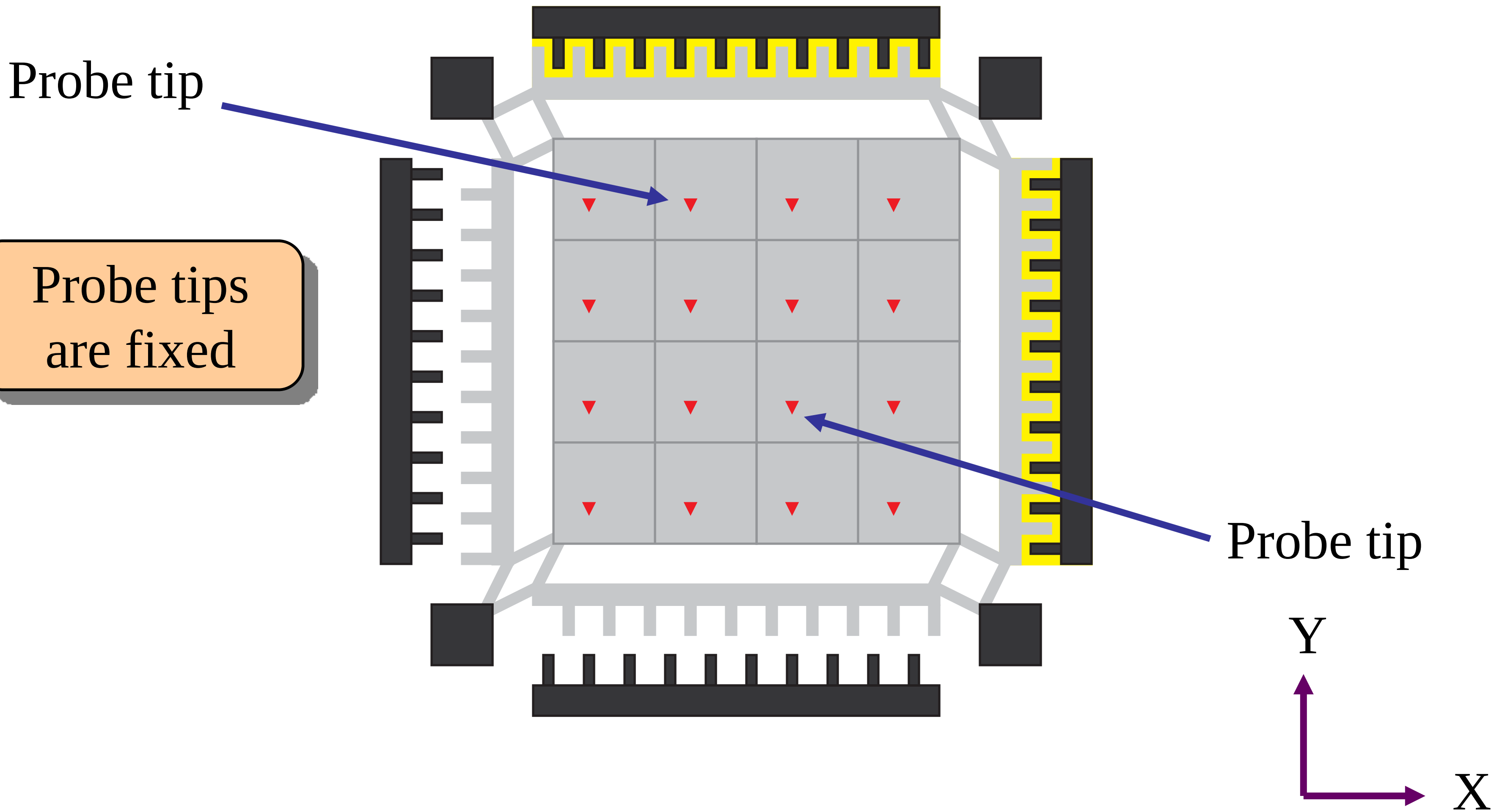
MEMS-based Storage



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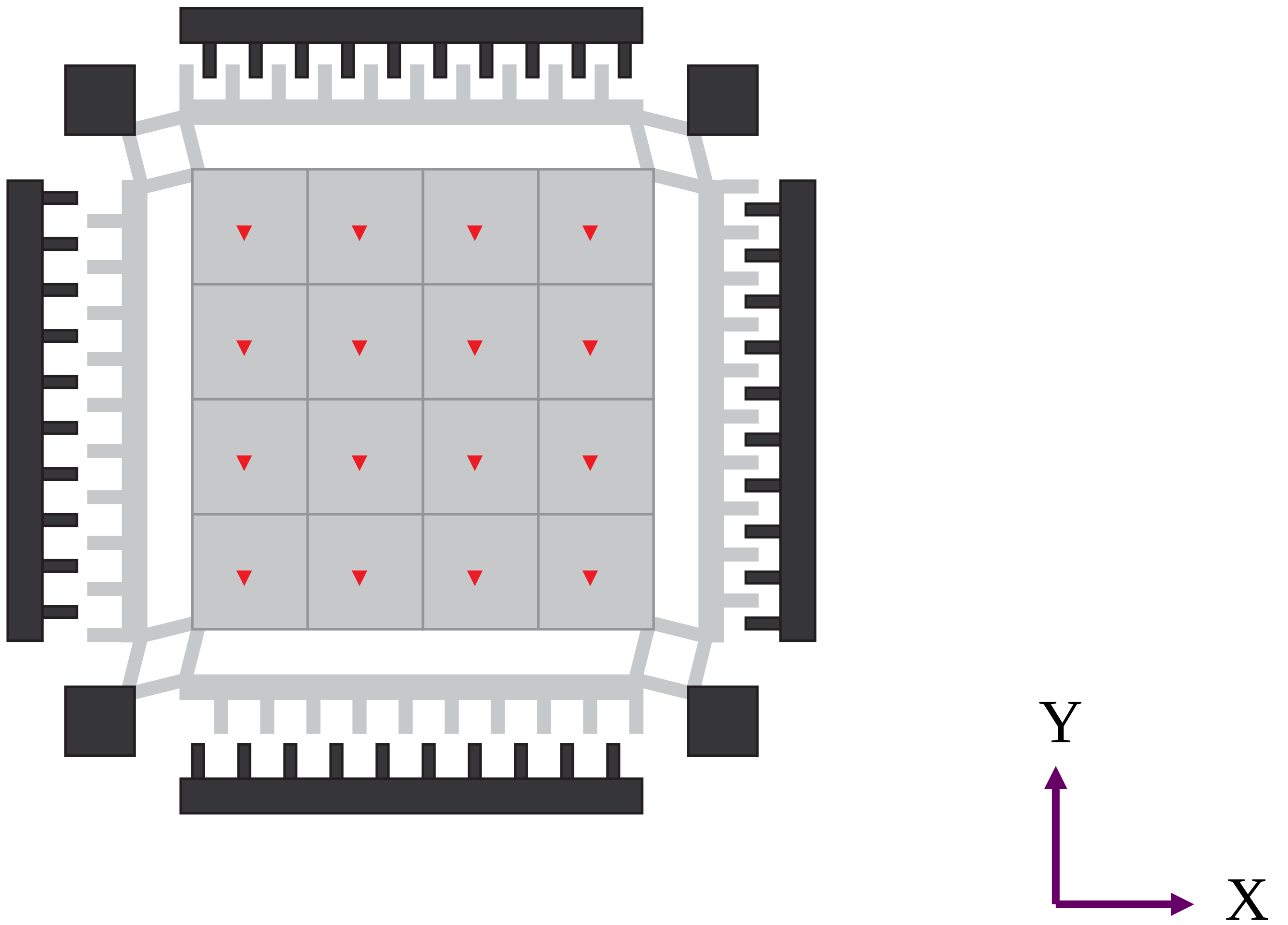
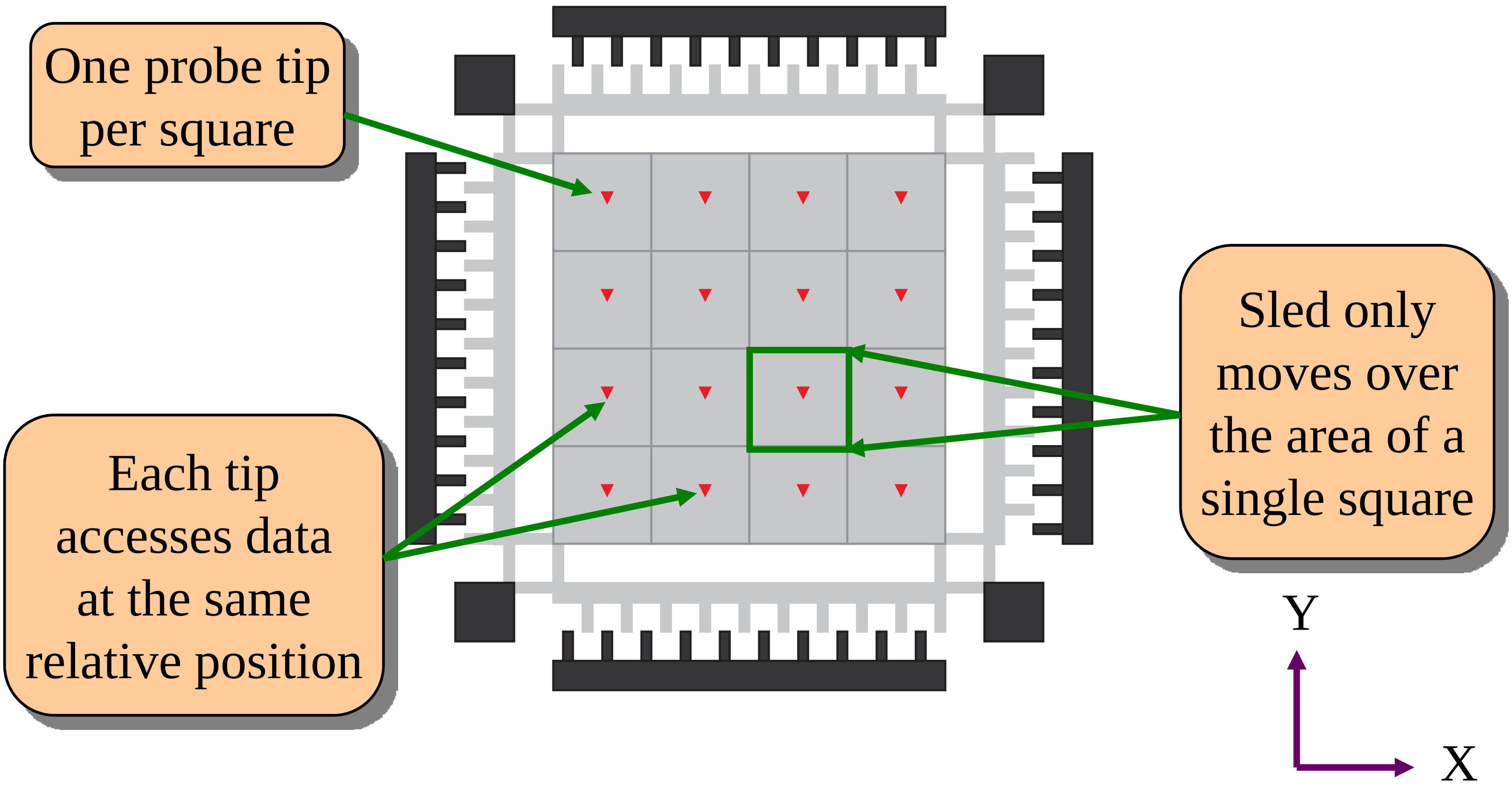
MEMS-based Storage

Probe tips are fixed



Nagel, Ganger, Schlosser, Griffin http://www.chips.ece.cmu.edu/

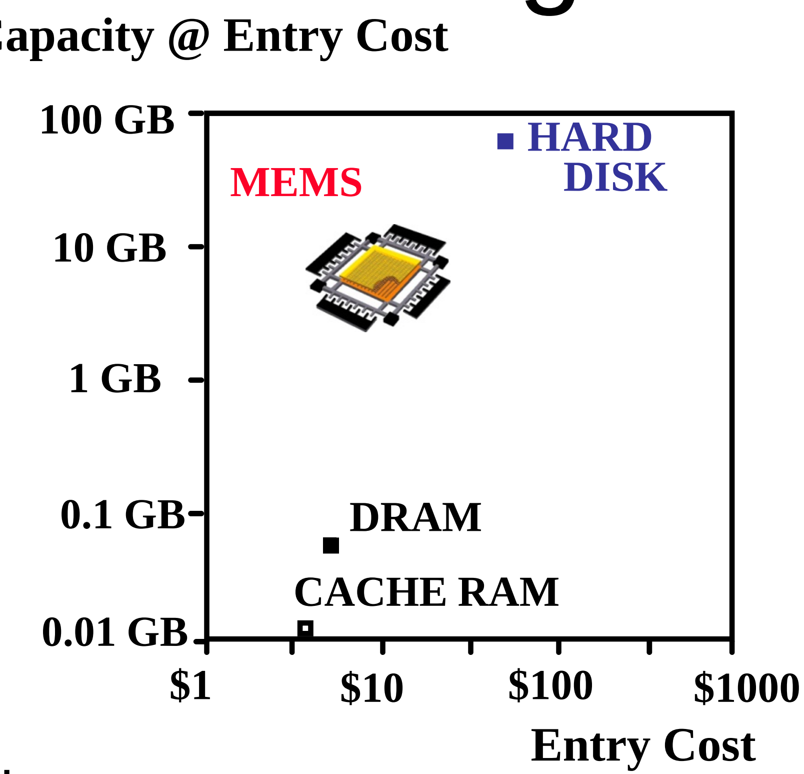
MEMS-based Storage



Nagel, Ganger, Schlosser, Griffin http://www.chips.ece.cmu.edu/

Why Use MEMS-based Storage?

- 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)



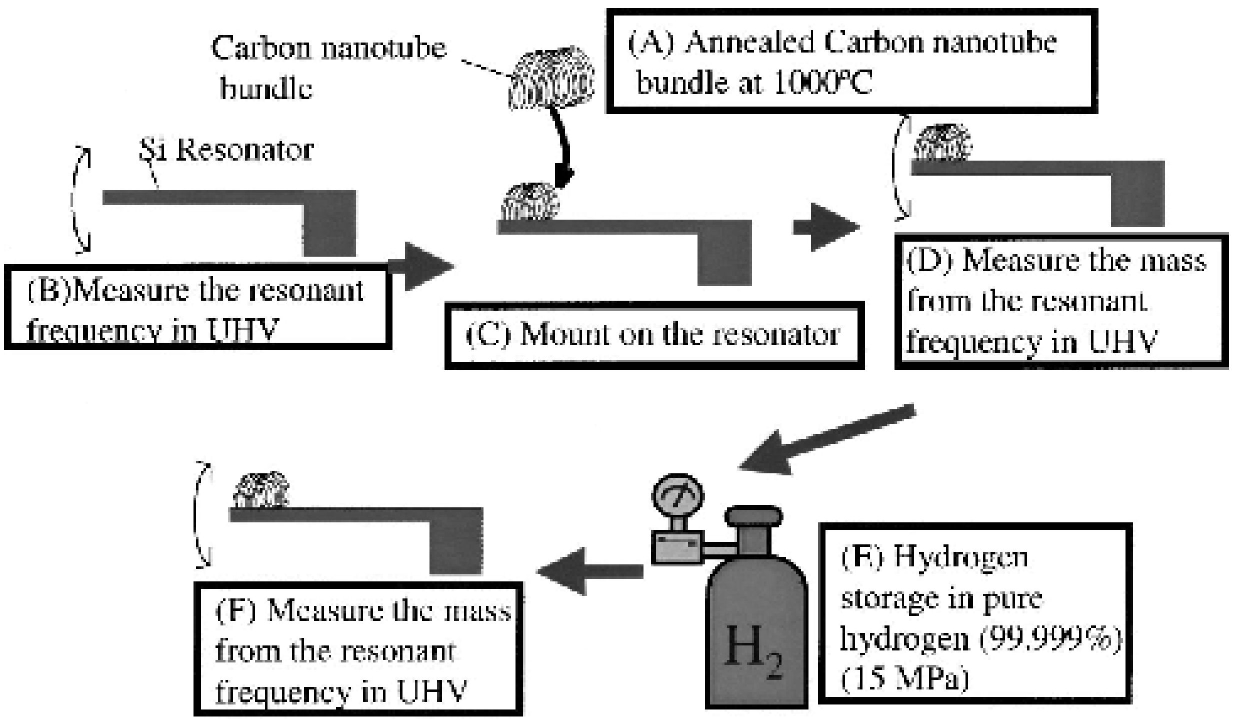
- Example Applications:
  - “throw-away” sensors / data logging systems infrastructure monitoring; e.g., bridge monitors, concrete pours, smart highways, condition-based maintenance, security systems, low-cost speaker-independent continuous speech recognition, etc.
  - Ubiquitous use in everyday world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

Nagel, Ganger, Schlosser, Griffin http://www.chips.ece.cmu.edu/

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:



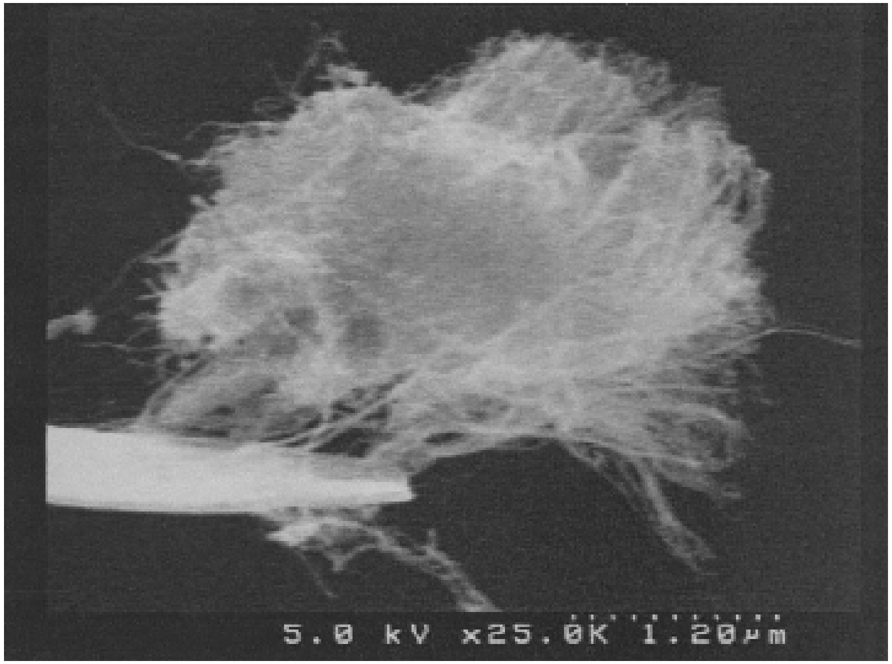
Ono *et al.*, Rev Sci Instr **74**, 1240 (2003)

Sensors

With proper treatment, can get their cantilevers to have *Q* ~ 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

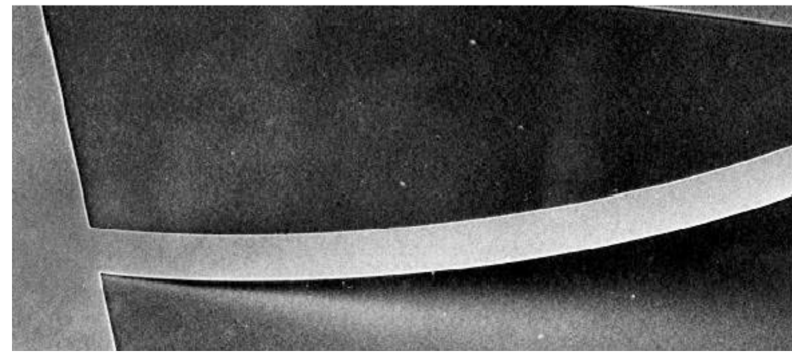
One can also look at steady state displacement of a cantilever.

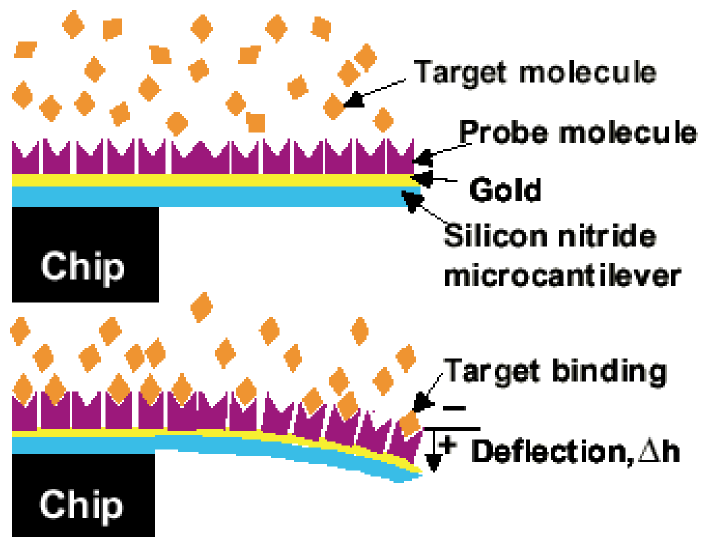
Recall our picture of surface stress effects in thin members:

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!





Wu *et al.*, Nature Bio. **19**, 856 (2001)

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