



Microsystems, Scaling, and Integration

Amit Lal, Program Manager

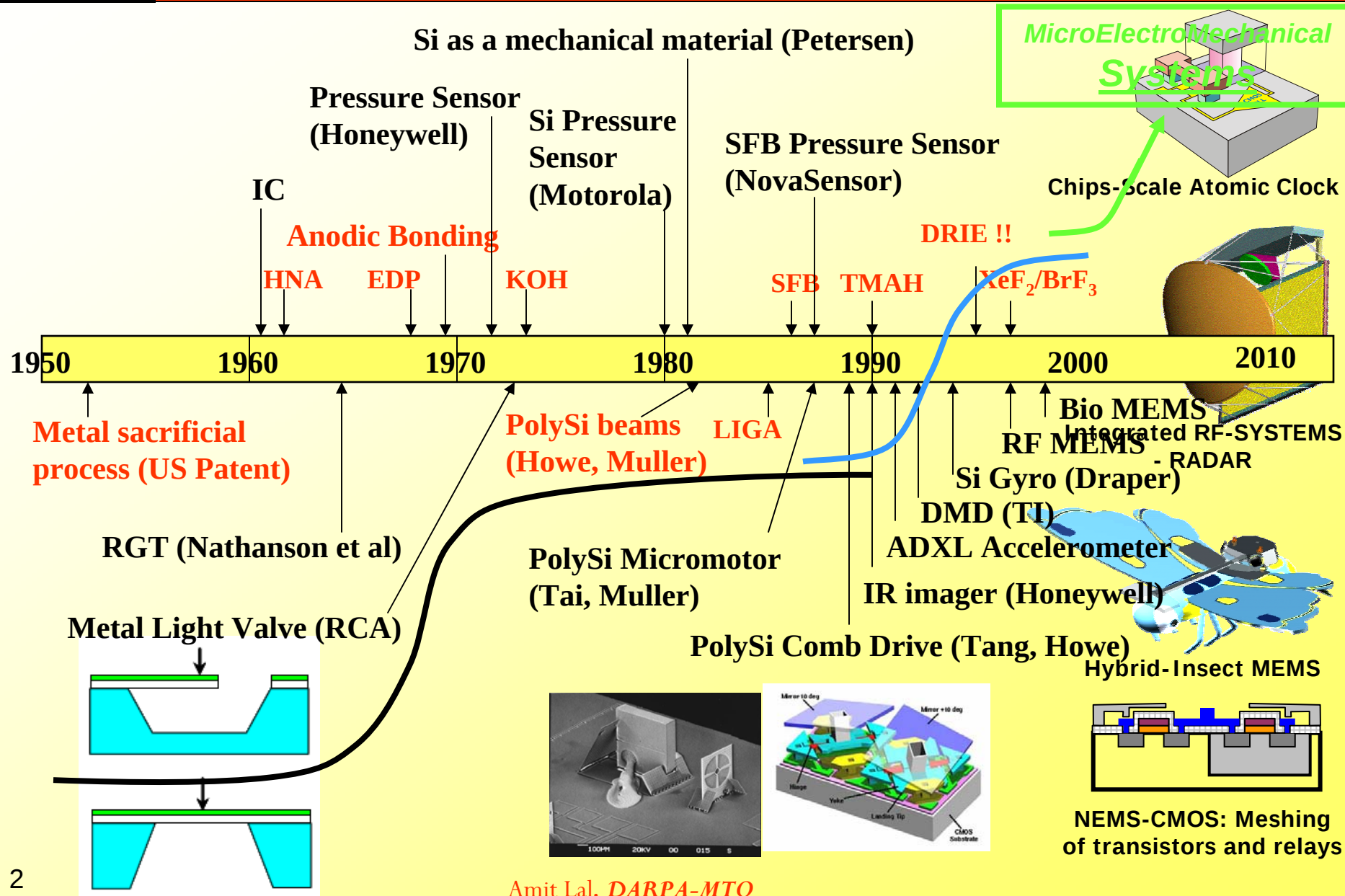
MTO/DARPA

Microsystems Technology Symposium

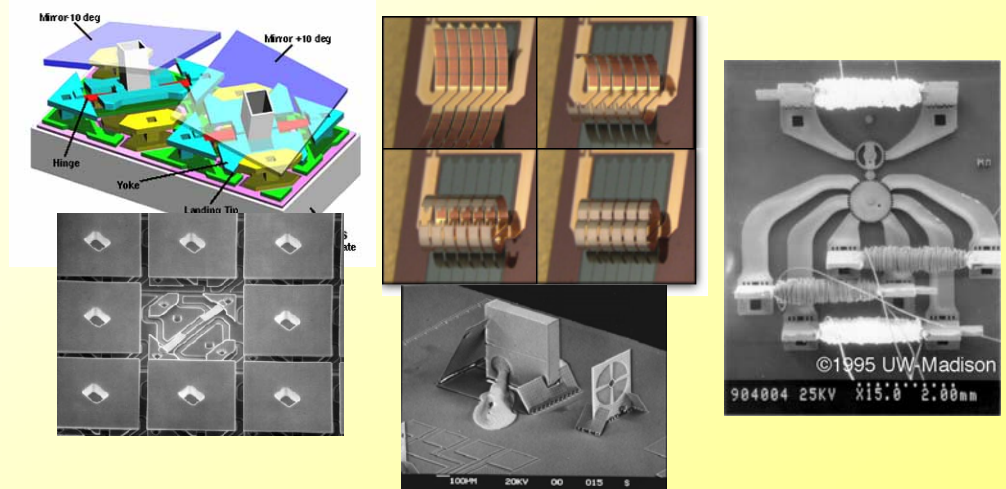
San Jose, CA, March 6, 2007

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Progression of MEMS



Two views of MEMS



**MEMS for
everyone / everything?**

**MEMS is like
Spanish moss on
the IC industry
tree**

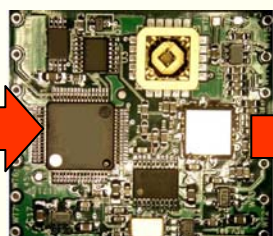


<http://www.mems-exchange.org>

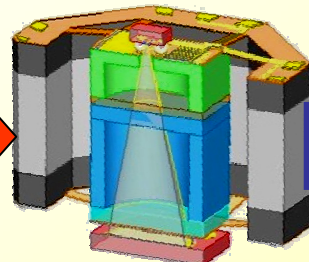
MEMS for Microsystems



Temex RMO
Vol: 230 cm³
Power: 10 W
Acc: 1 × 10⁻¹¹



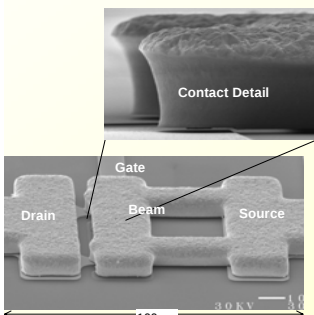
Symmetricom CSAC
Vol: 7.8 cm³
Power: 95 mW
Stab: 5 × 10⁻¹¹ / 100s



Integration of
Alkali-metal
vapor on chip for
atomic sensors

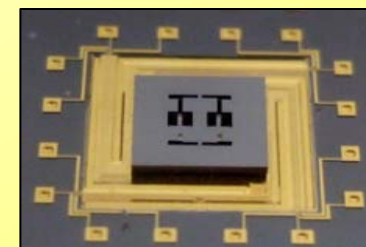
CSAC

Insect MEMS

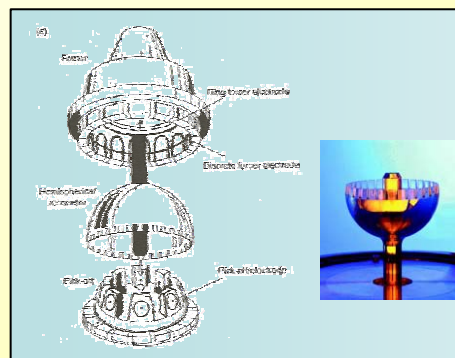


**RF-MEMS
switch**

- Miniaturization/ Integration – SWAP
- Scaling for higher performance
- Multiphysics
- Biological interfaces
- Gateways to nanoscale effects
- Environmental control over sensors and actuators

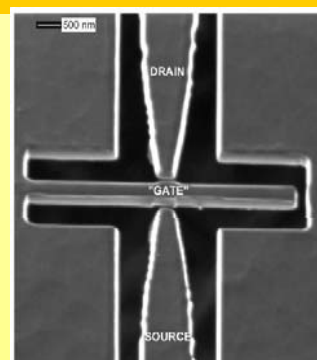


**Universal MEMS
package-HERMIT**

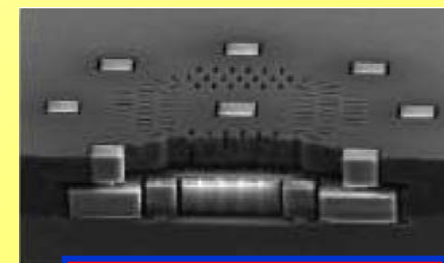


**Navigation grade
Gyroscope**

0.8 cm



NEMS - switch



**Embedded MEMS
- HERMIT**



Radant Demonstrates >900 Billion Switch Cycles

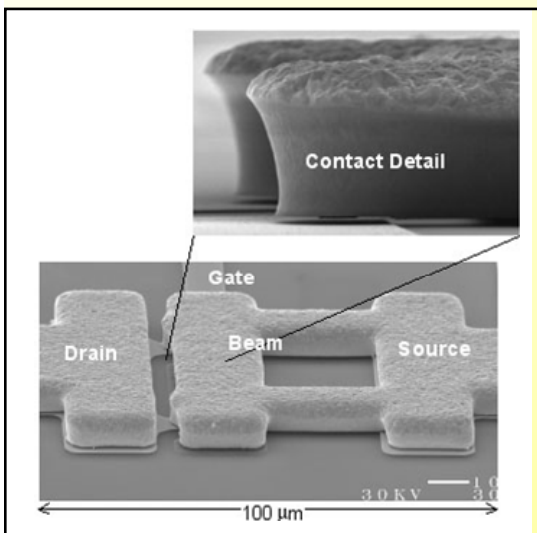
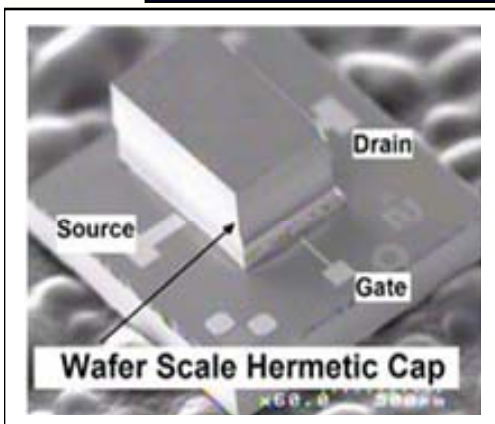
**MEMS:
Undeniable Reliability**

Wins Frost & Sullivan *Excellence in Technology Award*

PM: Amit Lal, HERMIT

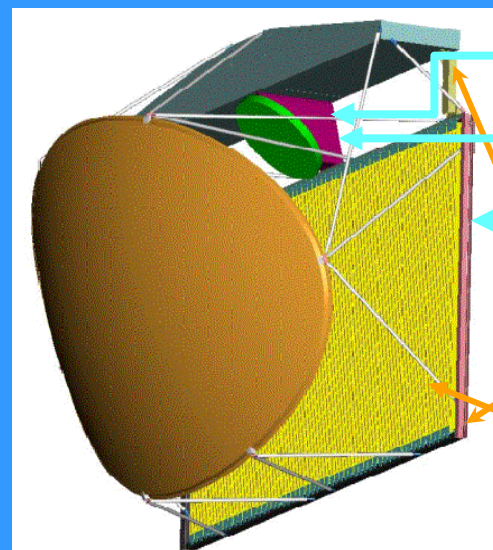


**Tri-Service DoD
Testing Team**

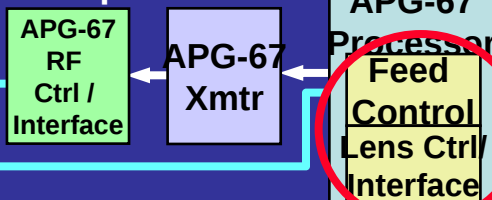


Demo Radar

**Modified
Hardware**



**Lockheed Martin
Modified APG-67 Radar
Components**



**Composite Frame
(Graphite / Epoxy)**

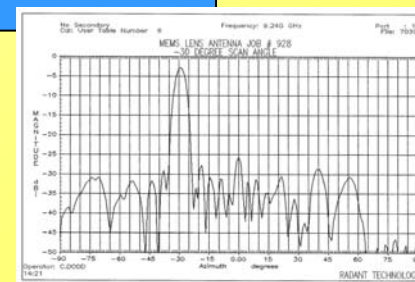
**New /
Modified
HW/SW**

**0.4 m² Azimuth Scanning
MEMS Radant™ Lens**



**MEMS Insertion into the Radant™
Lens Architecture has Been
Demonstrated**

**This Antenna is the First Large Scale
Use of MEMS Switches in the World**

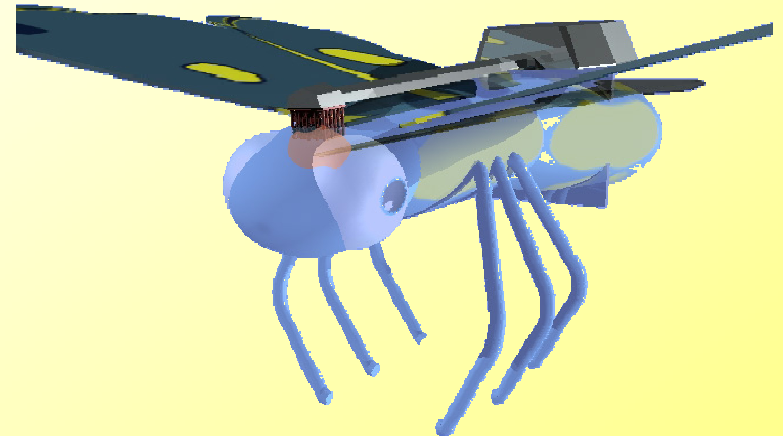


30 degree scan 0.4m² ESA

Hybrid-Insect MEMS

VISION

Create technology to reliably integrate microsystems payloads on insects to enable insect cyborgs

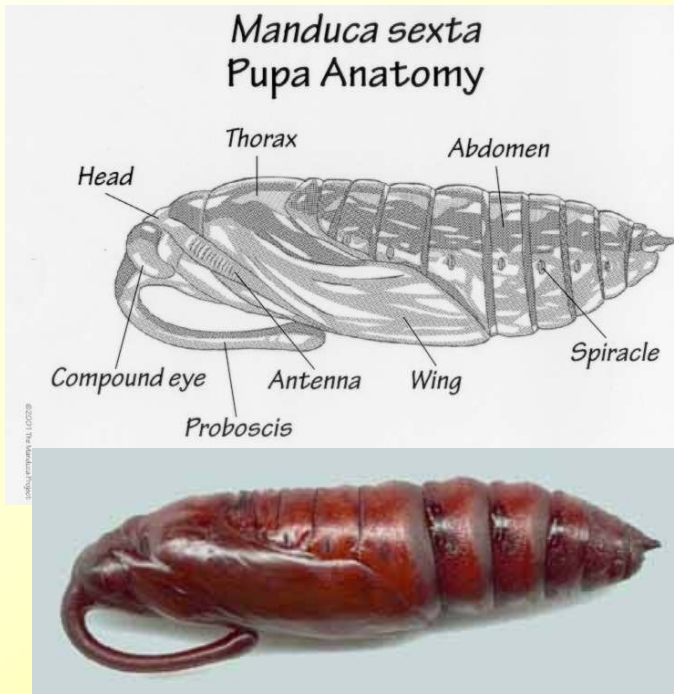
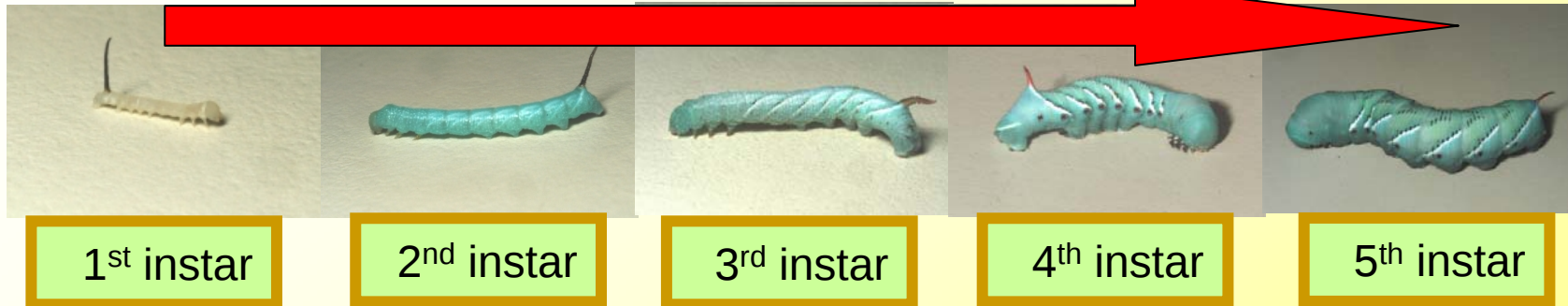


OBJECTIVES

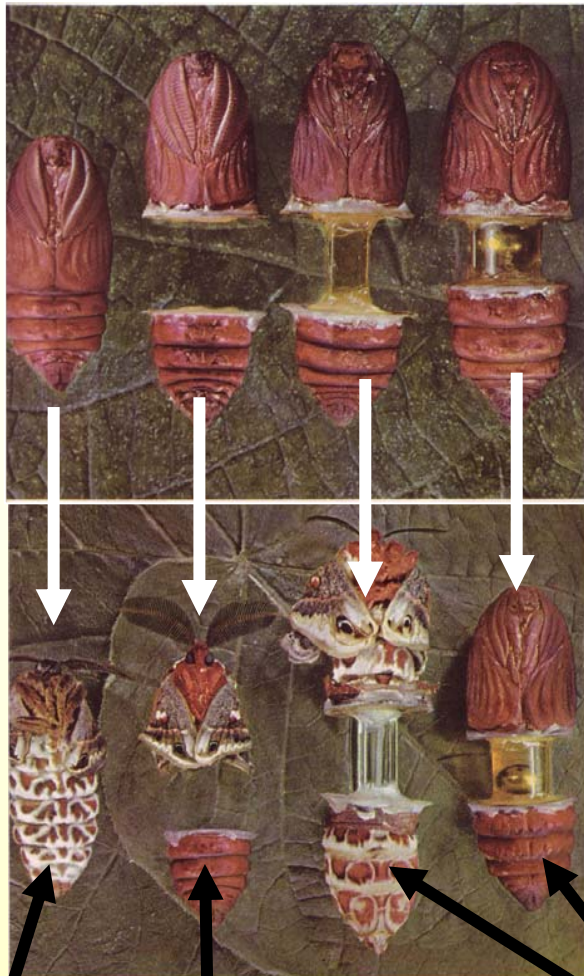
- Develop technology to enable highly coupled electro mechanical interfaces to insect anatomy
- Demonstrate MEMS platforms for electronic locomotion control, power harvesting from insect, and eliminate extraneous biological functions

Background: Insect Metamorphosis

Storage of energy over weeks to use later for flight



Key Experiments in 1940s



Normal
growth

8

Pupa halved and
front develops into
moth

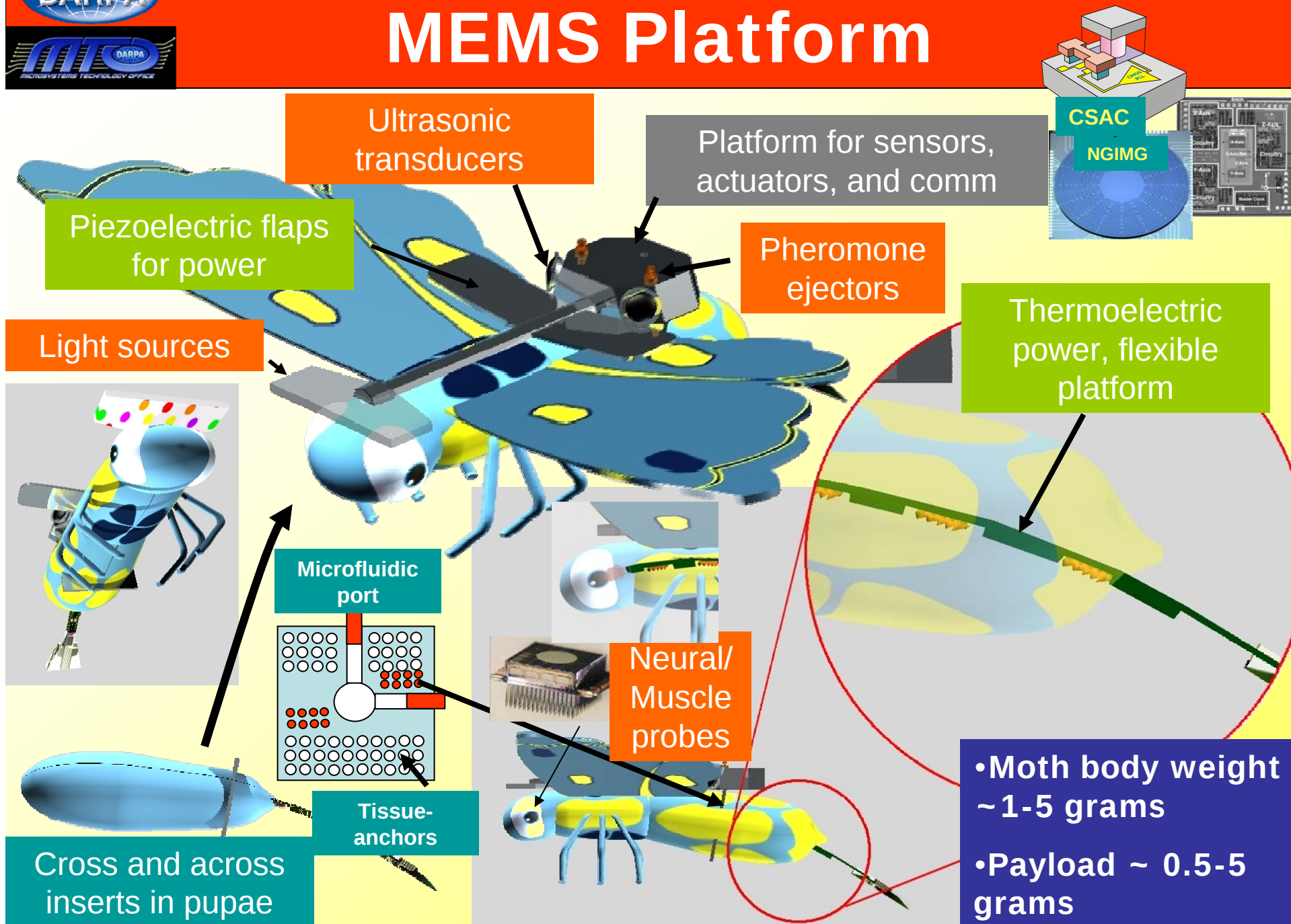
Sectioned Pupa with pipe inserted for hormone
transport – grows into moth shown above. Insertion of
chemical blocking ball bearing results in no growth

Amit Lal, DARPA-MTO



DARPA Program :
Use object
insertion ability into
pupas to *reliably*
insert
microsystems
(instead of glass
tube) for insect
control

MEMS Platform

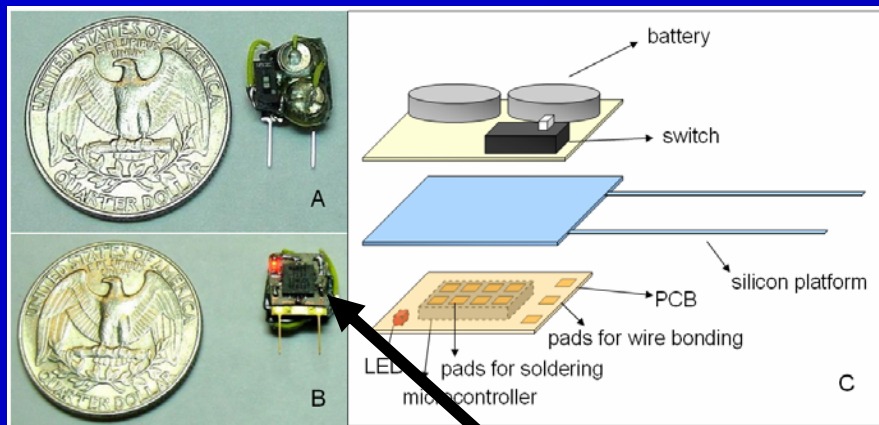




HI-MEMS

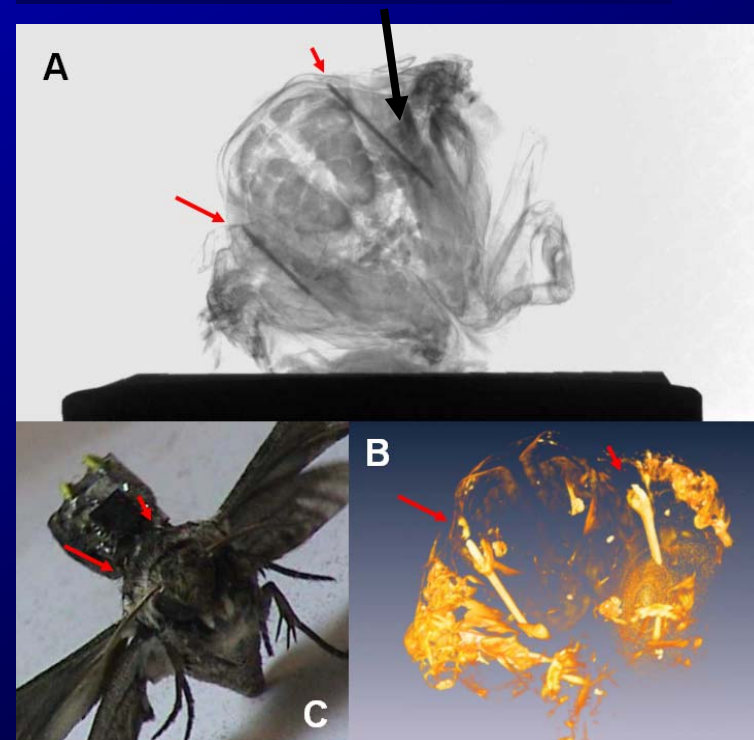
Hybrid Insect MEMS

PM: Amit Lal

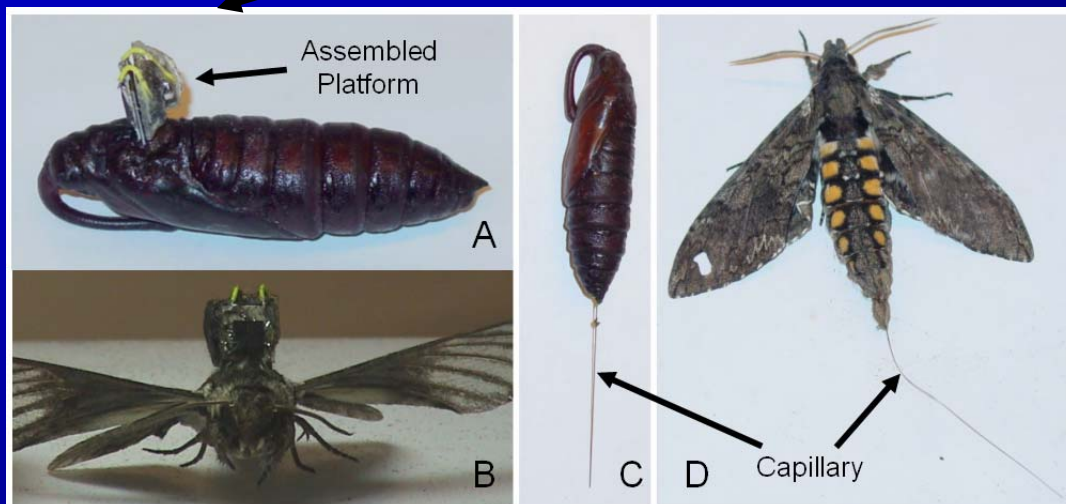


Boyce Thompson Institute: Insect Sentinals

X-ray images of probes in
muscles show good tissue
growth around inserted
probes

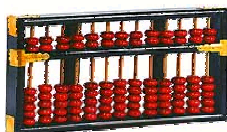


Microsystem platform inserted into moth in pupae
stage, and successful emergence of adult moth
with microsystem

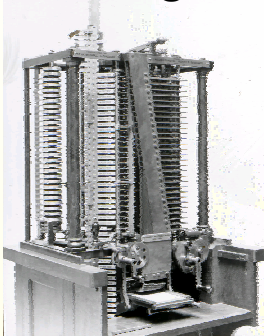


Hybrid NEMS Electronics

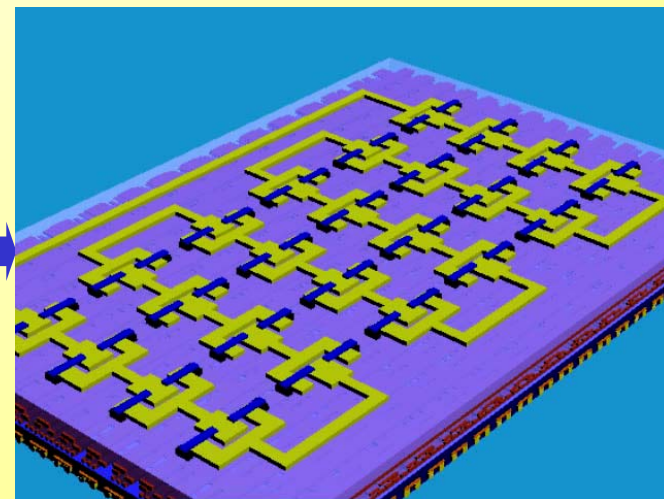
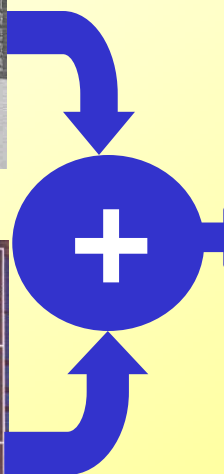
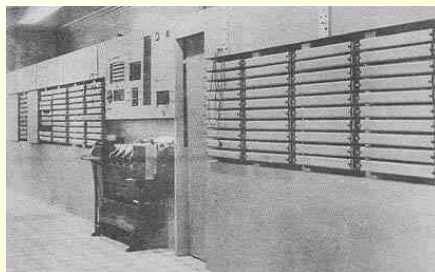
Abacus



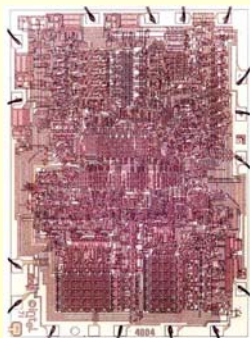
Babbage



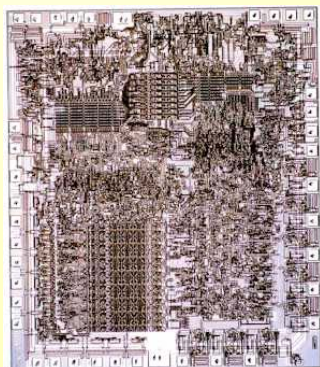
Relay computer
(circa 1950)



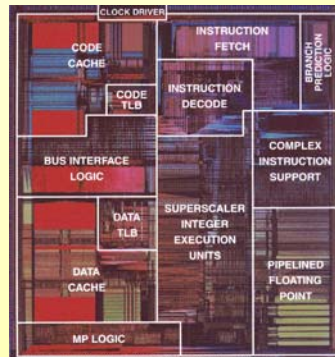
NEMS/CMOS



4004
(1971)



8086 (1978)



Pentium (2006)

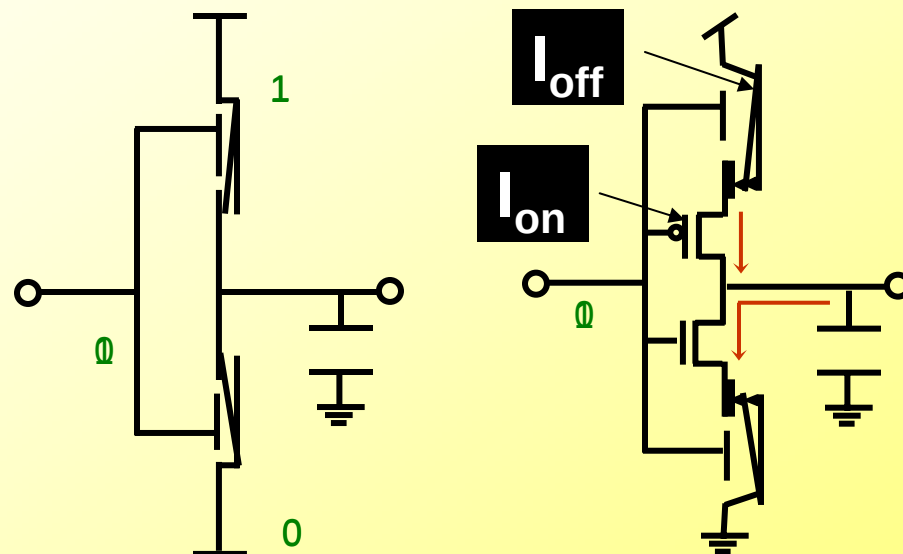
Hybrid NEMtronics

Objectives

- Eliminate leakage power in electronics to enable longer battery life and lower power required for computing.
- Enable high temperature computing for Carnot efficient computers and eliminate need for cooling

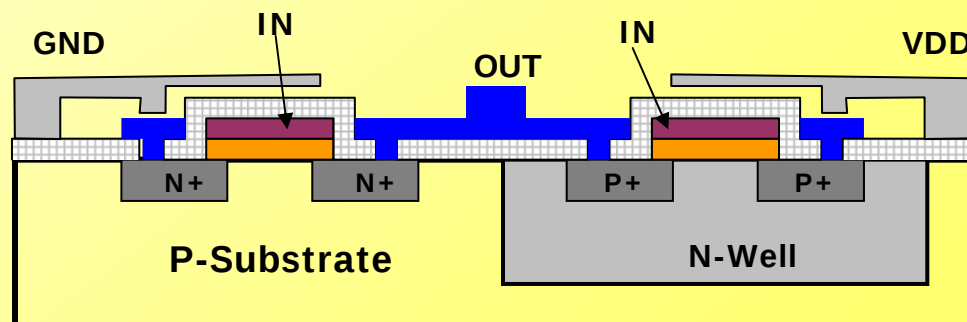
Approaches

- Use NEMS switches with and without transistors to reduce leakage – I_{on} : Transistor, I_{off} : NEMS
- NEMS can work at high temperature, enabling high efficiency power scavenging.



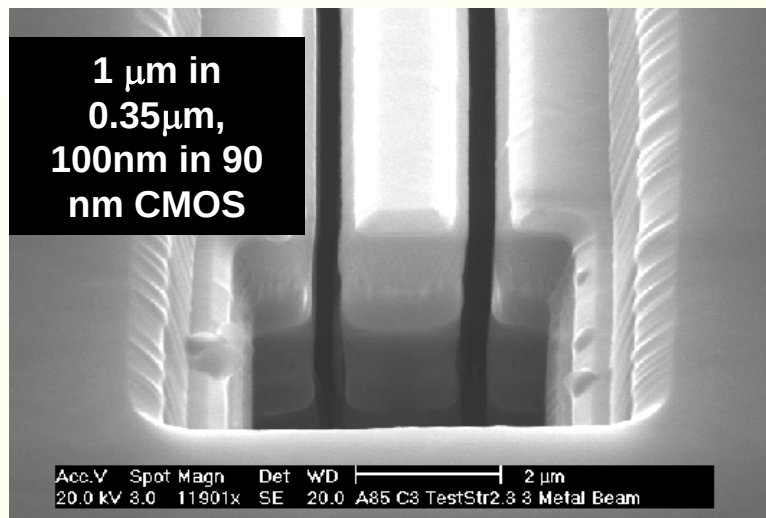
All Mechanical Computing

Hybrid NEMS/CMOS component integration

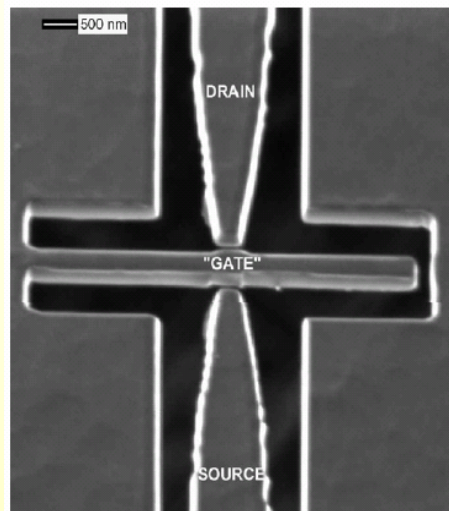


Hybrid NEMS/CMOS Device integration

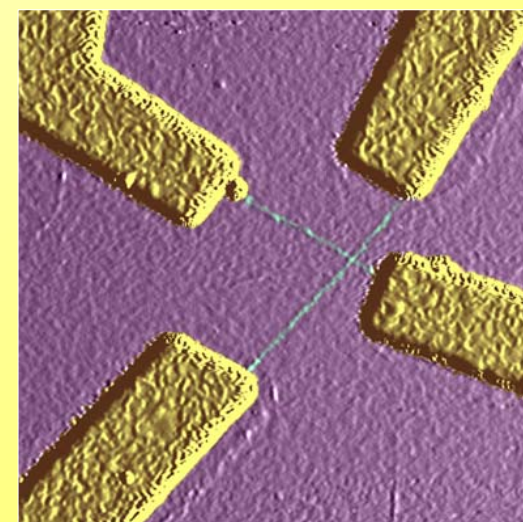
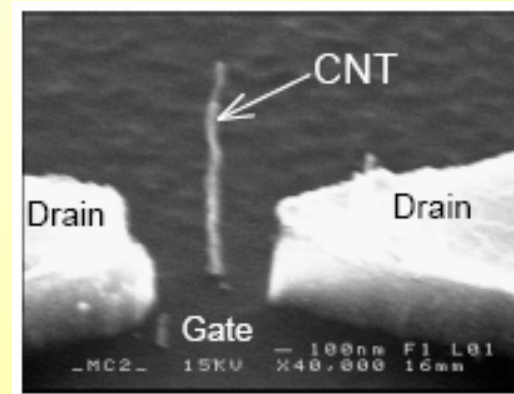
Nano Switches



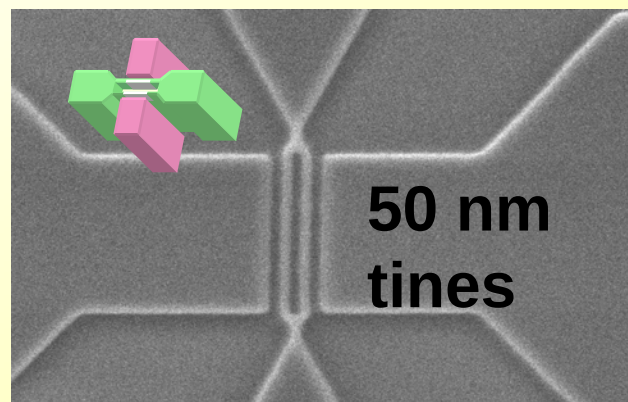
CMOS Integrated NEMS



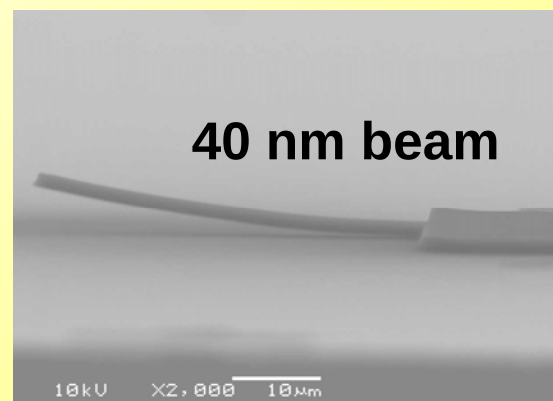
Nanoscale e⁻ shuttle



Nanotube/Fiber switches

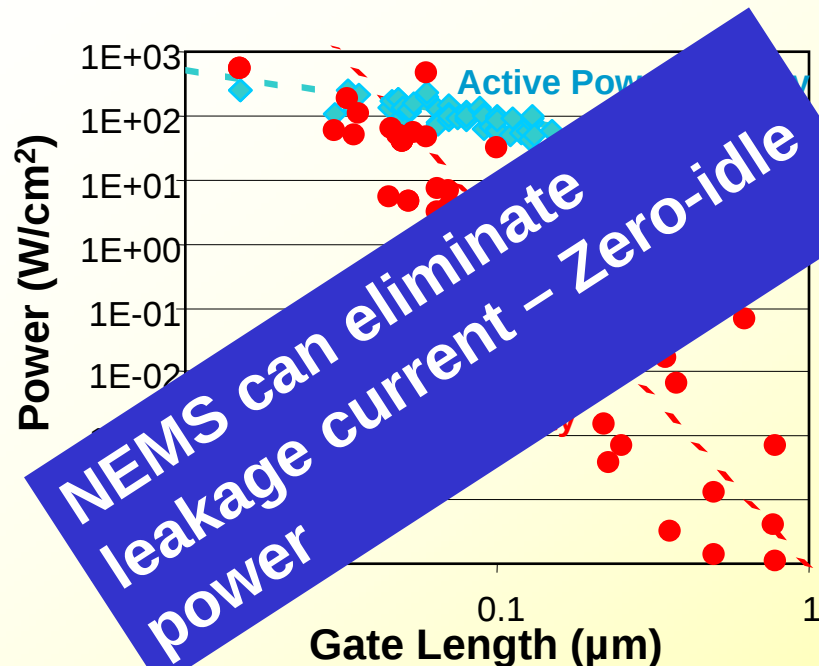


Released FinFET NEMS switch

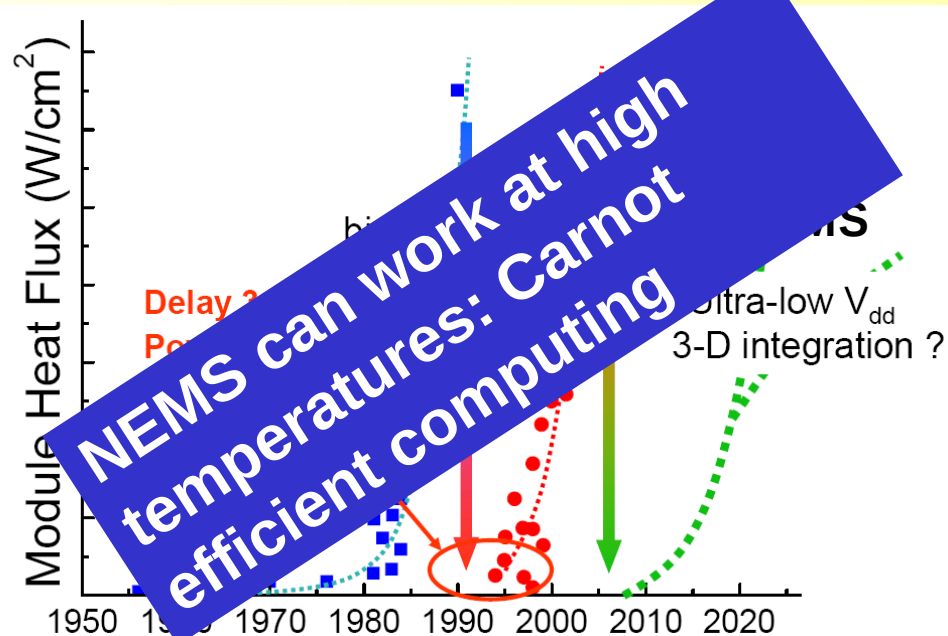


Nano-machined switches

The Problems: Max Heat Removal Rate and Leakage Power



Excessive I_{off}

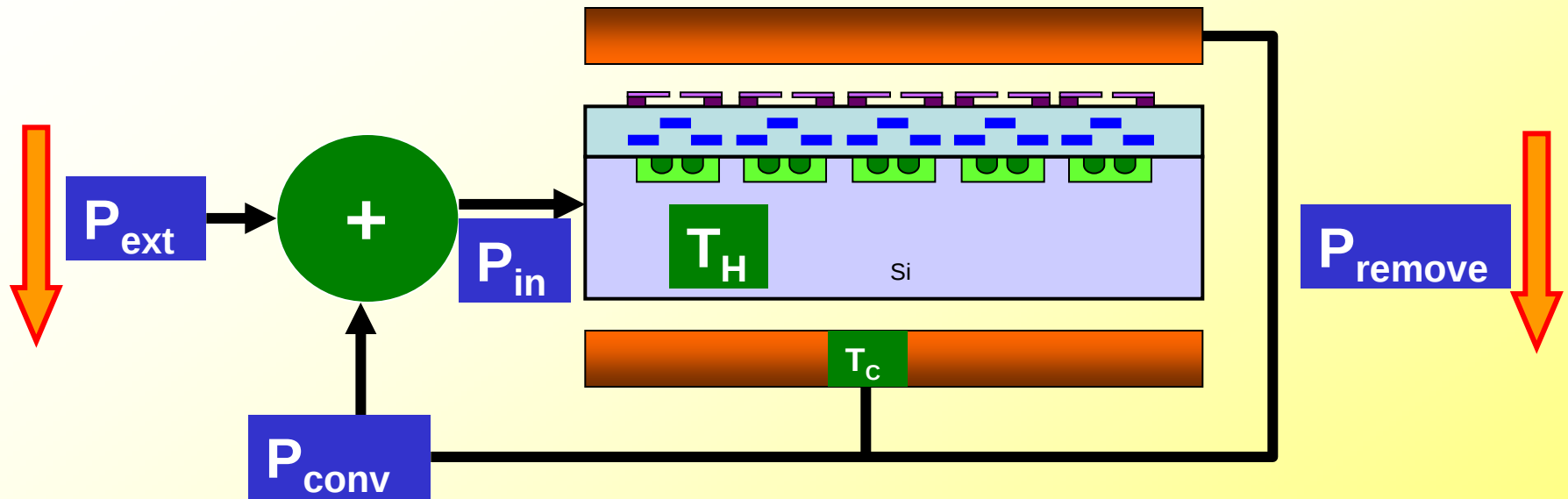


Excessive Heat Generation

$L_g/V_{DD}/V_T$ trends → increases in:

- Active Power Density ($\propto V_{DD}^2$) ~1.3X/generation
- Passive Power Density ($\propto V_{DD}$) ~3X/generation

The Carnot Optimized Computer



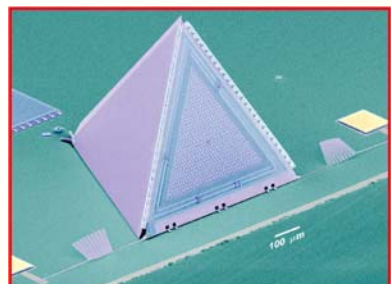
$$P_{ext} = P_{in} - \eta_G \frac{T_H - T_C}{T_H} P_{in} = P_{in} \left(1 - \eta_G \frac{T_H - T_C}{T_H}\right)$$

- T_H should be maximized for high Carnot efficiency
- $700C \Rightarrow 973 - 300 / 973 = 0.70$
- If 50% of Carnot $\Rightarrow 35\%$ power can be reclaimed
- Cooling could be eliminated
- Needs fast switching technology at high temp – NEMS

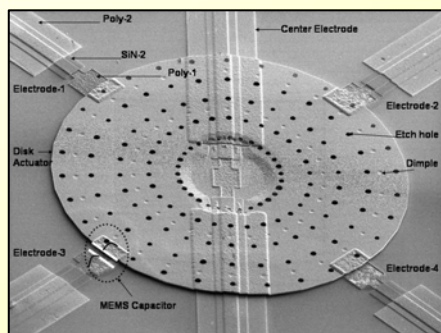


Past Example

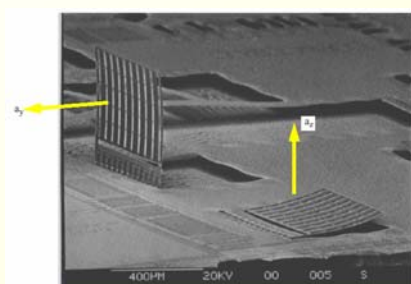
Self-calibrating Micro Sensors: Shoe-Implanted Perpetual Personal Navigation



CMOS-MEMS Micro 3-axis accelerometer/gyro possible but have offsets due to imprecise fab. Develop ppm accurate sensor model using on-chip calibration techniques – eliminate temp control to reduce power



Sonic pulsing, fluid MEMS to sense velocity directly



Precision and stable resonators provide frequency for self-calibration



State-of-Art (without electronics or GPS)
IMU: 14cc, 250 mW



Power scavenging from motion in shoe ~ 10 milliWatt average over mission



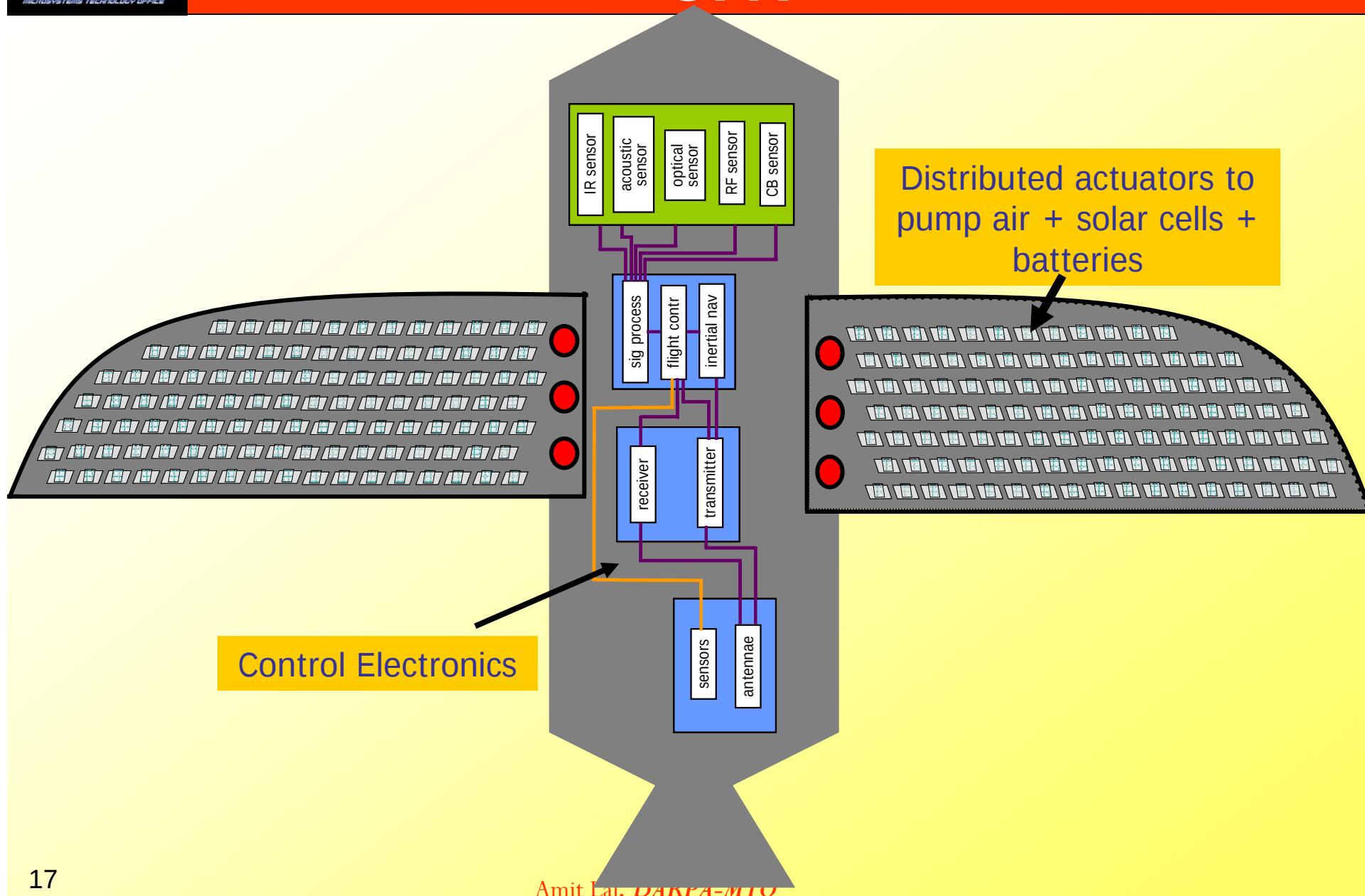
1 cc, 5-mW average IMU

>10x reduction in size, >100x reduction in power

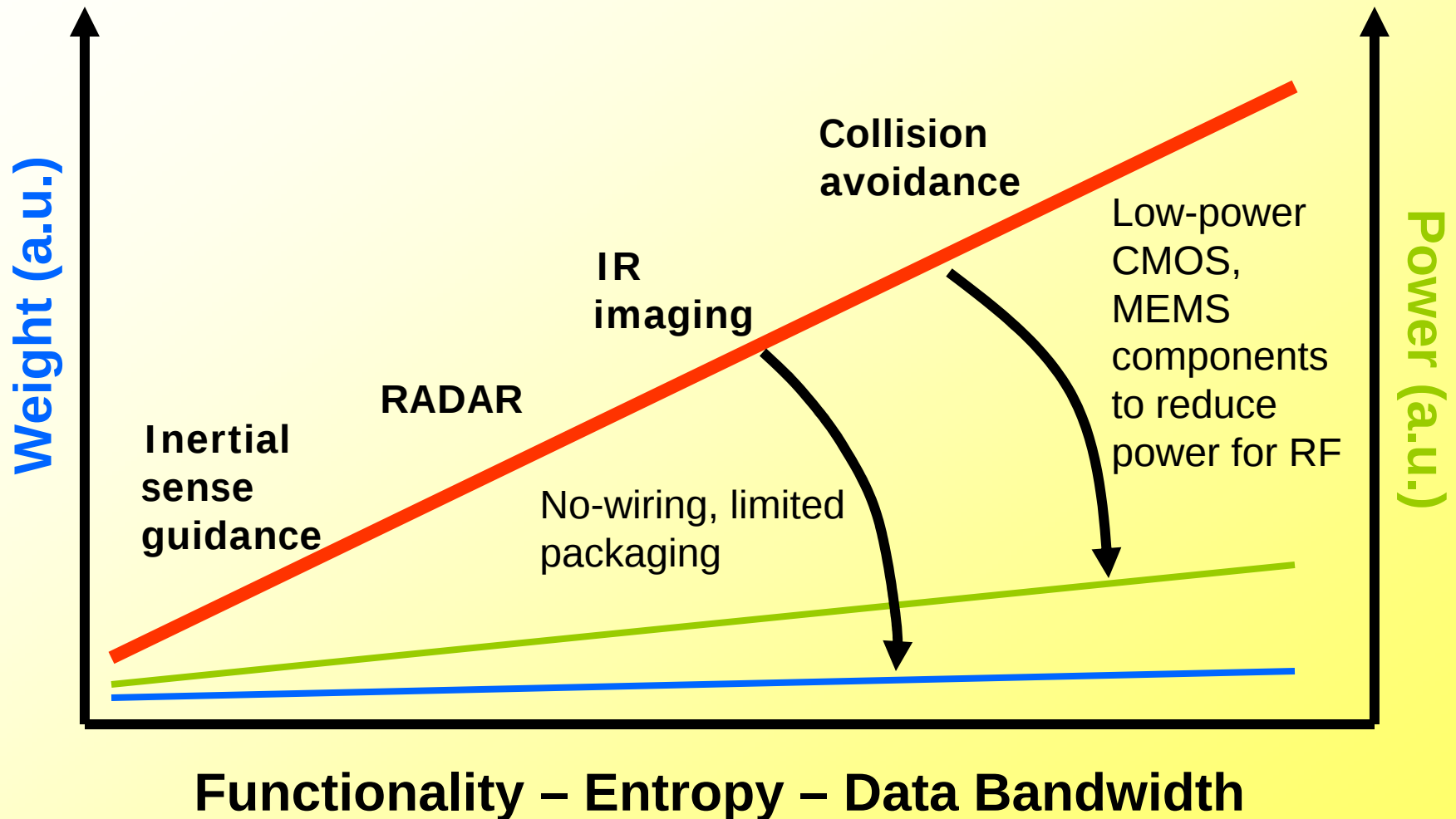


HI-MEMS insect power output >5 milliWatt average

MTO Mostly-silicon UAV



Benefits of mostly-silicon MAV







Summary

- **MEMS offers pathways to miniaturized and chip-scale sensor and actuator systems for reduced SWAP and increased functionality**
- **Upcoming MEMS will result in cost / performance benefits by integrating functionality**
- **The future for MEMS-IC symbiosis is bright**

QUESTIONS?