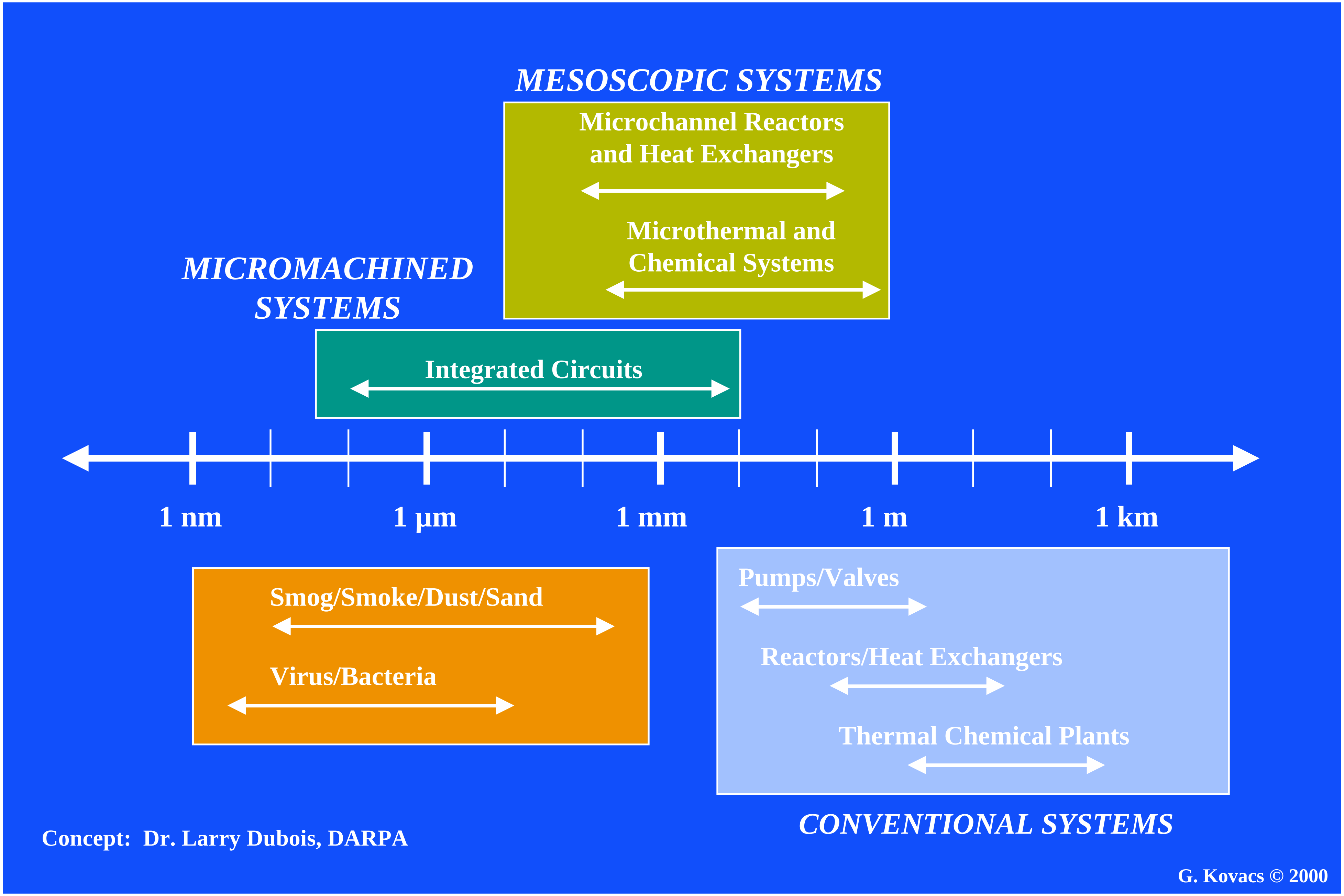
THE PROS AND CONS OF SCALING

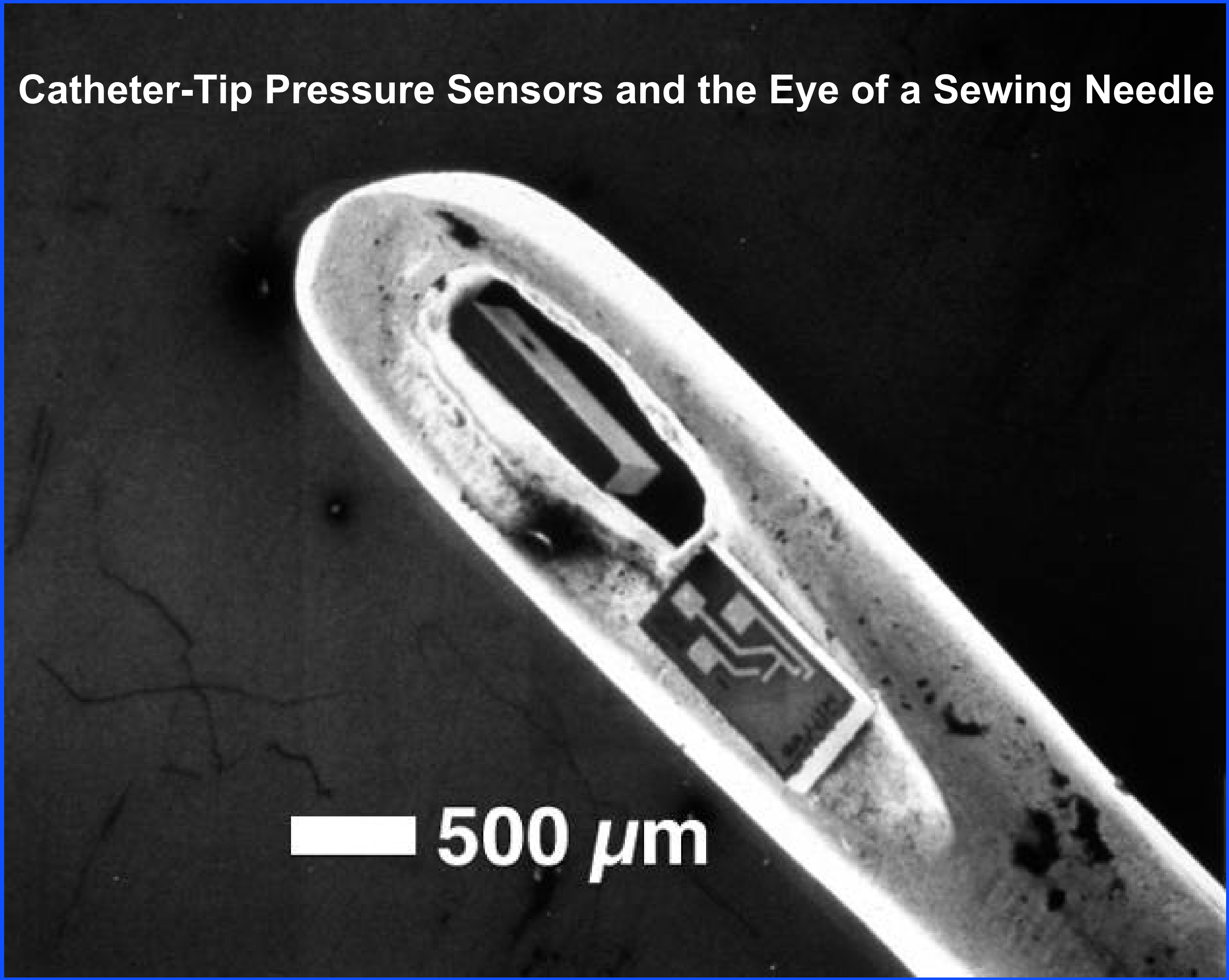
EE312, Prof. Greg Kovacs

Stanford University

“Never confuse motion with action.”

Benjamin Franklin

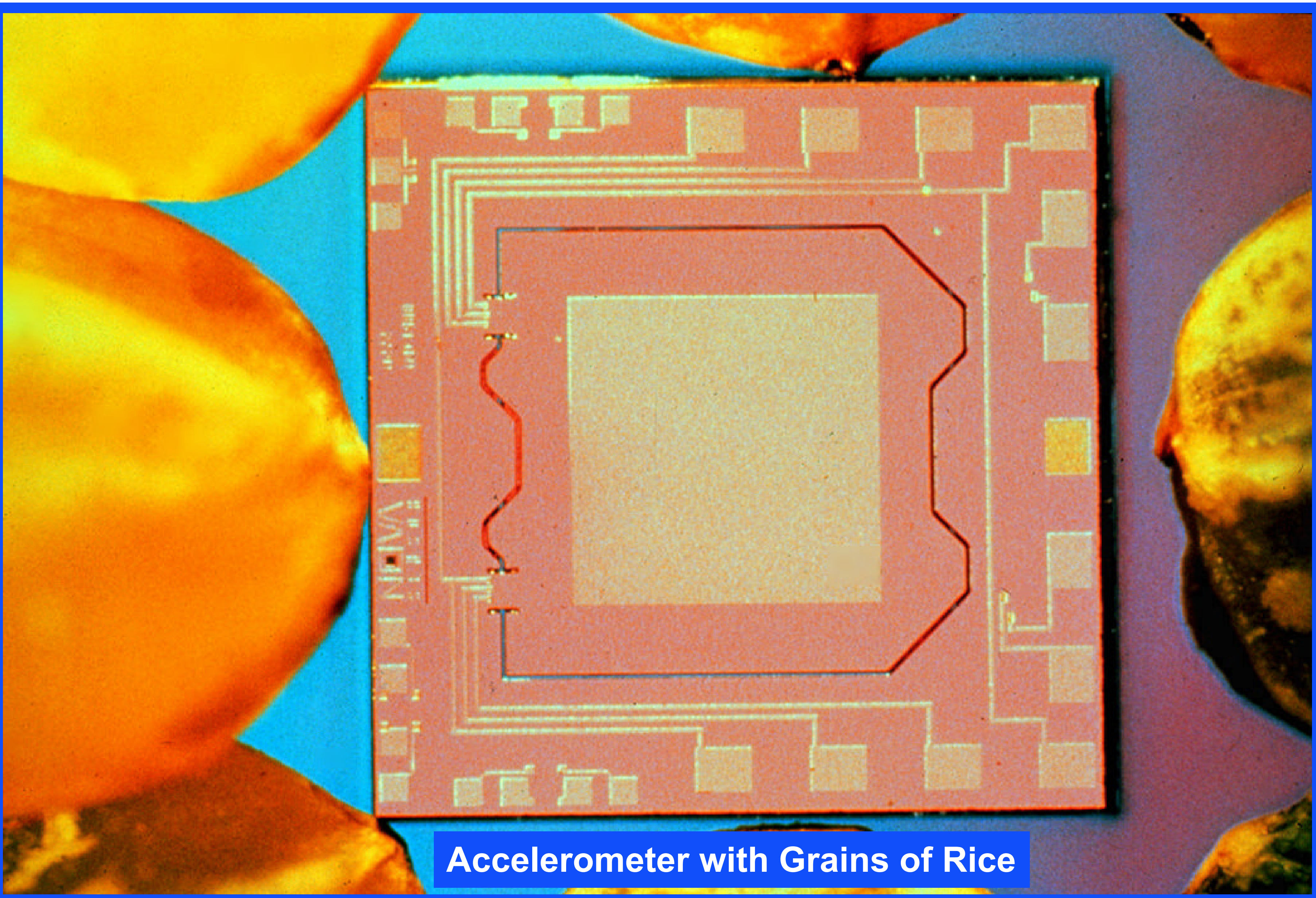

MESOSCOPIC SYSTEMS
Microchannel Reactors and Heat Exchangers
Microthermal and Chemical Systems
MICROMACHINED SYSTEMS
Integrated Circuits
1 nm
1 µm
1 mm
1 m
1 km
Smog/Smoke/Dust/Sand
Virus/Bacteria
Pumps/Valves
Reactors/Heat Exchangers
Thermal Chemical Plants
CONVENTIONAL SYSTEMS
Concept: Dr. Larry Dubois, DARPA
G. Kovacs © 2000



Courtesy of Lucas NovaSensor. Used with permission.

Implantable Strain Gauges on a Penny

Reference: Angell, J. B., "Transducers for in vivo measurement of force, strain and motion," in Physical Sensors for Biomedical Applications, Neuman, M. R., Fleming, D. G., Cheung, P. W., and Ko, W. H., (Eds.), CRC Press, Boca Raton, FL, 1980, pp. 46 - 53.



Courtesy of Lucas NovaSensor. Used with permission.

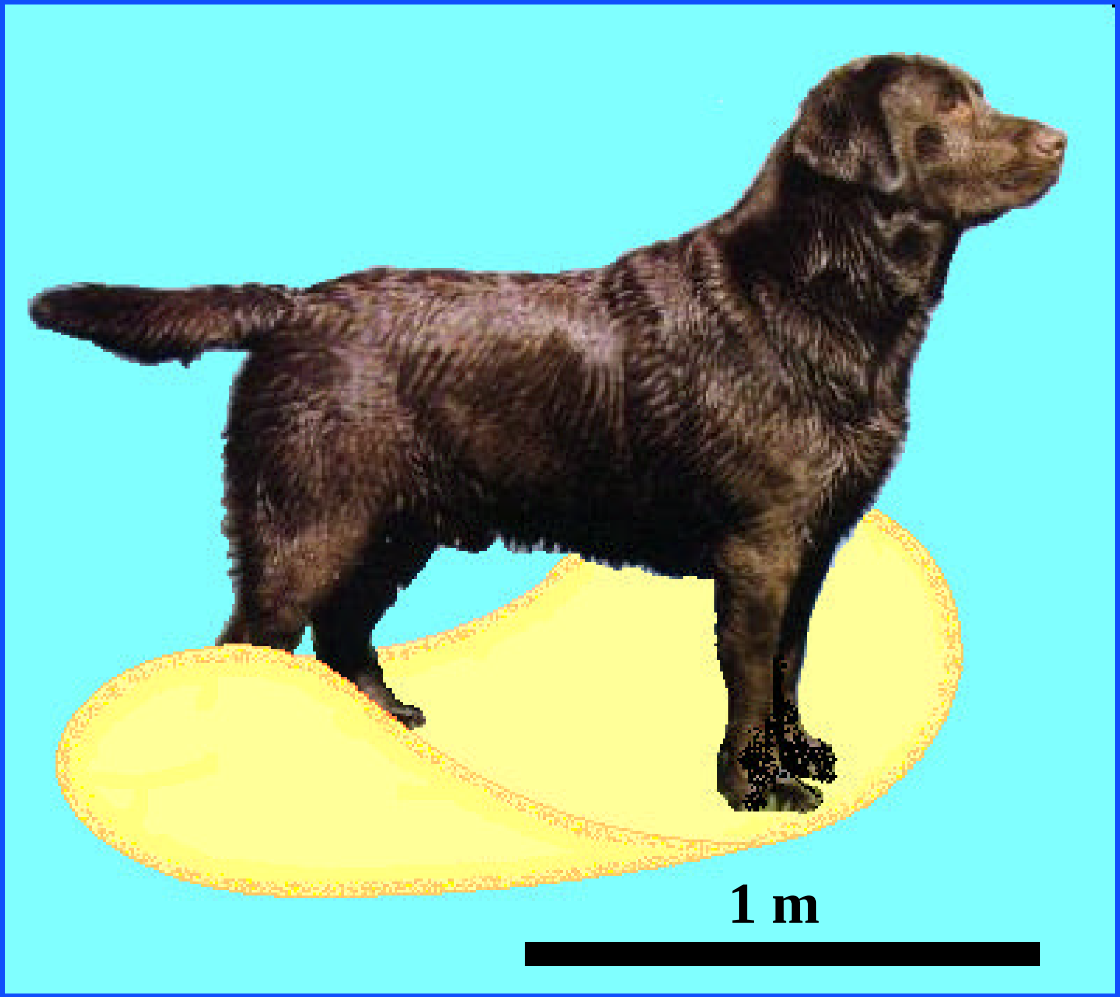
WHY SCALE?

- Changed qualities of thermal, electron, momentum and mass transport.
- Changes in mechanical properties.
- Improvements in separations such as capillary electrophoresis and chromatography.
- Stabilization of reactions that are unstable at a macroscopic scale.
- Point-of-use generation/destruction of chemicals.
- Reduction of the “tyranny of interconnects.”
- Potential for systems size reduction (?).
- Potential for cost reduction (mass production).

REASONS NOT TO SCALE...

- Expectations of a complete analytical lab in the palm of your hand (not everything shrinks).
- Expectations of automatic cost reductions (consider amortization of R&D, packaging and testing costs!).
- Lack of clear user pull.
- If fluid/battery/packaging volumes do not scale well with the system.
- If alternative “lower tech” approaches cannot be ruled out as competitors.

"LAB-ON-A-CHIP"



VOLUME & MASS SCALING

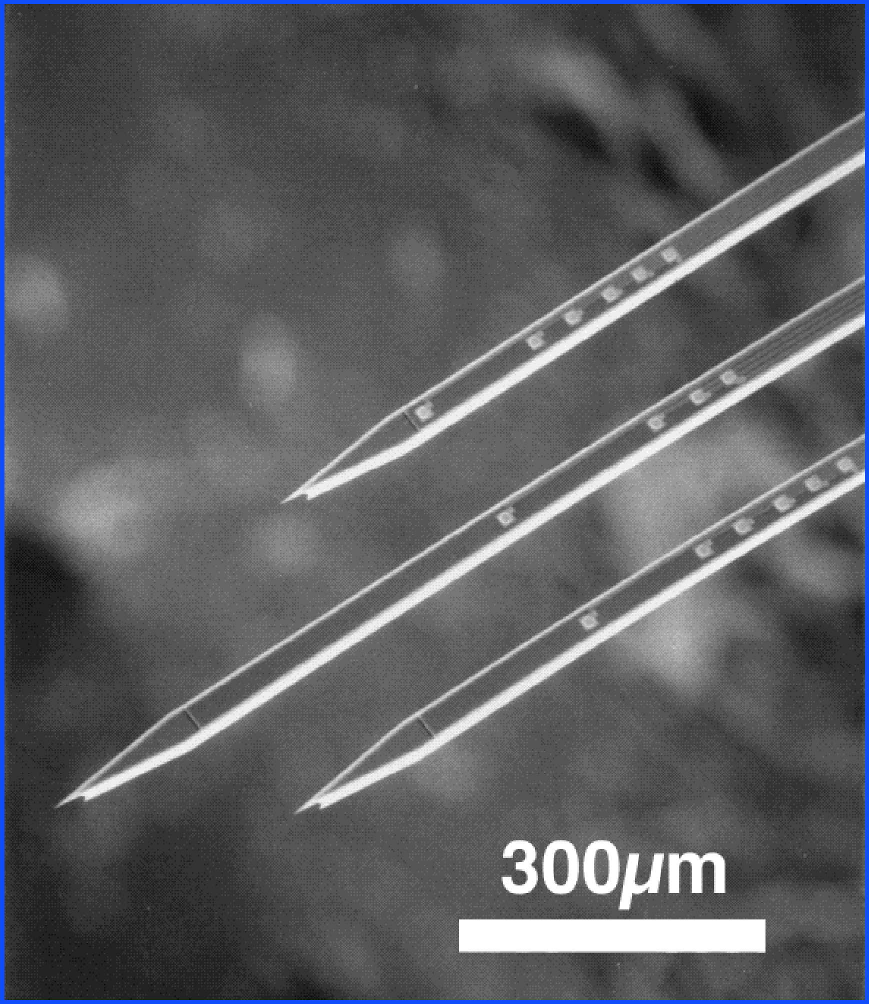
- Micromachining can *potentially* result in lighter and smaller devices if their bulk is not packaging, power sources or reagents.
- Example: field portable, small volume bioagent detectors.
- Example: Implantable drug delivery - cannot readily change concentration of pharmaceuticals or size of power sources, thus volume stays ≈ same.

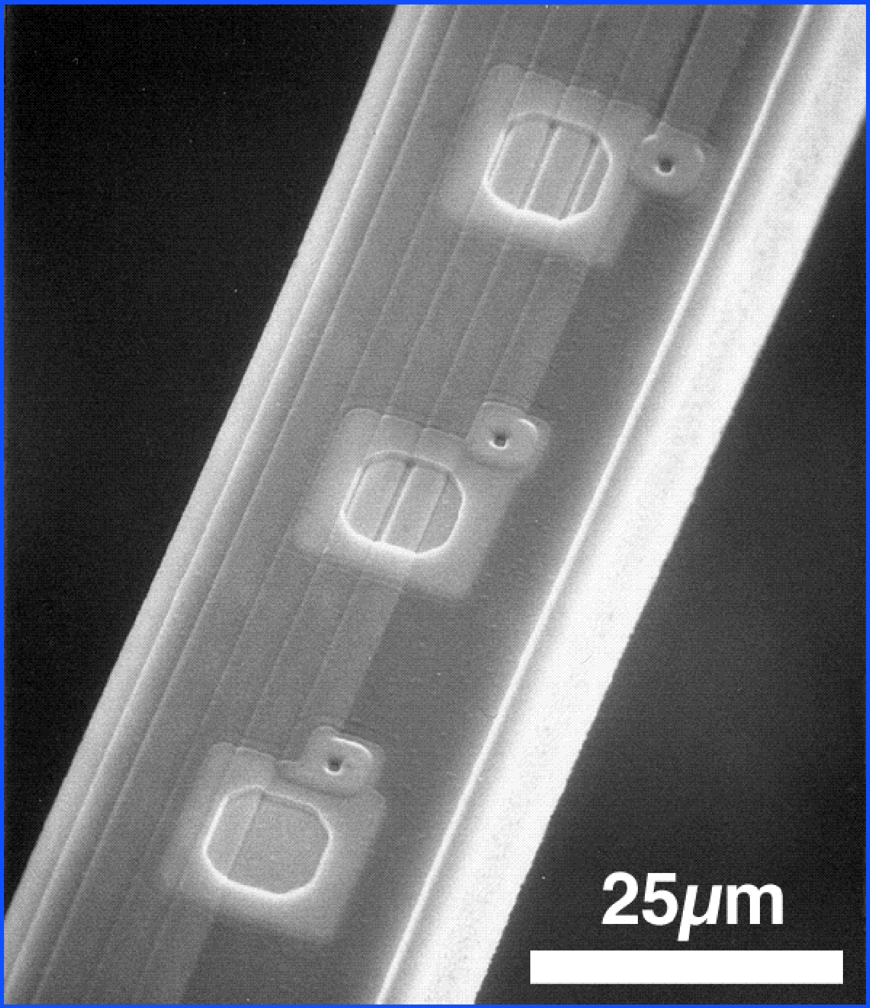
Courtesy of Kurt Petersen, Cepheid.

IMPLANTABLE DRUG PUMP

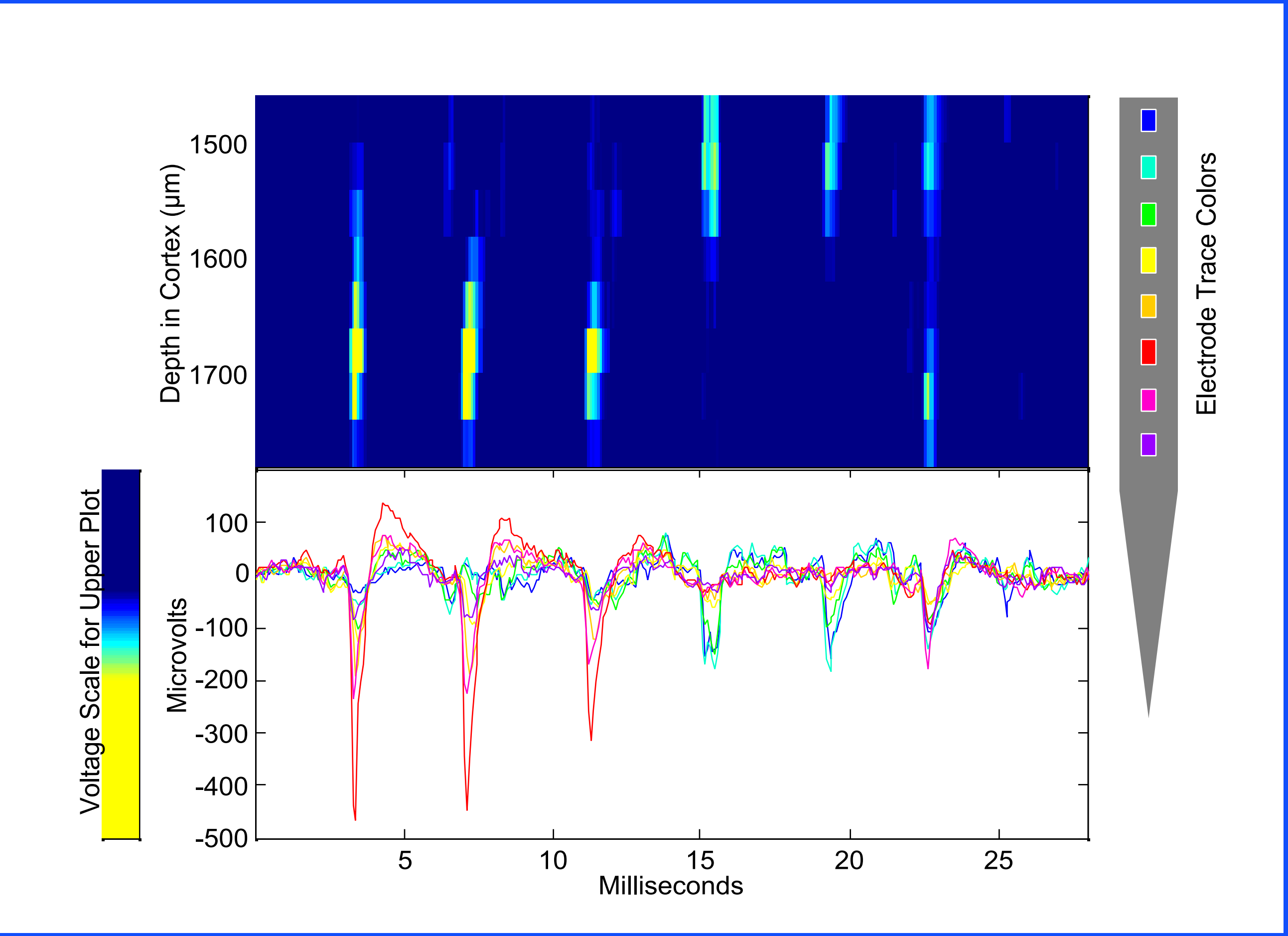
Courtesy John Meador, Medtronic, Inc.

NEURAL INTERFACES

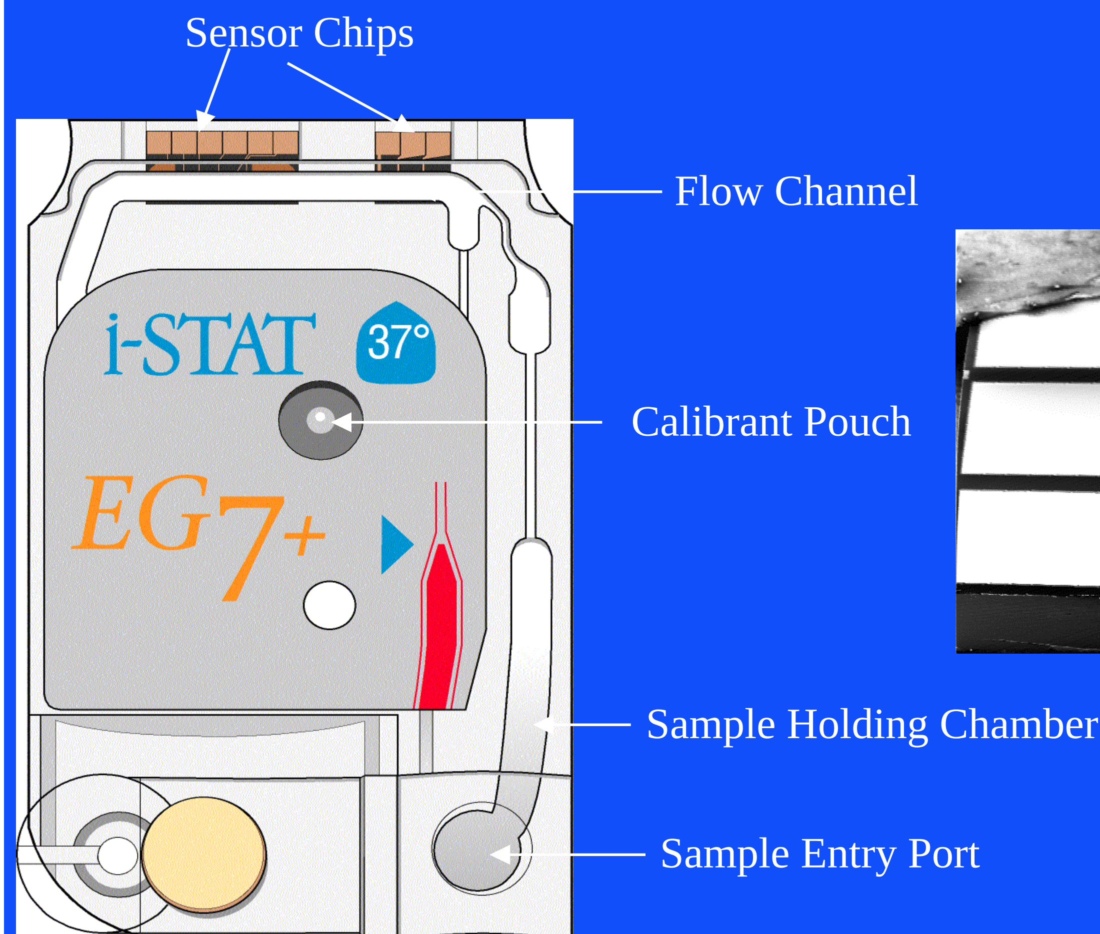


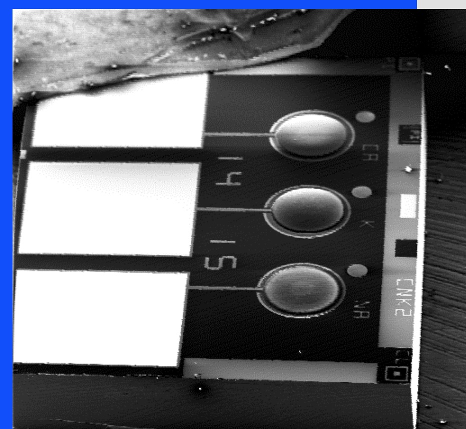


EIGHT-CHANNEL RECORDINGS FROM RAT CORTEX



Miniaturized POC Diagnostic



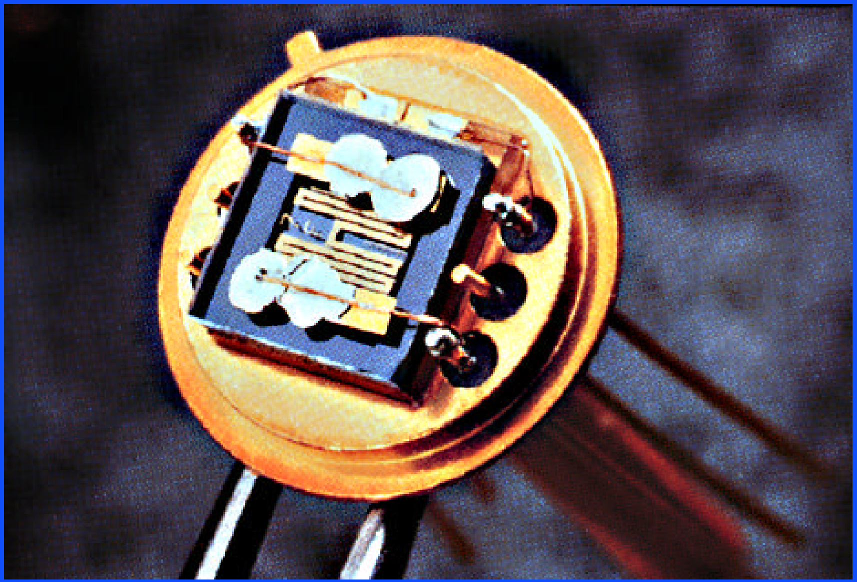


Courtesy Dr. Anca Varlan, I-Stat.

Courtesy Dr. Anca Varlan, I-Stat.

ACTUATOR AND ENERGY SCALING

- Actuation schemes generally do not scale well.
- Thermal actuation generally used (high power).
- Current alternatives have significant drawbacks.

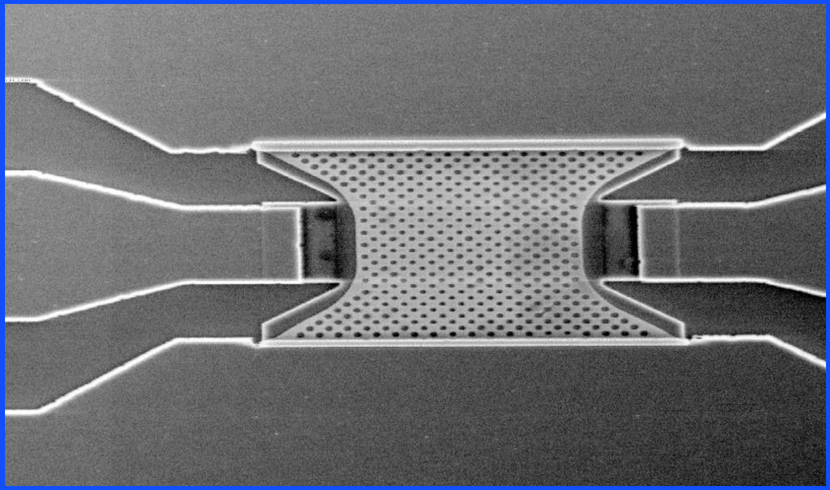


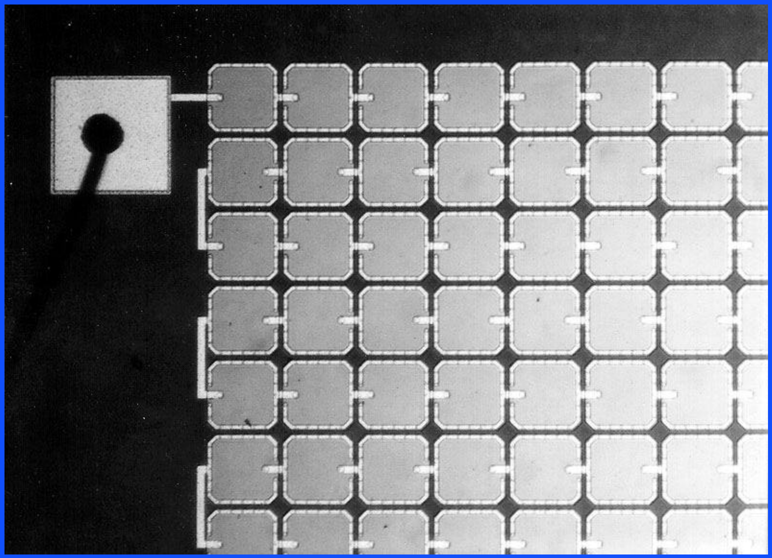
Courtesy Dr. Mark Zdeblick, Redwood Microsystems, Inc.

- Power source scaling is even worse.
- Many portable or implantable systems are dominated by battery volume/mass.

GOOD PAIRINGS OF ACTUATORS AND ENERGY SOURCES DO EXIST

- Electostatic actuators, like the RF switch shown, require relatively high voltages (often greater than logic levels), but almost no current.



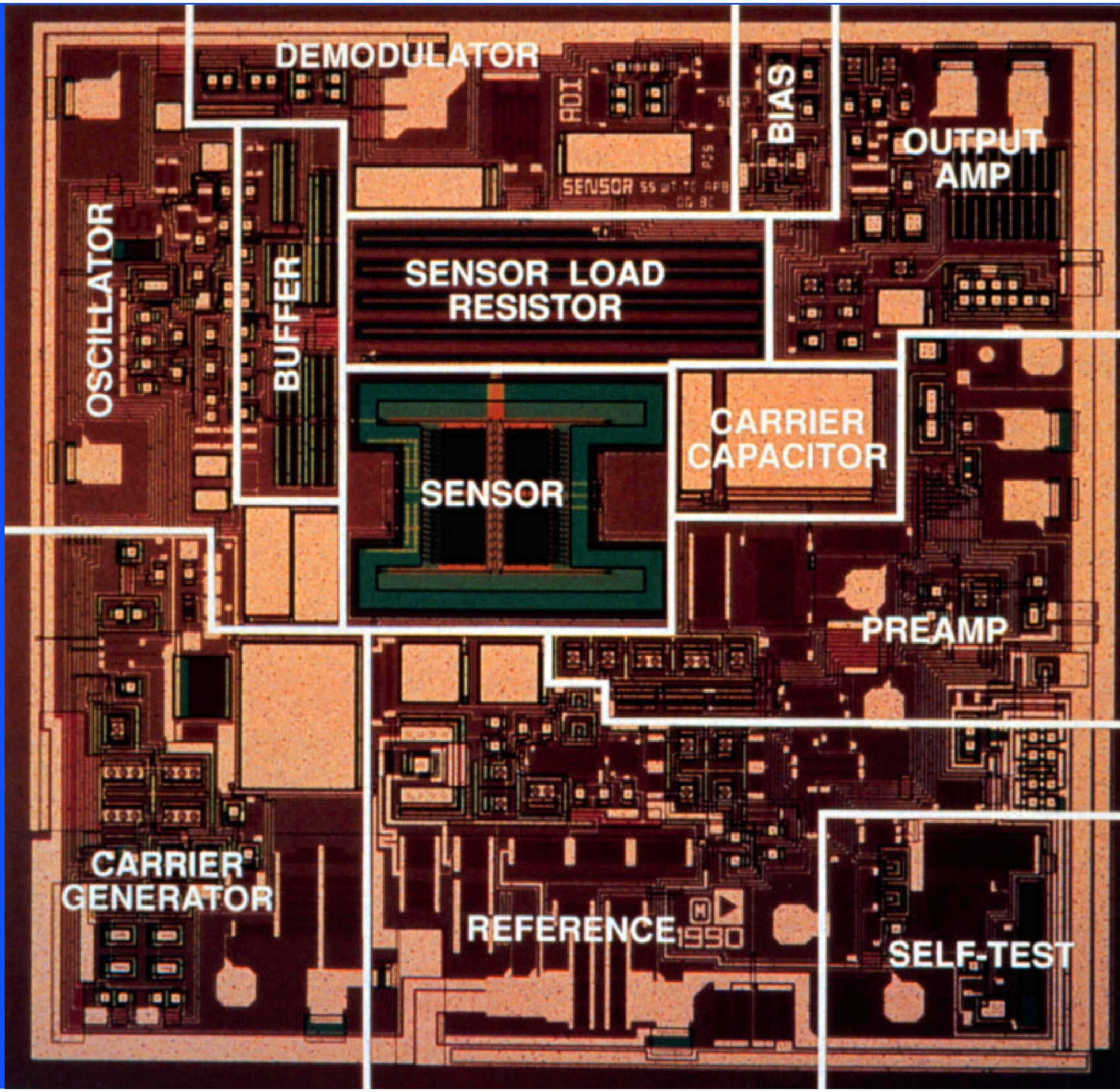


- Photovoltaic arrays in SOS or SOI provide a practical alternative to batteries in some applications.
- PV actuation of RF switches has been demonstrated.

MECHANICAL SCALING

- Fatigue properties for ultra-thin films are radically different.
- Young's modulus, Poisson's ratio, yield strength and other parameters are difficult to measure accurately, and even more difficult to control.
- Caution is necessary when using published mechanical property values!
- Residual stresses and stress gradients can dominate for smaller scales, and are also very difficult to control.
- Mechanical designs can be unusual and seemingly non-intuitive due to mass/volume scaling.
- Thermal noise can dominate over electronic noise as masses become very small.

ADXL-50 Integrated Accelero -meter

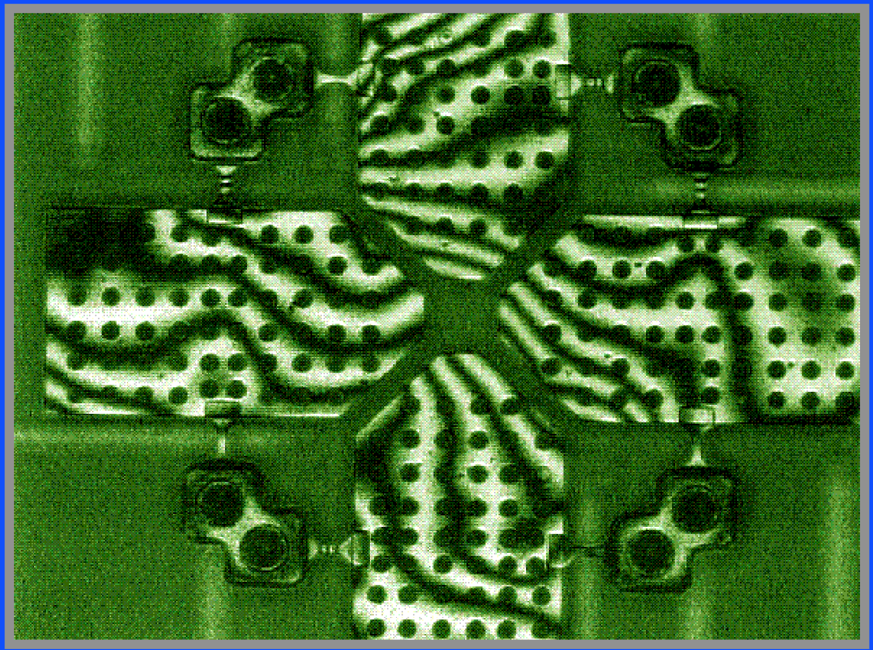


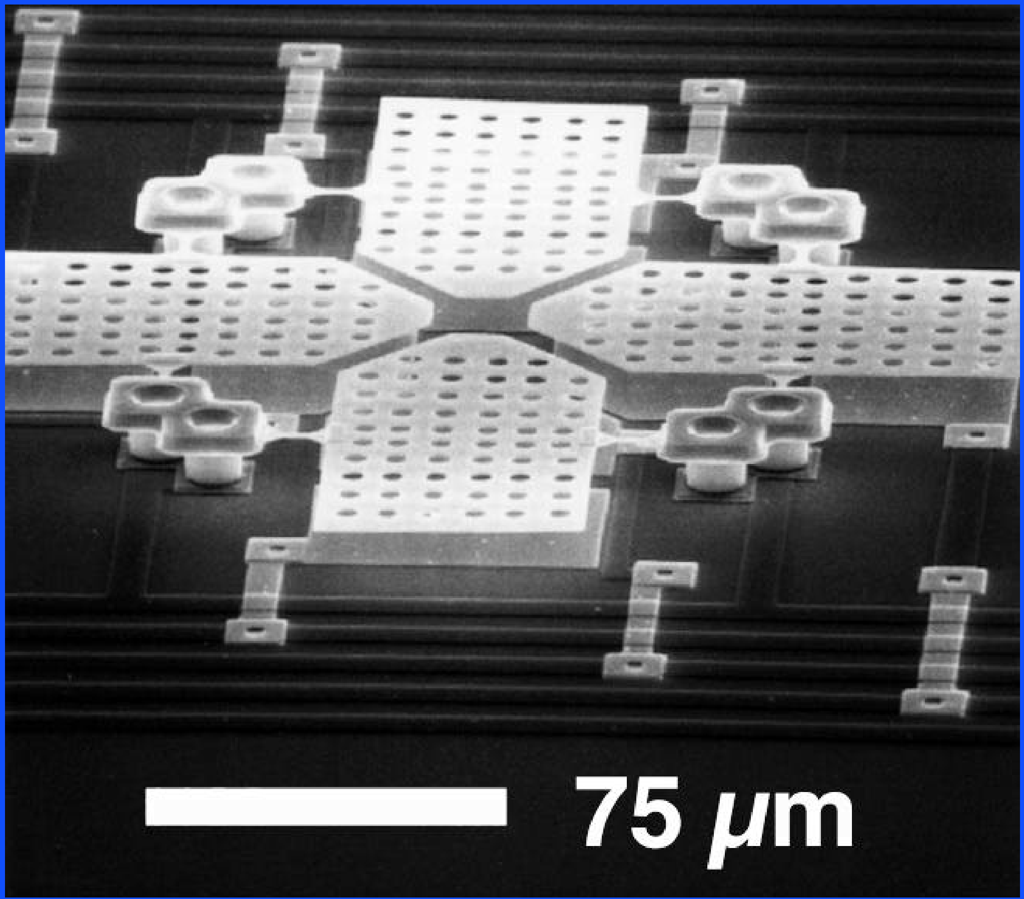
Courtesy Dr. Richie Payne, Analog Devices, Inc.

G. Kovacs Stanford University

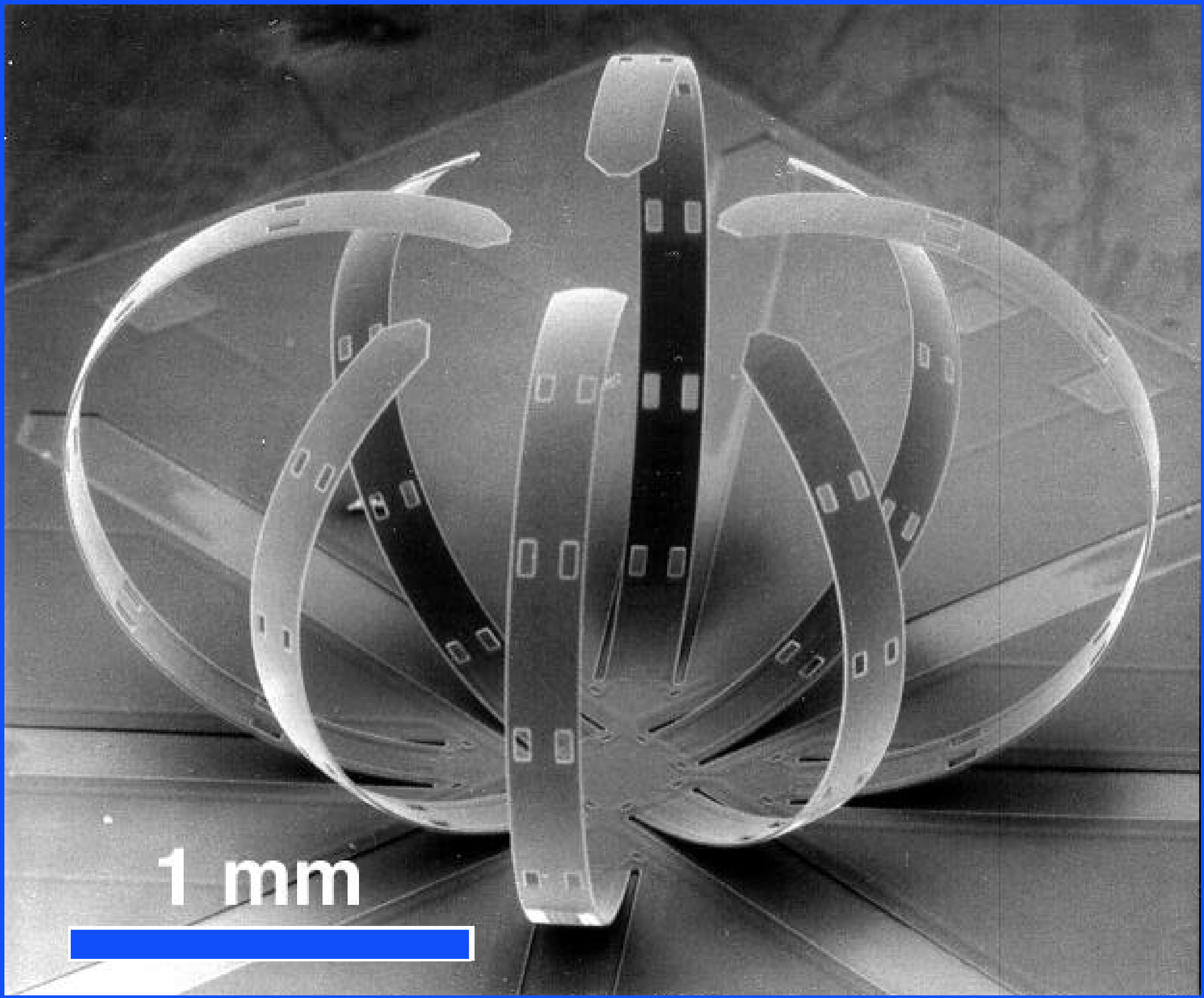
• **Thin-film metallic structures can operate in ways impractical with macroscopic machines.**

• **However, mechanical properties do not all scale ideally!**



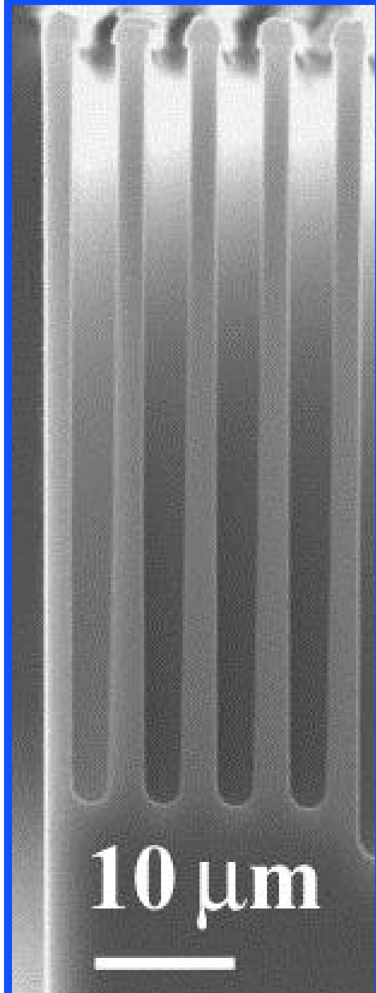


Storment, C. W., Borkholder, D. A., Westerlind, V., Suh, J. W., Maluf, N. I., and Kovacs, G. T. A., “Flexible, Dry-Released Process for Aluminum Electrostatic Actuators,” IEEE/ASME Journal of Microelectromechanical Systems, Sept. 1994, vol. 3, no. 3, pp. 90 - 96.

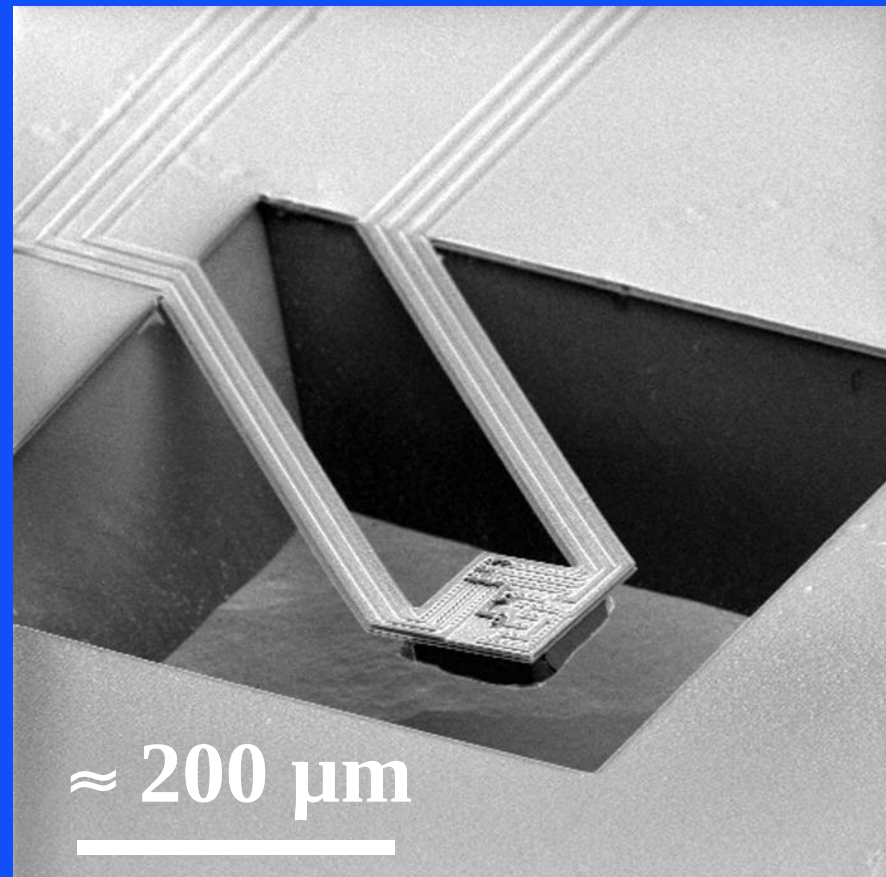


Suh, J. W., Glander, S. F., Darling, R. B., Storment, C. W., and Kovacs, G. T. A., “Organic Thermal and Electrostatic Ciliary Microactuator Array for Object Manipulation,” Sensors and Actuators A, vol. 58, no. 1, Jan. 1997, pp. 51 - 60.

THERMAL TRANSPORT SCALING



- Thermal transport (and isolation) achievable with microstructures far exceeds what can be done with larger-scale devices.
- Small size = fast temperature swings.
- Potential for localized chemical reactions + stable operation of reactions not feasible at macro-scale.



Klaassen, E. H., Reay, R. J., Storment, C. W., and Kovacs, G. T. A., “Micromachined Thermally Isolated Circuits,” Sensors and Actuators A, vol. 58, no. 1, Jan. 1997, pp. 43 - 50.

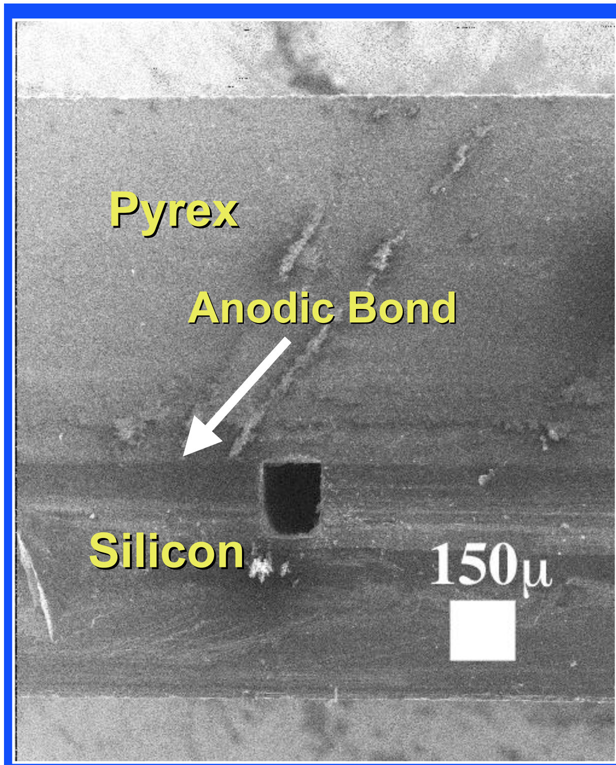
MASS TRANSPORT SCALING

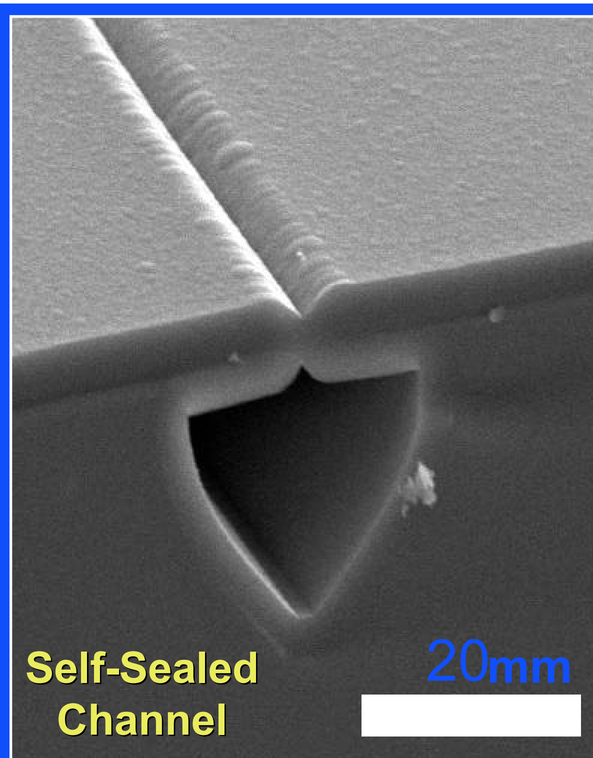
- Fluid flows at the micro-scale are almost certainly laminar.
- Separations are enhanced by surface-area-to-volume ratio increases.
- As sensors scale down, so do their "fields of view" – interaction with a measurand becomes statistically rarer and localized.
- As described by Manz, for an ideal (single molecule) sensor, the volume containing a molecule is given by,

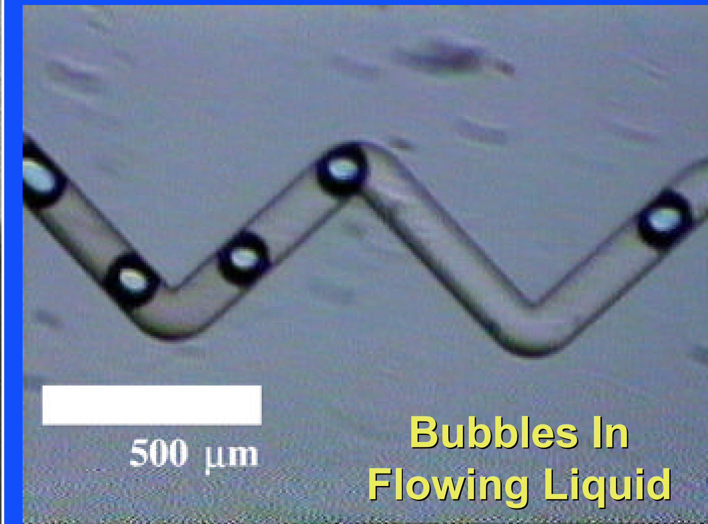
$$V_{sm} = \frac{1}{C\,N_A}$$

(C = concentration, N_A = Avogadro's number)

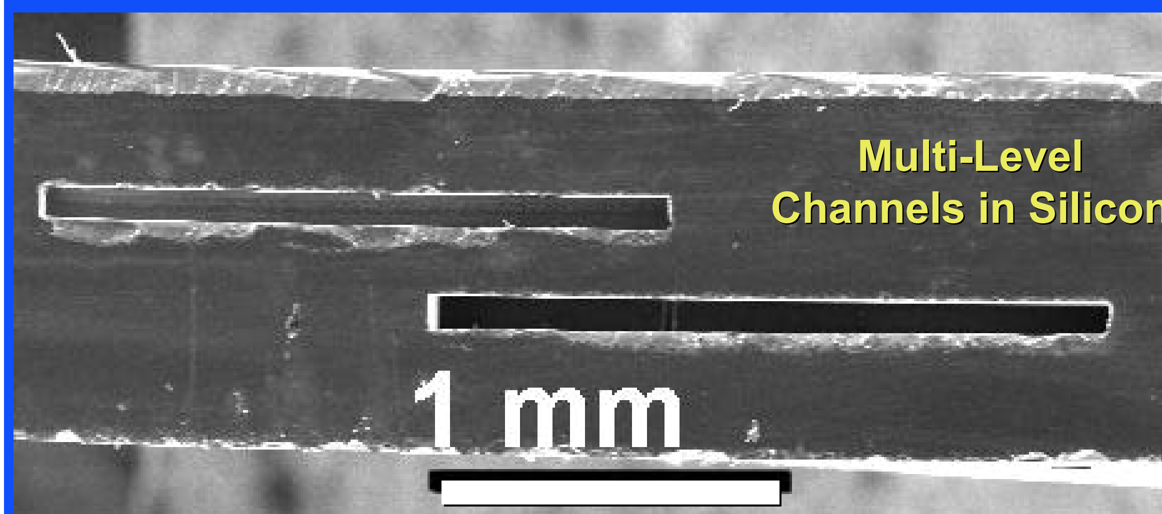
- *Affinity* techniques are often needed.
- *Amplification* techniques may also be applicable if not noisy.





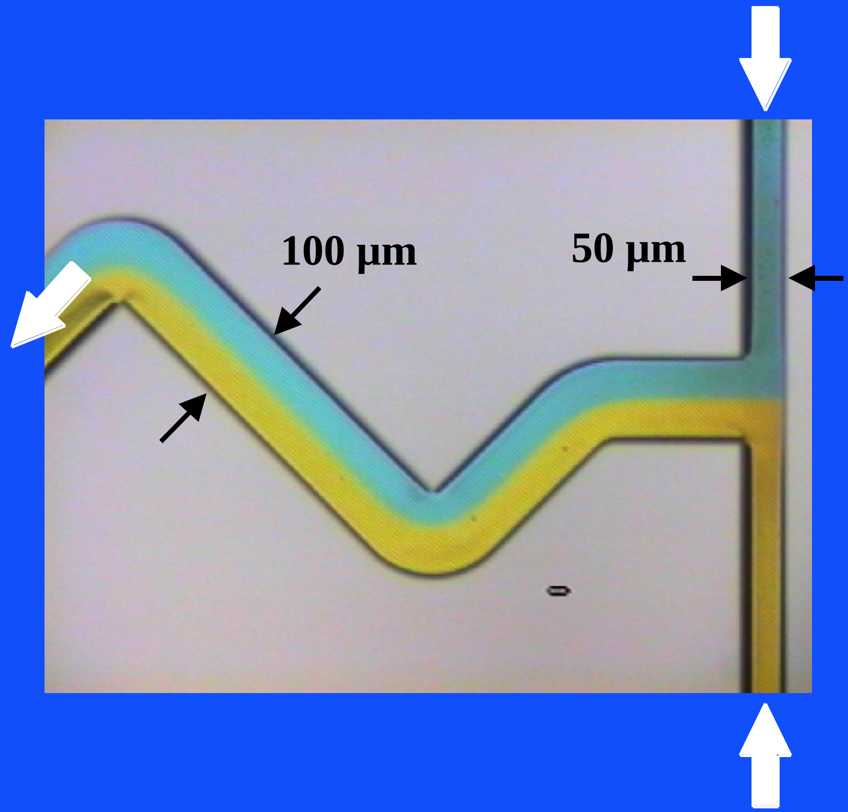


EXAMPLE MICROFLUIDIC CHANNEL STRUCTURES



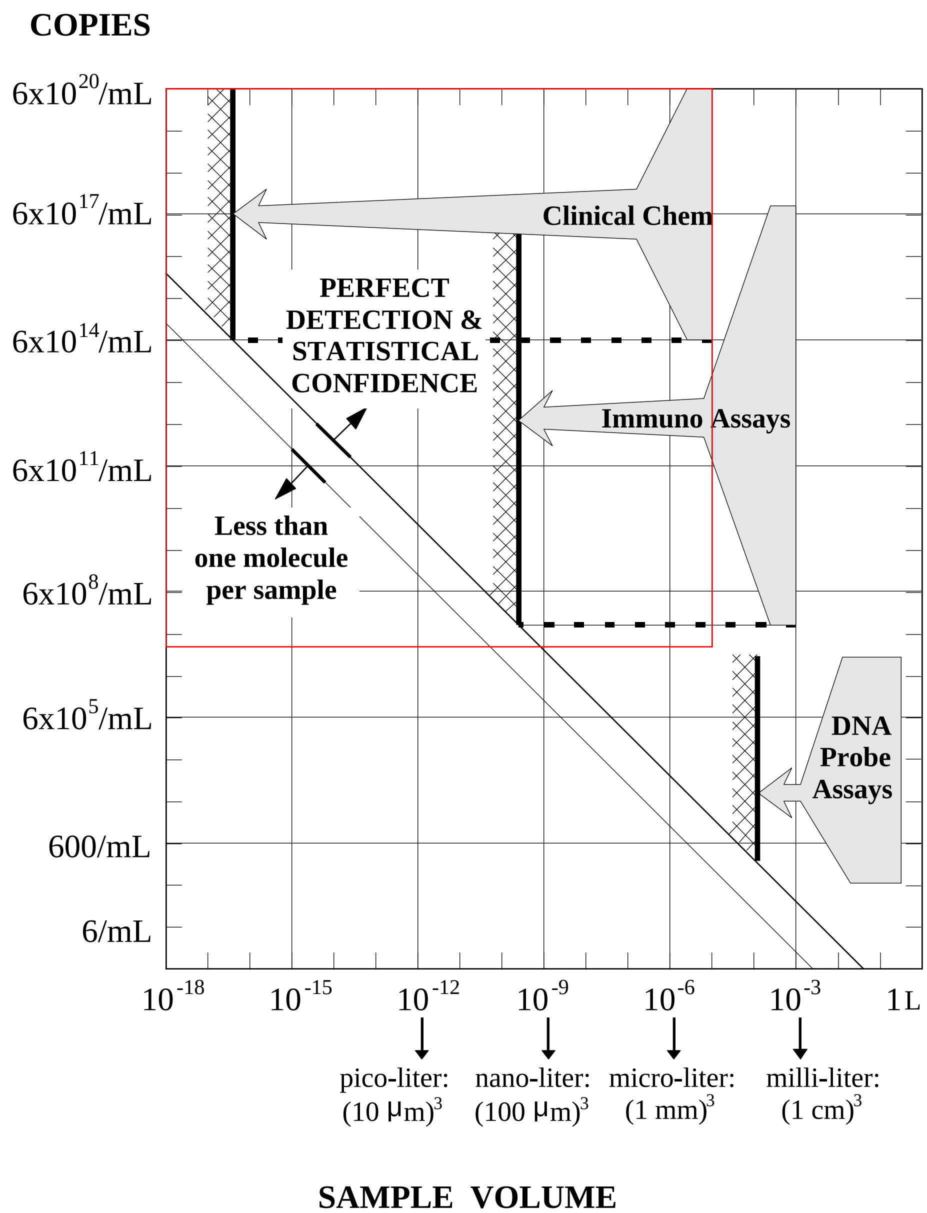
FLOWS AT LOW REYNOLDS NUMBER

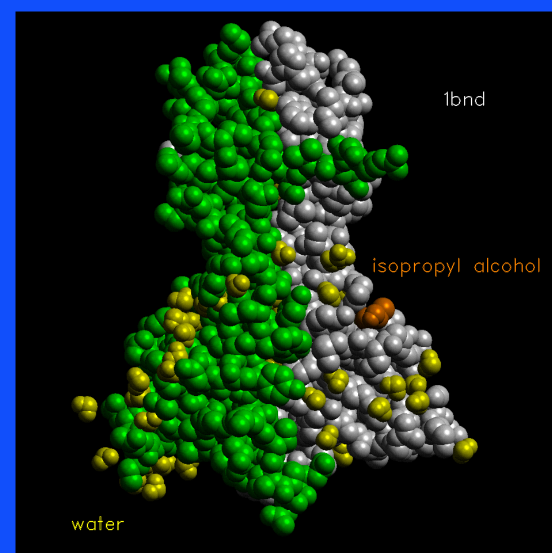
Q = 10 µl/min
v = 67 mm/s
R_e = 4.4



Two parallel streams of dyed water showing mixing by diffusion only.

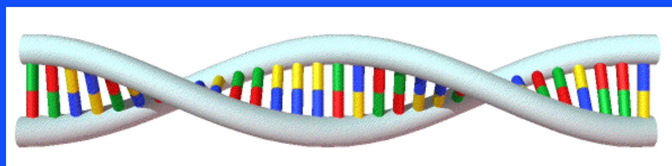
DETECTION LIMITS OF MICROFLUIDIC ASSAYS

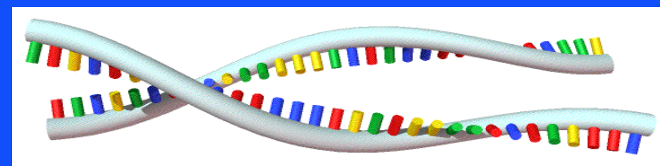




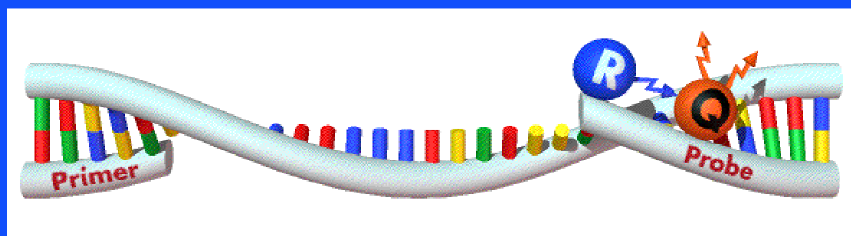
Courtesy Dr. Kurt Petersen, Cepheid, Inc.

PCR TAQMAN™ DNA AMPLIFICATION

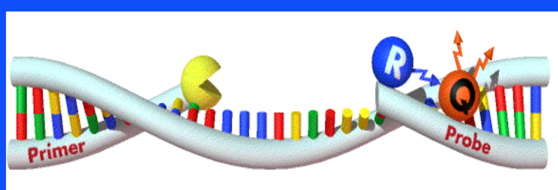




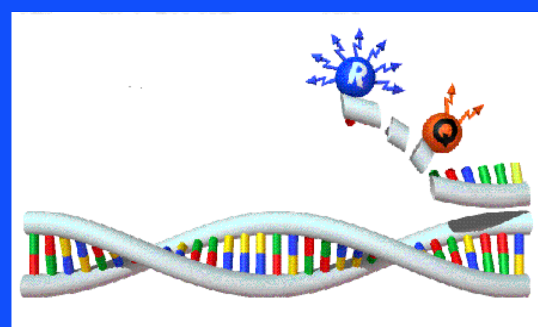
Denature DNA



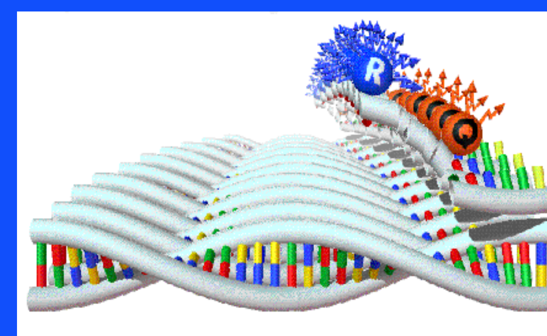
Anneal Primer & Probe



Polymerize



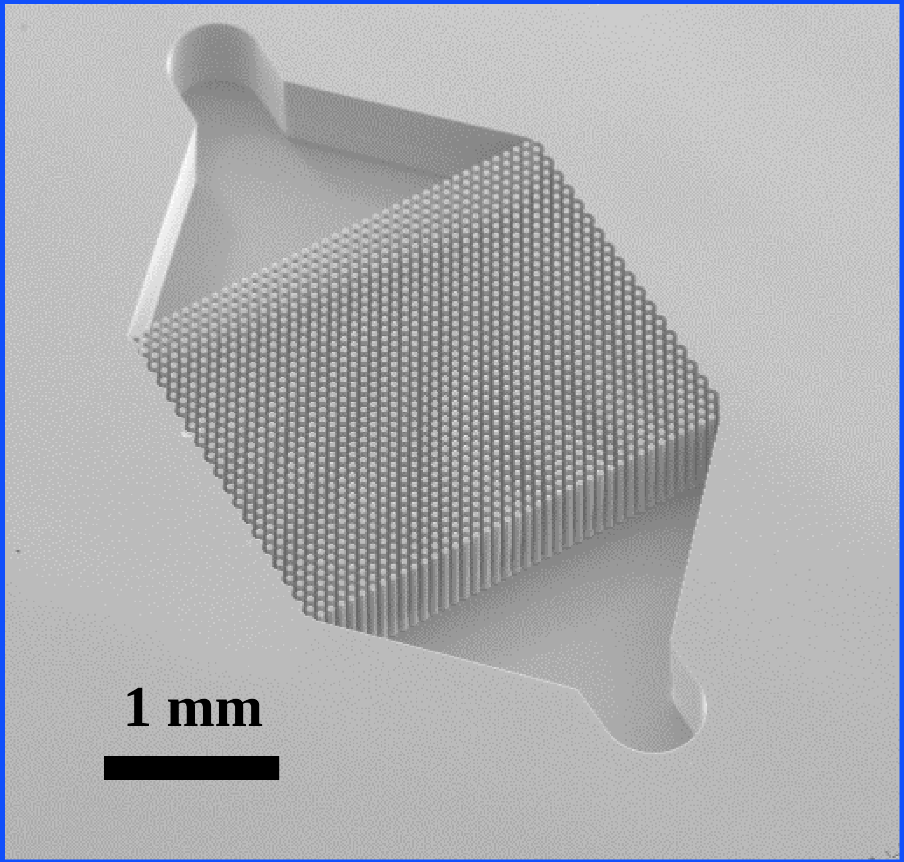
Increase Fluorescence

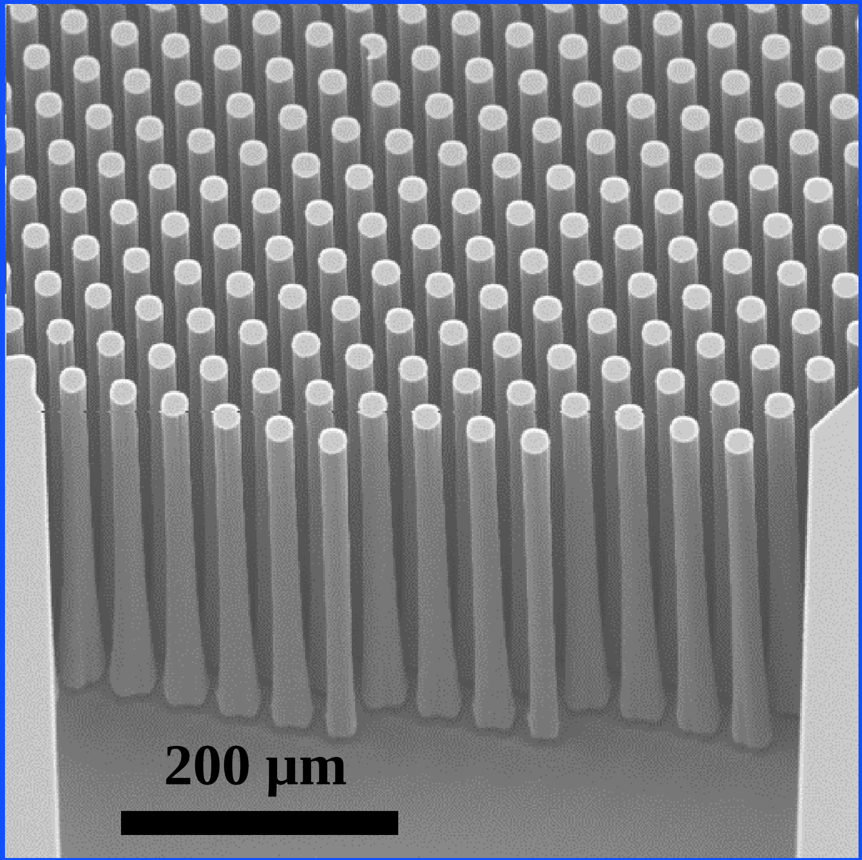


Repeat N-times

Courtesy Perkin-Elmer, Applied Biosystems Division. TAQMAN is ™ of Roche, Inc.

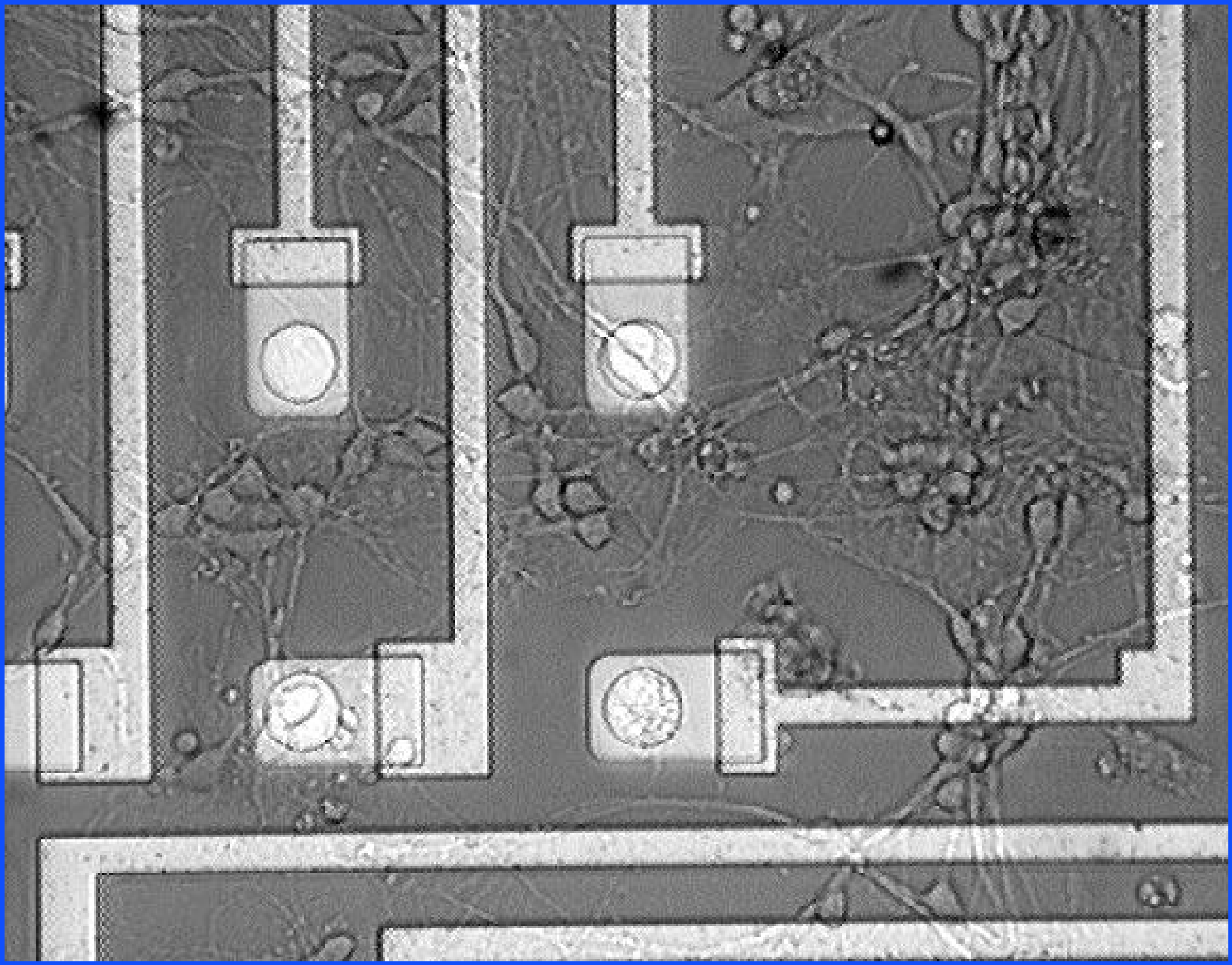
HIGH SURFACE AREA STRUCTURES FOR ANALYTE CONCENTRATION





Courtesy Dr. Lee Christel, Cepheid, Inc.

AFFINITY + GAIN VIA BIOSENSORS



COST REDUCTION

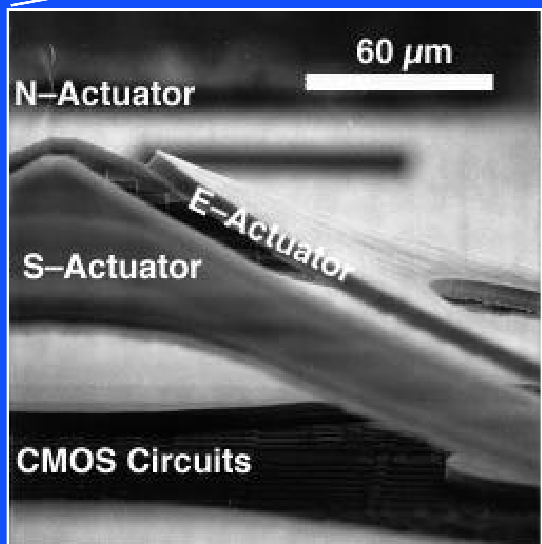
- For many sensors, packaging and test comprise 80% of the final cost, so if the sensor itself is *totally free*, it only saves 20%!
- Cost reductions through micromachining are *NOT* automatic! Non-silicon approaches have great promise for this purpose.
- Whether a device is disposable or re-usable can have a profound impact on cost.
- Design for low cost may include redundancy to improve yield, incorporation of features previously embodied in many components, self-test features, and differentiation of product after fabrication.
- New materials and non-lithographic fabrication methods (e.g., injection molding) can also greatly reduce cost... use expensive technologies only where needed in a system.

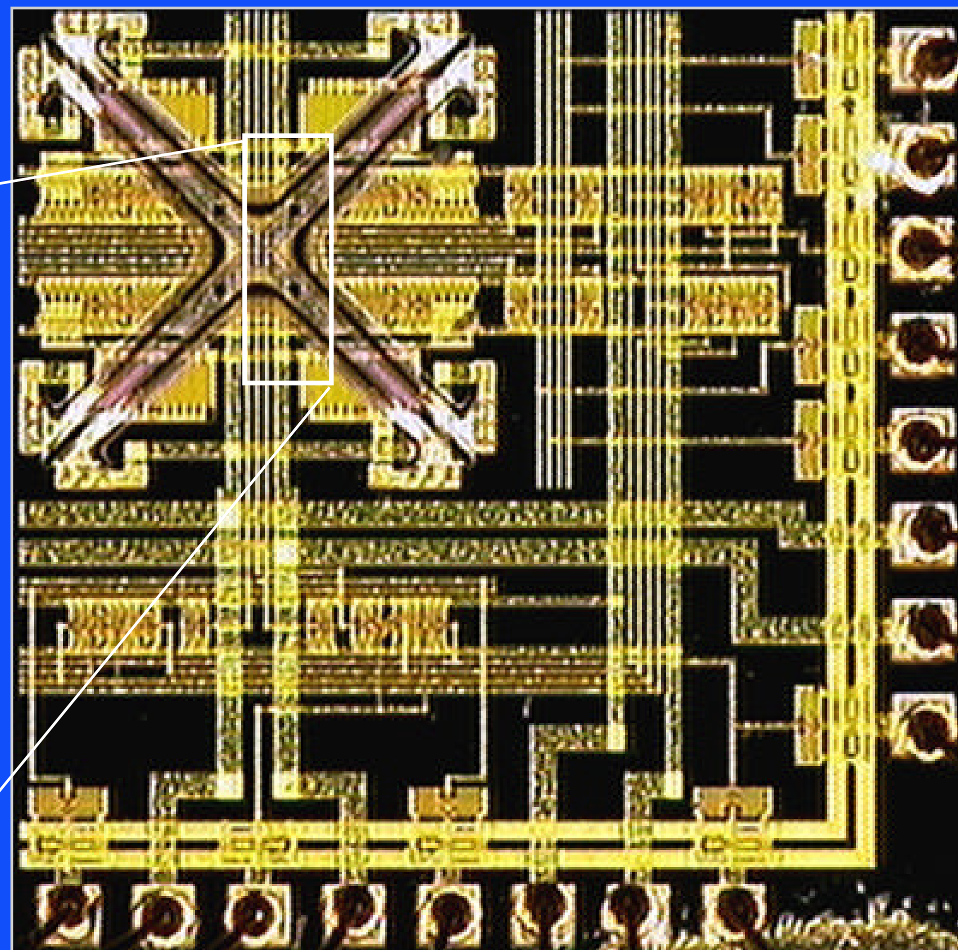
LEVERAGING EXISTING TECHNOLOGIES:

SOME EXAMPLES

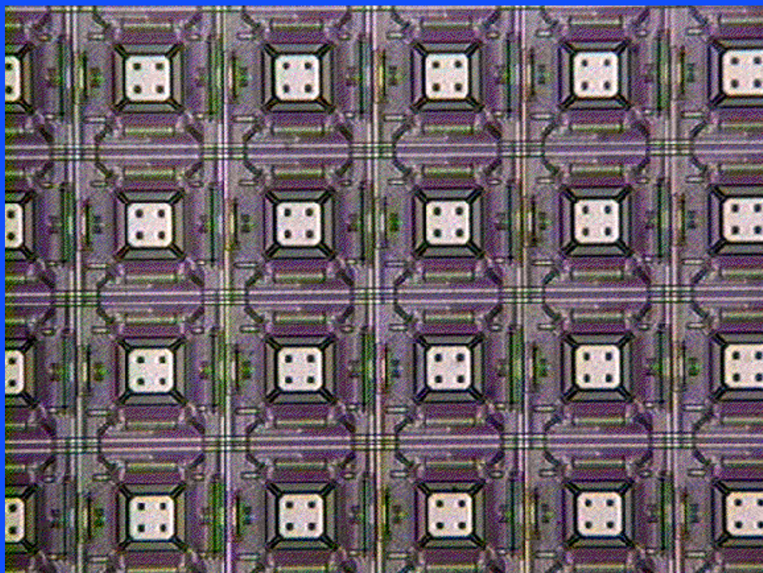
Ordinary CMOS wafers can be converted into a wide variety of MEMS devices through selective wet/dry etching and the deposition of metals, organic and inorganic materials.

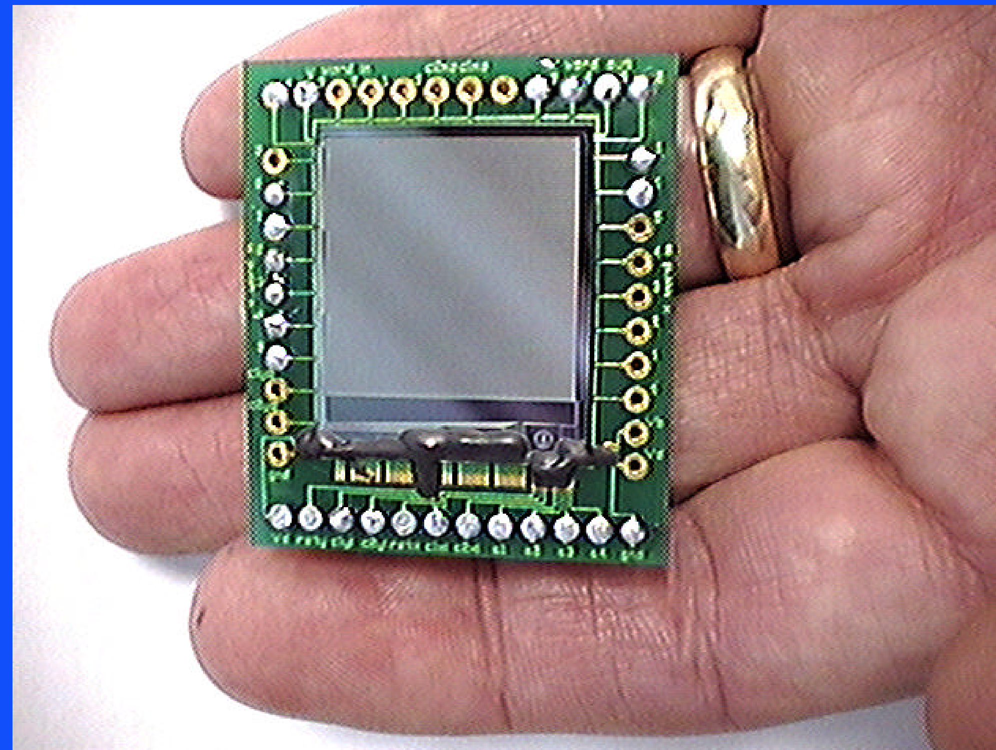
THERMAL ACTUATORS WITH CMOS

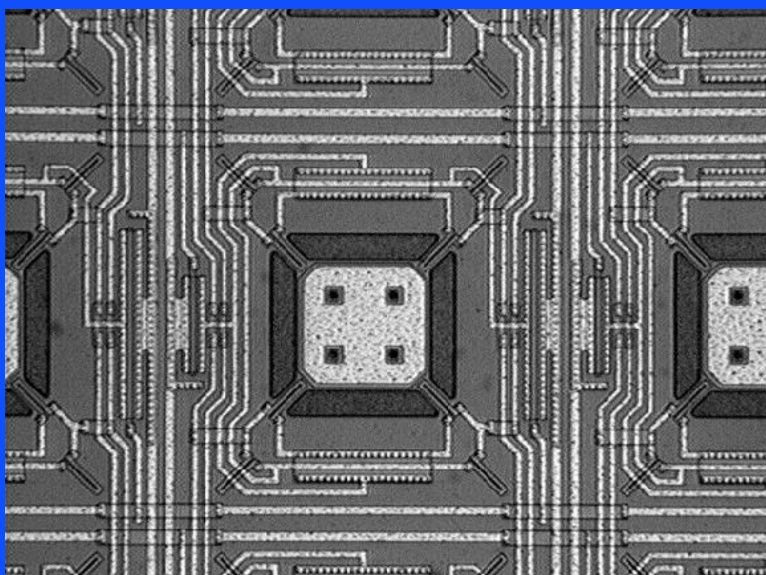




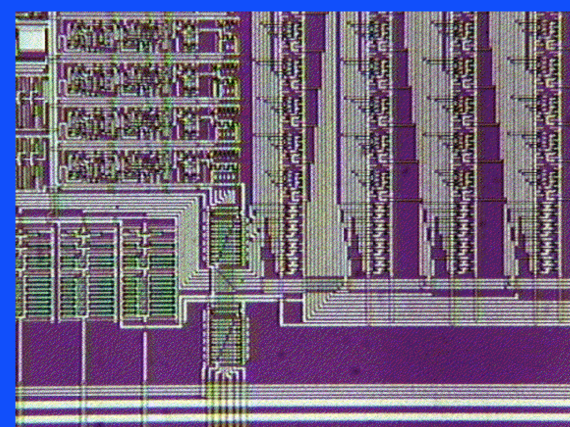
This work was funded by DARPA and NSF.





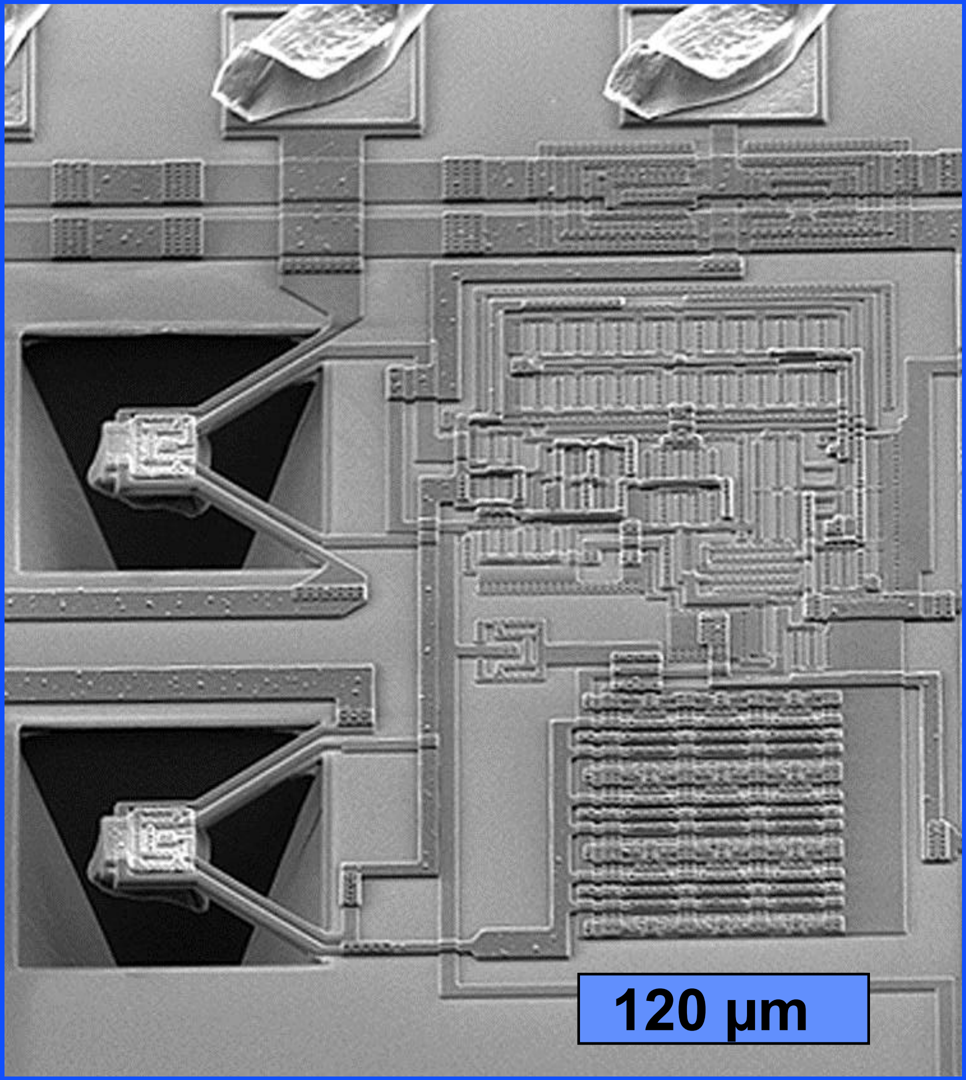


Reference: Kane, B. J., Cutkosky, M. R., and Kovacs, G. T. A., "CMOS-Compatible Traction Stress Sensor for Use in High-Resolution Tactile Imaging," Sensors and Actuators A, vol. A54, 1996, pp. 511 - 516.



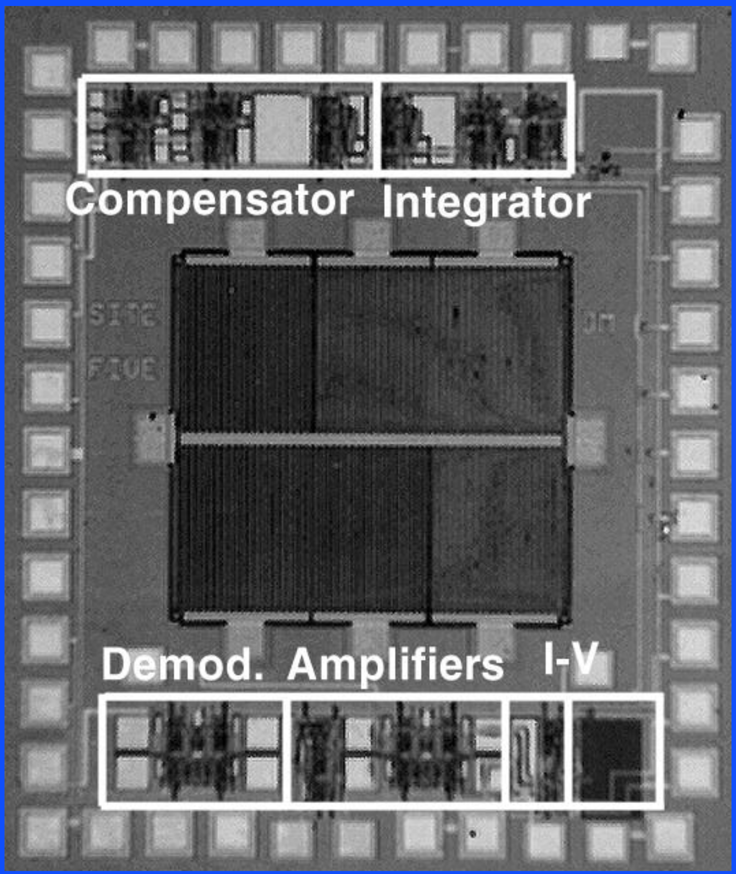
THERMAL RMS CONVERTER

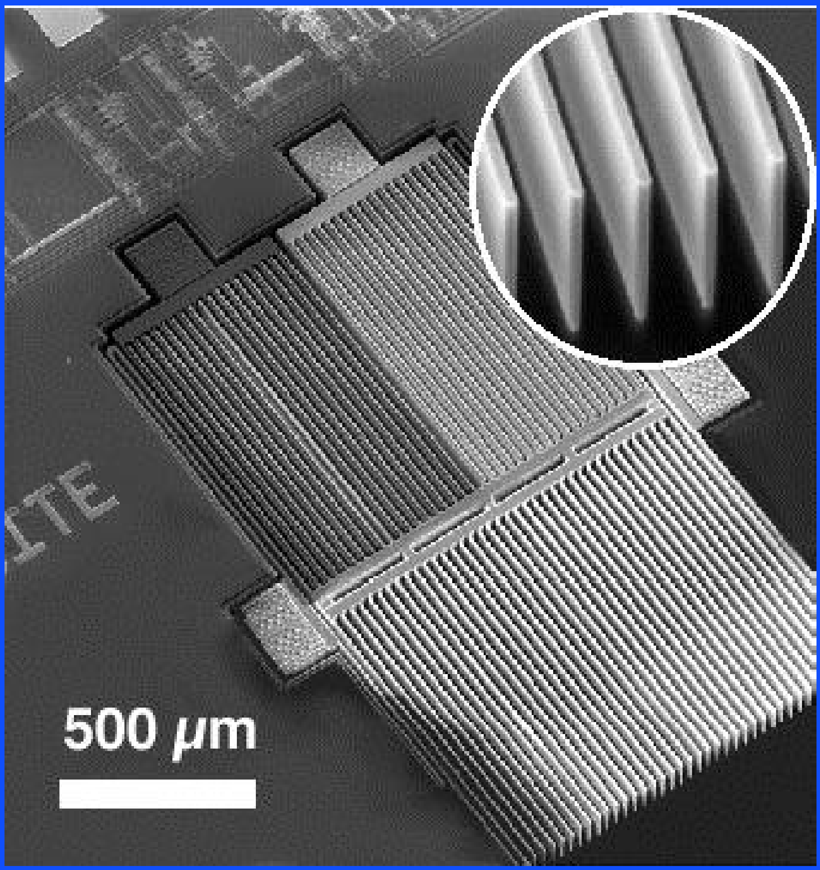
- Electrochemically-modulated wet etch on standard CMOS.
- Excellent performance (> 400 MHz response, 60 dB dynamic range, < 1% nonlinearity).
- Essentially available "for free" in the corner of a CMOS mixed-signal chip.



Klaassen, E. H., Reay, R. J. and Kovacs, G. T. A., "Diode-Based Thermal RMS Converter with On-Chip Circuitry Fabricated Using Standard CMOS Technology," Digest of Technical Papers from Transducers '95/Eurosensors IX, Vol. 1, June 25 - 29, 1995, Stockholm, Sweden, pp. 154 - 157.

DEEP REACTIVE ION ETCHED SINGLE-CRYSTAL SILICON ACCELEROMETER

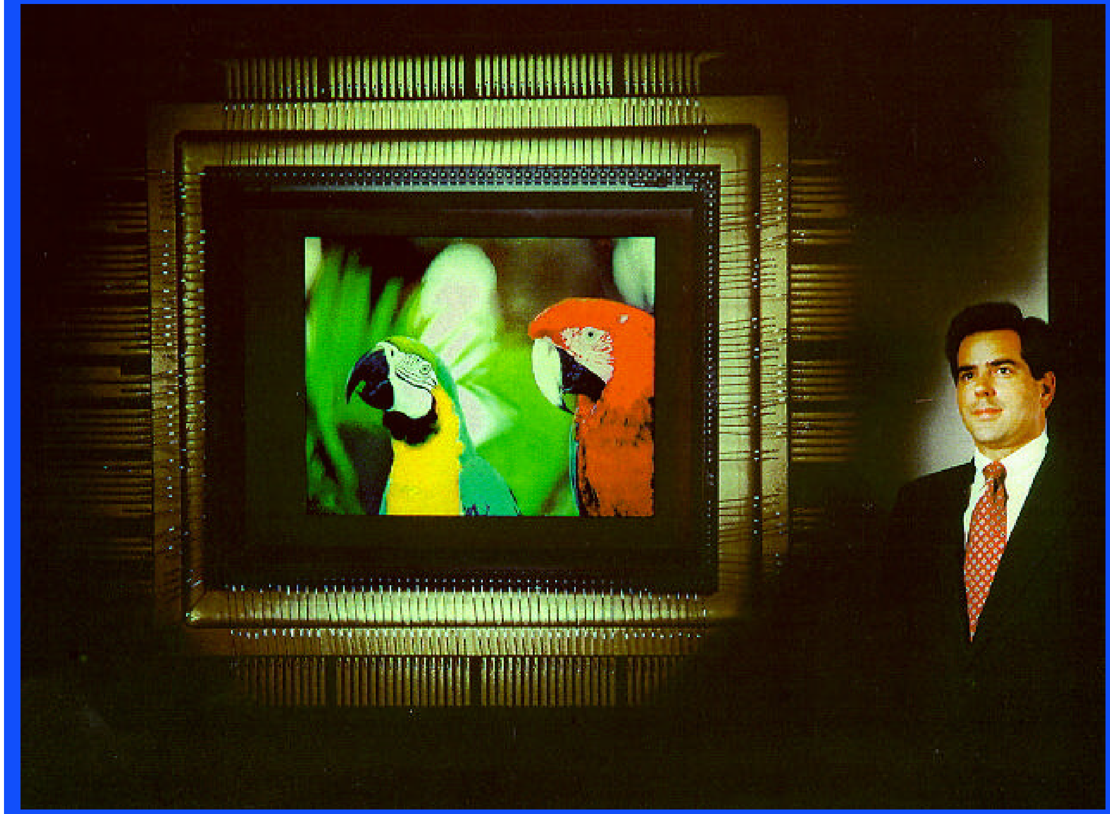


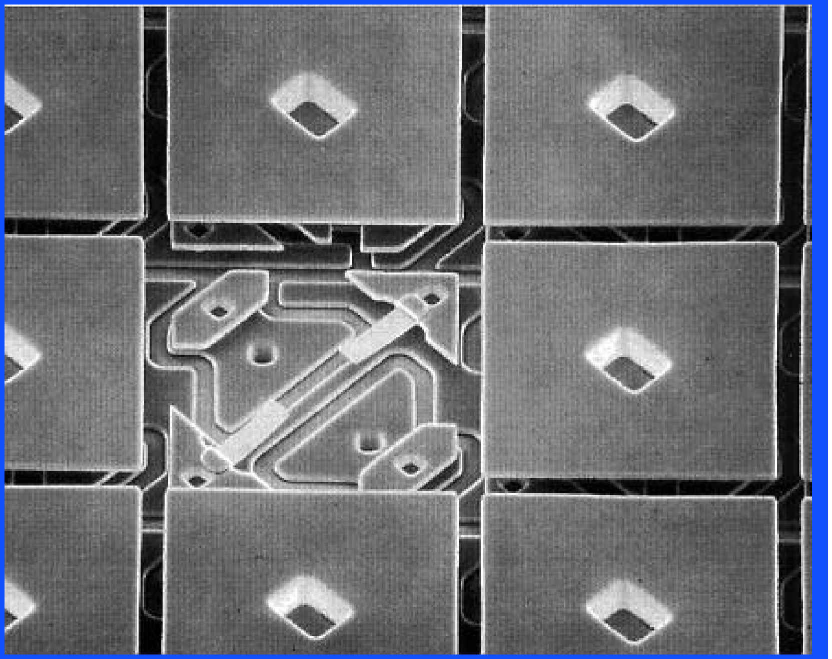


This work was funded by DARPA and carried out jointly with Lucas NovaSensor.

• Digital micromirror displays with aluminum alloy torsional hinges have flex lifetimes on the order of trillions of cycles.

• Built atop "standard" circuit process.





Images courtesy Dr. L. Hornbeck, Texas Instruments, Inc.

SYSTEM-LEVEL ISSUES

- **Interconnects are key system enablers.**
  - **Electrical interconnects made the modern IC possible.**
  - **Fluidic interconnects, for example, are still very primitive.**
- **Packaging is critical and tends to be application-specific.**
- **Films and structural materials for the devices themselves must be compatible with application environments.**
- **Seamless integration of different materials is critical (e.g., plastic ± glass ± silicon ± metal).**
- **Testing of transducers and structures varies greatly by domain and may be a massive hindrance.**

PROBLEMS & SOLUTIONS

- **Problem: Extreme Temperatures, Pressures, Shock, Radiation**
- **Solutions: silicon-on-insulator, ceramics, careful design**

- **Problem: Need for "Local Intelligence"**
- **Solutions: CMOS post-processing, SOS/SOI, multi-chip**

- **Problem: Low-Cost Prototyping**
- **Solutions: simple fabrication methods, inexpensive CAD tools**

- **Problem: Low-Volume, Non-Commercial Devices**
- **Solutions: foundries (MOSIS, MCNC, SNF, etc.), DoD laboratories (SPAWAR, NRL, etc.)**

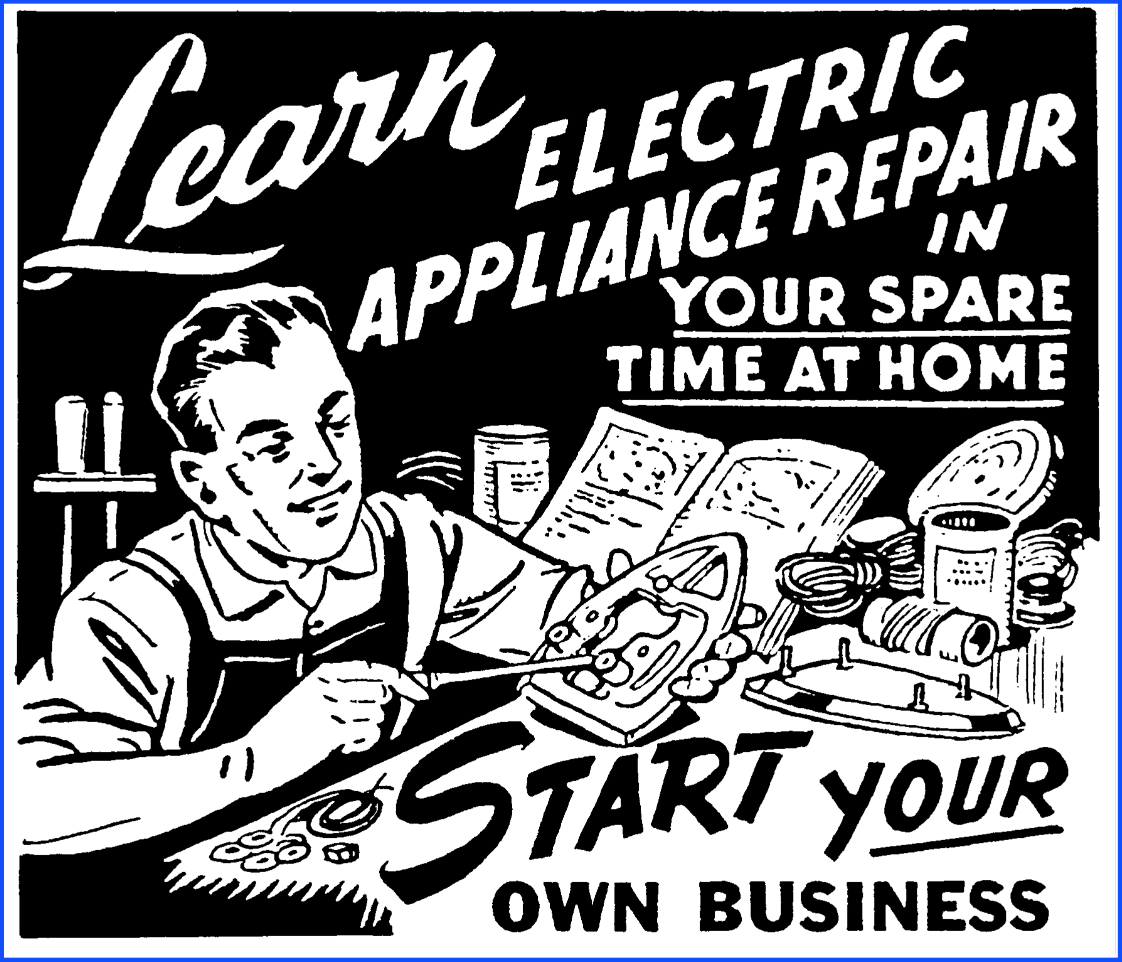
HARDER PROBLEMS & POTENTIAL SOLUTIONS

- **Problem: High-power/voltage, nonlinear and inefficient actuators.**
- **Potential Solutions: Polymers and other “unconventional” actuators such as gas expansion, or use “conventional” actuators, also clever control strategies.**

- **Problem: Lack of knowledge about long-term mechanical properties.**
- **Potential Solutions: Basic science research, brute-force failure testing/analysis.**

- **Problem: Long “gestation periods” for MEMS.**
- **Potential Solutions: Inventory and leveraging of existing technologies.**

INTERDISCIPLINARY EDUCATIONAL MATERIALS ARE NEEDED

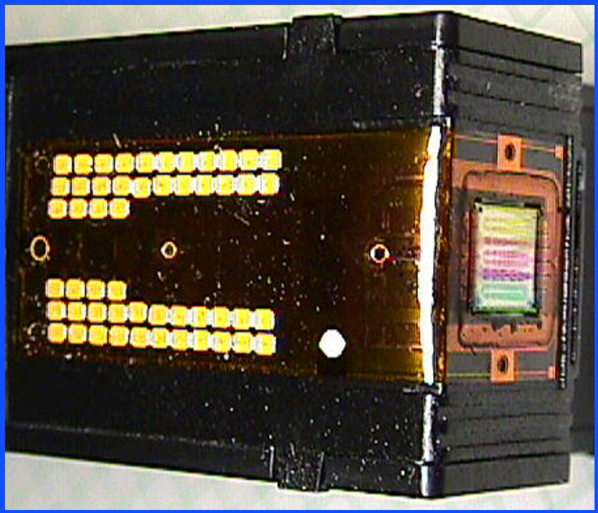


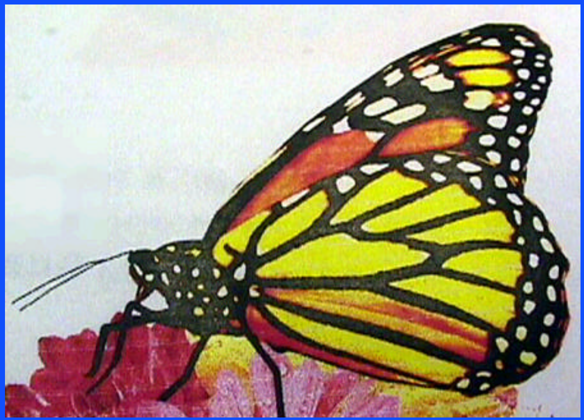
IS MEMS REALLY GROWING EXPONENTIALLY?

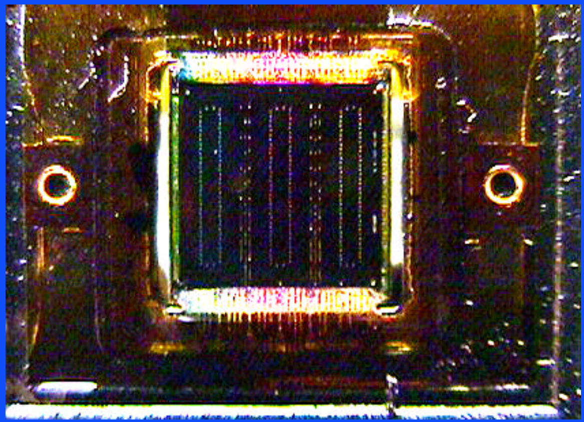
- Many groups have made predictions of exponential growth in the MEMS industry.
- Micromachined devices are far more case-specific than DRAMS!
- There is not likely to be a single “dominant” technology in MEMS like MOS processes in the digital arena.
- There are few (no?) “standard” MEMS parts.
- MEMS may be more like printed circuit boards than the IC itself - ultimately ubiquitous, but hidden in products.

MEMS: AN ENABLING TECHNOLOGY

THERE ALREADY ARE "KILLER APPS" FOR MEMS







CONCLUSIONS

- Micromachining technologies will have a major impact on automotive, aerospace, medical, basic science and other.
- The successful application of micromachining approaches requires broad knowledge of physical principles and scaling laws as well as technology leveraging methods.
- Micromachining methods should not be used unless functionally equivalent "conventional" methods (injection molding, etc.) have been considered and ruled out.
- Careful consideration must be given to system-level issues of complexity, packaging, testing and manufacturability.
- New materials, skillful combinations of micromachining and "conventional" technologies and materials, packaging and interconnect concepts will be key to successful systems.

THOUGHTS ON THE FUTURE

- The long-term growth will likely be in new markets, rather than in replacing existing sensors.
- There is huge market potential in medical and consumer markets ("disposables").
- Smarter sensors will be more common, but will not universally replace "dumb" microstructures - it is a case-by-case issue.
- Packaging will remain a major issue for most devices.
- The big money probably will not be at the "plankton" level of manufacturing, but where microstructures are embedded in larger systems.

REMEMBER: NOT EVERYTHING SCALES WELL!