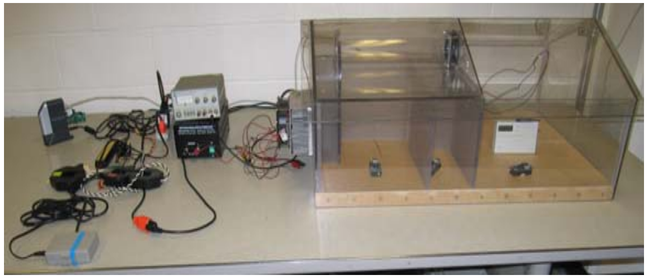
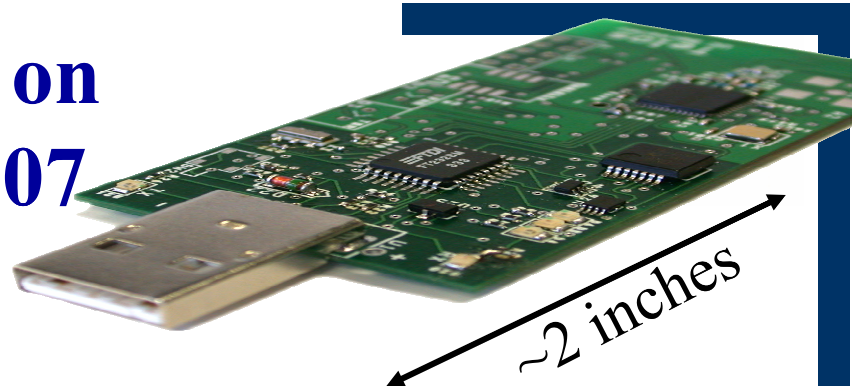
Micro-integration for DR-ETD

- **New Thermostat, New Temperature Node, & New Meter**
- **Phase One: 3/2003 – 8/2005; Phase Two 9/2005 – 8/2007**
- **Multi-disciplinary Collaboration Team:**
  - David Auslander: ME Dept.
  - Ed Arens & Charlie Huizenga : Center for Built Environment
  - Kris Pister: Berkeley Sensor & Actuator Center, EECS Dept.
  - Jan Rabaey: Berkeley Wireless Research Center, EECS Dept
  - Dick White: Berkeley Sensor & Actuator Center, EECS Dept.
  - Paul Wright: Berkeley Manufacturing Institute, ME Dept.
  - 20 Graduate Student Researchers (13 are funded)
    - Many thanks to all colleagues and students for their contributions

DR Applications running on "motes" made in 2003-2007

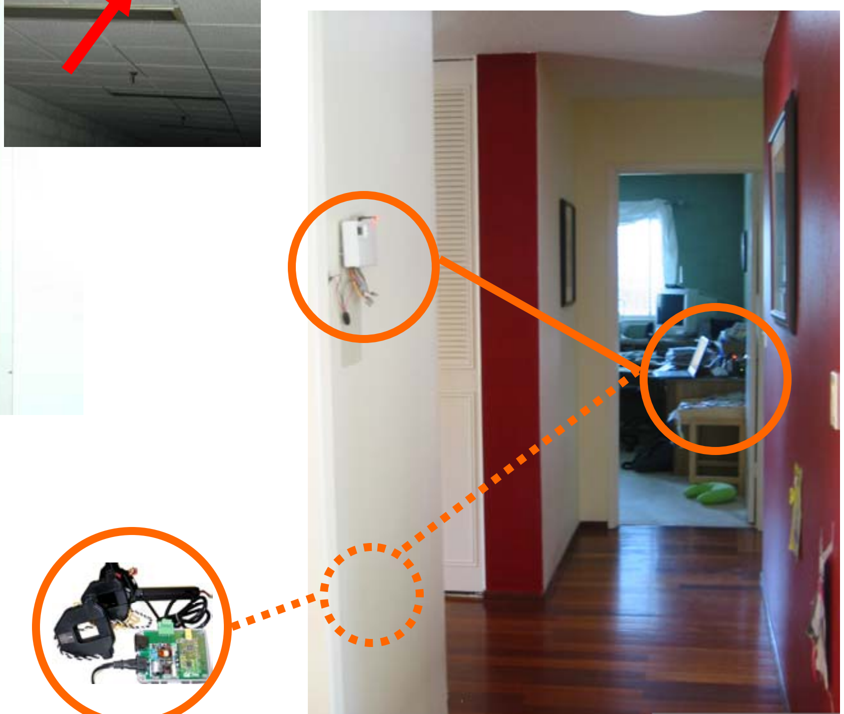


2003



2004/5

2006



2006 field deployments of REM multi-agent system with sense and actuation utilizing multi-hop wsn.

DR Applications running on "motes" made in 2003-2007

- **So far, the DR-ETD project has proven that microcomputers, cheaper radios, TinyOS, MEMS sensors, energy scavenging and WSNs are the enabling technology for a DR responsive system**
- **Enabling technology for**
  - New Meter
  - New Thermostat
  - New TempNode
    - Example of TempNode from 2004/5 publications

The way forward: Micro-integration by the millions = “super cheap”

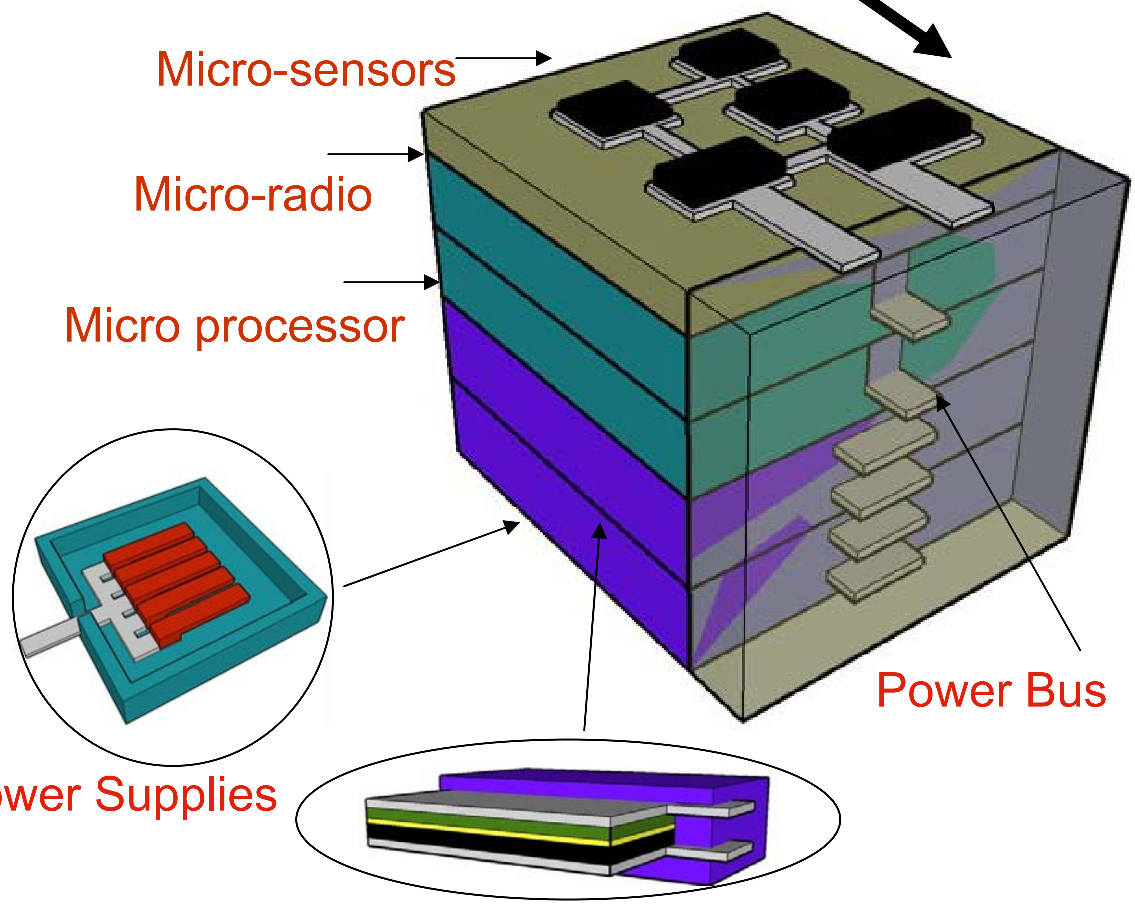
Software applications **run on the** **Hardware platforms**

Control logic

Learning algorithms

Automation

Distributed throughout all computers in the system



Pause: Today's "Take-away"
The way forward

- 1. Make DR technologies significantly less expensive and thus more appealing to customers (integrated/seamless)
- 2. Accelerate innovations in the electricity sector by integrating technologies into "packages" that don't exist in marketplace
- 3. Package technology in forms/footprints that meet energy/DR requirements
- 4. Radios, Computation, Sensors, Scavengers, Storage

Recent highlights

- 1. Radio power reduction and using MEMS based high-quality factor FBAR resonators
- 2. Scavenging power more efficiently and in a smaller MEMS package
- 3. Micro-storage, MEMS methods for power
- 4. Beginning micro-packaging of MEMS devices

MEMS
(Micro-electromechanical systems)

- **Meter (m, little over a yard)**
- **Millimeter (mm, 10^{-3} meters)**
  - Grain of sand = 0.2 to 2 mm diameter
- **Micrometer (µm, 10^{-3} mm)**
  - Human hair ~ 10-100 µm
  - Domain of electronics and MEMS
- **Nanometer (nm, 10^{-3} µm)**
  - Molecular bonds are tenths of nm)

1. Micro-Power Wireless

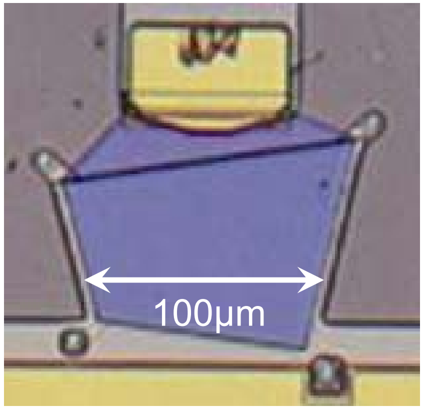
Main result:

“Reactive radios” represent a new paradigm in wireless transceivers:

- **Low power**
- **Low cost**
- **Low duty-cycle**

RF-MEMS

Agilent 1.9 GHz FBAR (BAW)



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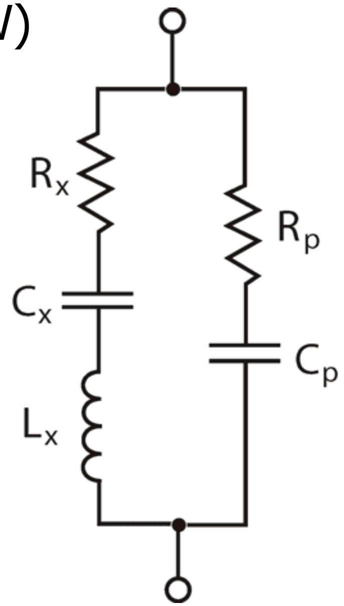
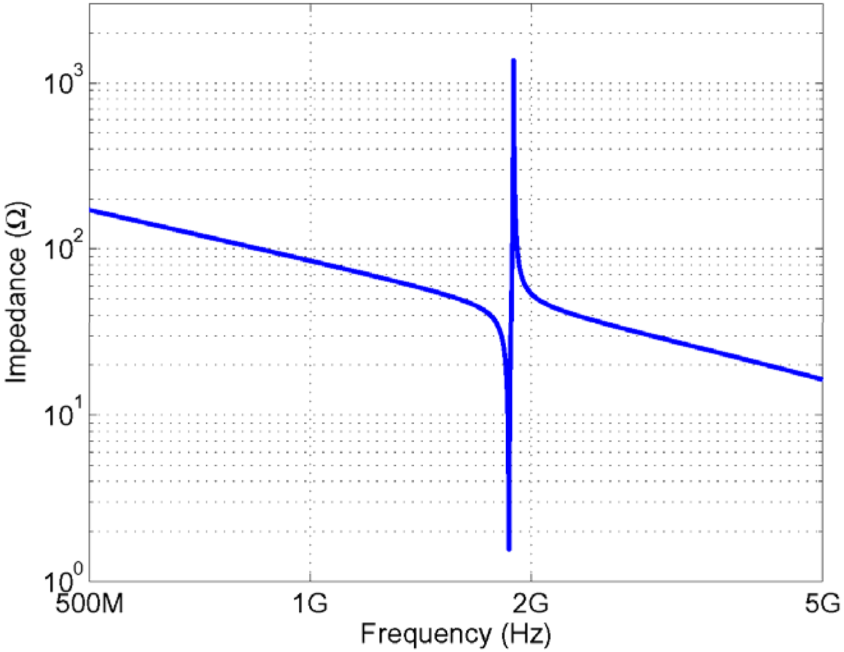


Provides high accuracy frequency reference or high Q filtering

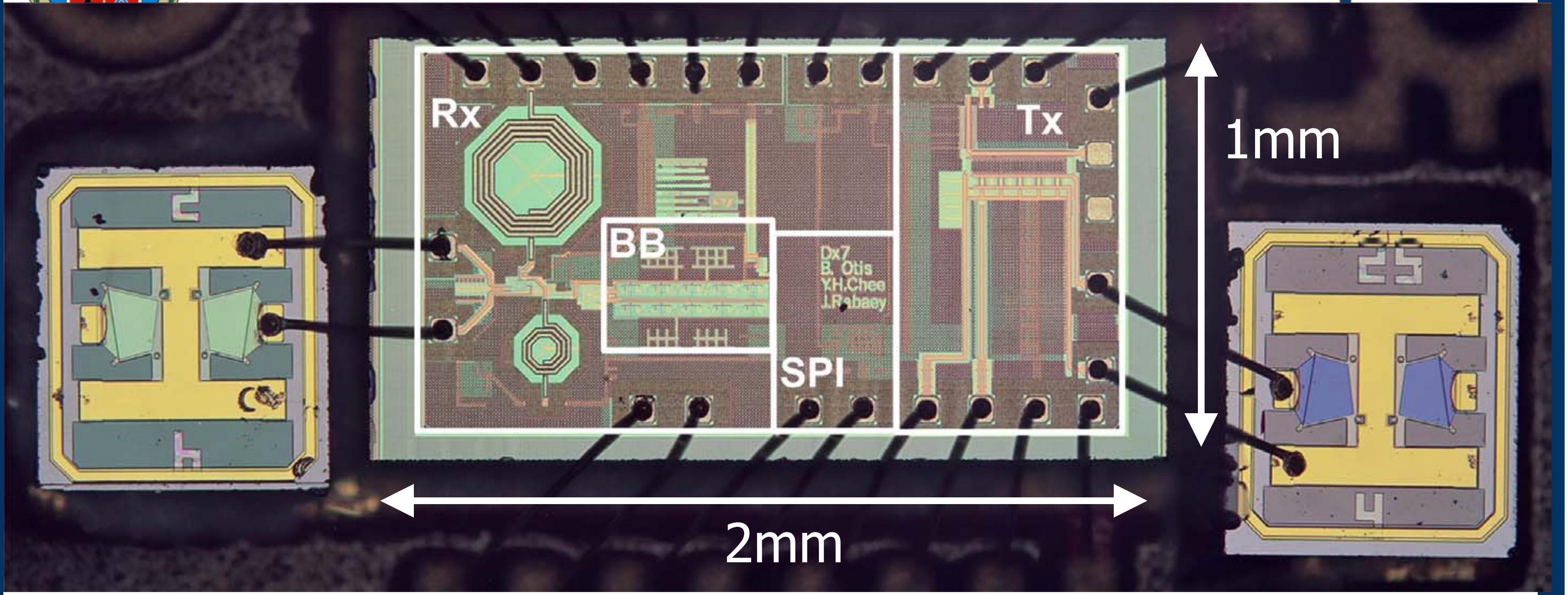
Simulated FBAR impedance response



MEMS can replace traditional external components (like crystals) for highly integrated transceivers:

- Reduction in implementation size
- Cost reduction

Fully Integrated 1mm^3 Rx/Tx



Presented at ISSCC 2005

- No external components (inductors, crystals, capacitors)
- 0.13µm CMOS
- Very small implementation volume

B. Otis, Y.H. Chee

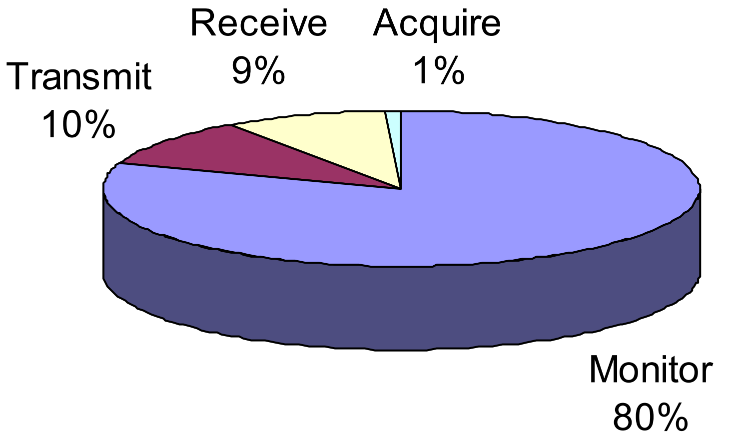
Further Reduction of Power

Key Characteristics of Sensor Networks:

- **Low packet traffic rates**
- **Short packets (< 200 bits)**
- **Reduce monitor power**
  - ***Reactive radio with automatic wakeup***

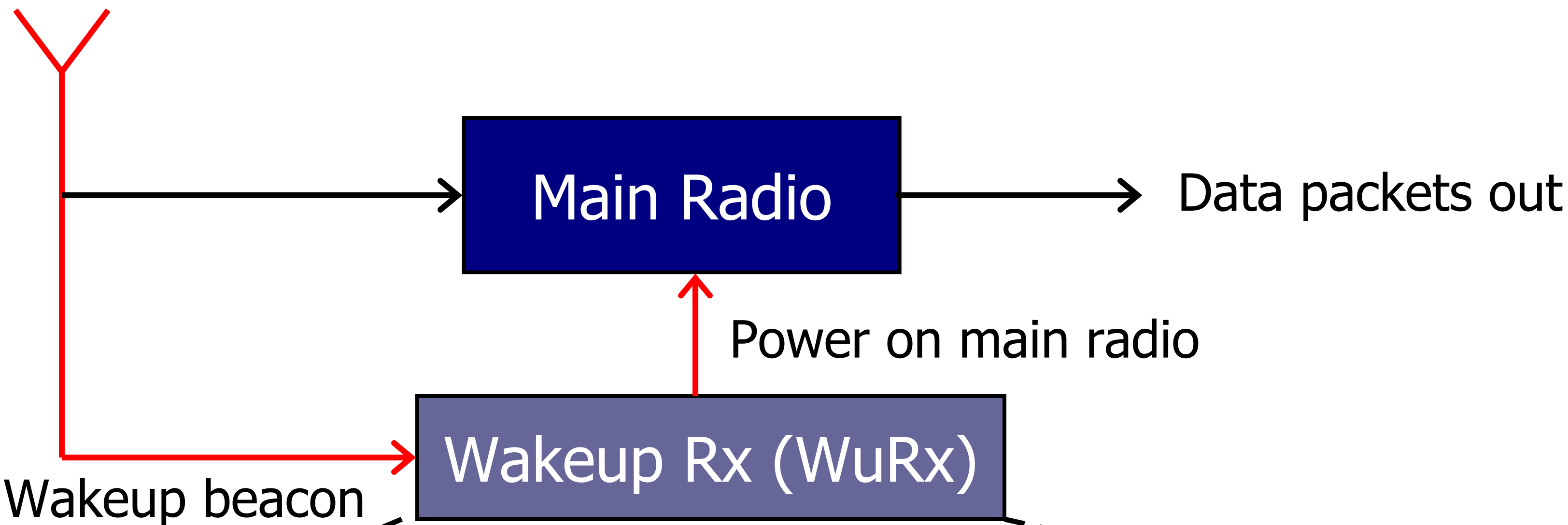
Time spent in different states for a CSMA/CA MAC protocol

(802.11 @ 10 packets/sec)



Adapted from: Lin Ph.D. 2005

Reactive Radio with WuRx

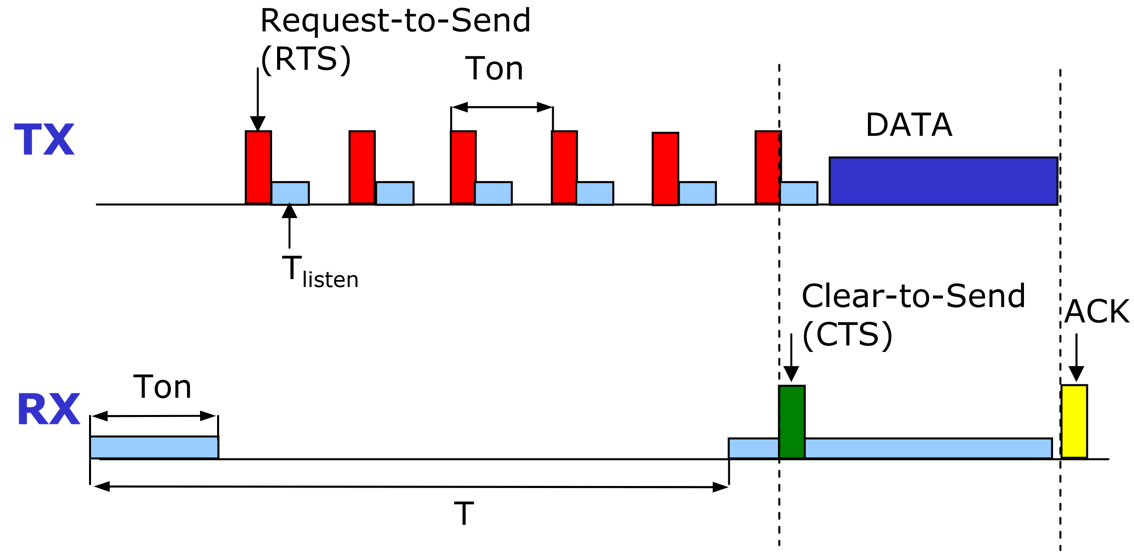


- **Reactive radio improves network latency and power consumption**
- **WuRx must be very low power compared to main data radio » 50µW**

Synchronization Schemes

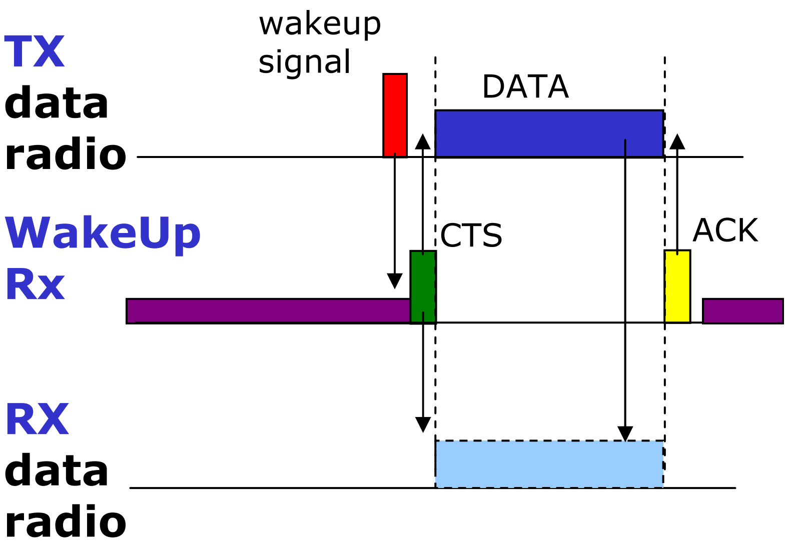
Pseudo-asynchronous:

- Tx node beacons while the Rx node periodically monitors the channel
- Rx channel monitoring power and Tx beaconing power is significant



Asynchronous ("Reactive"):

- Rx node monitors the channel continuously with very low power
- Overall network power savings possible, also latency reduced significantly

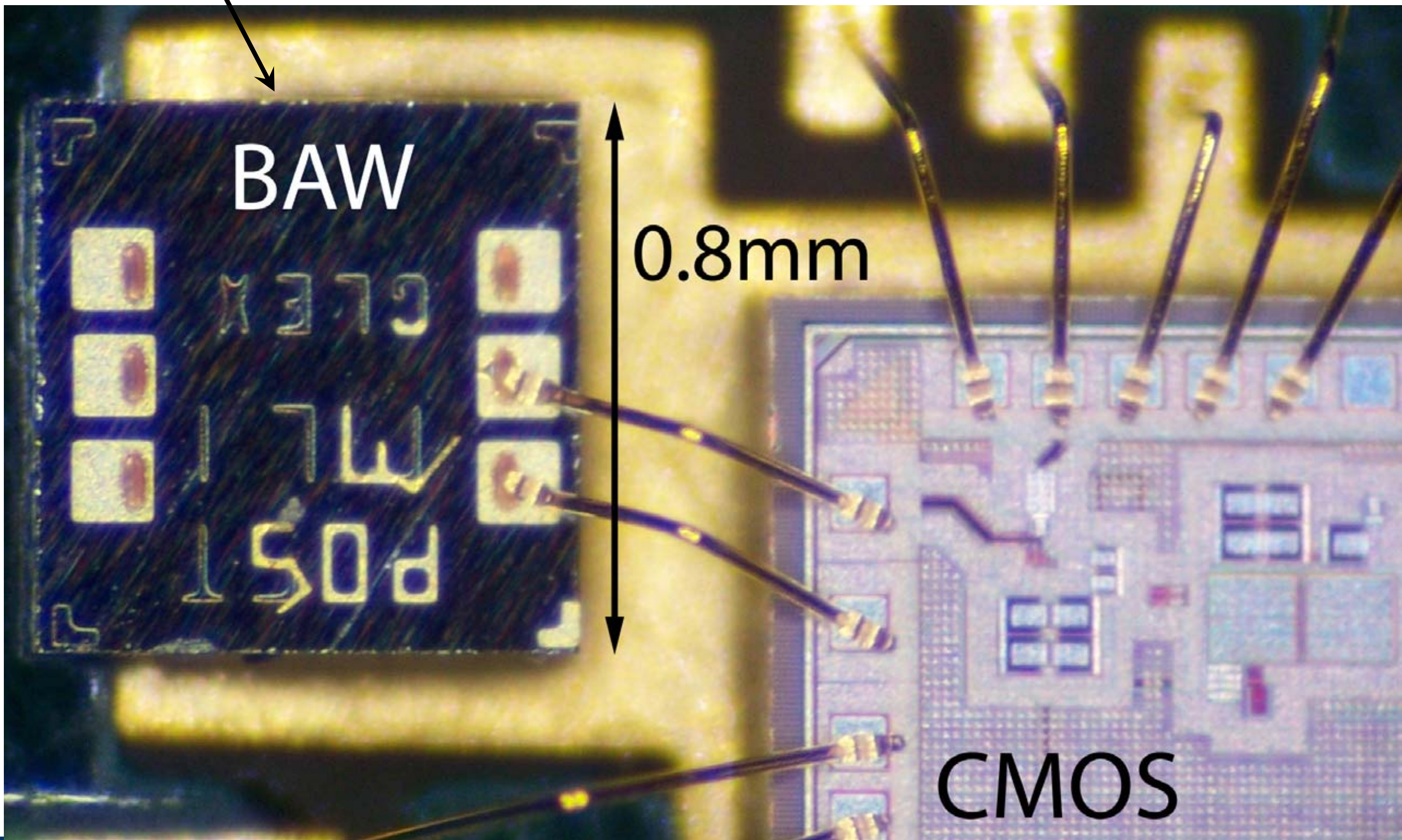


Ref [2]: E. Lin, Ph.D. thesis, 2005.

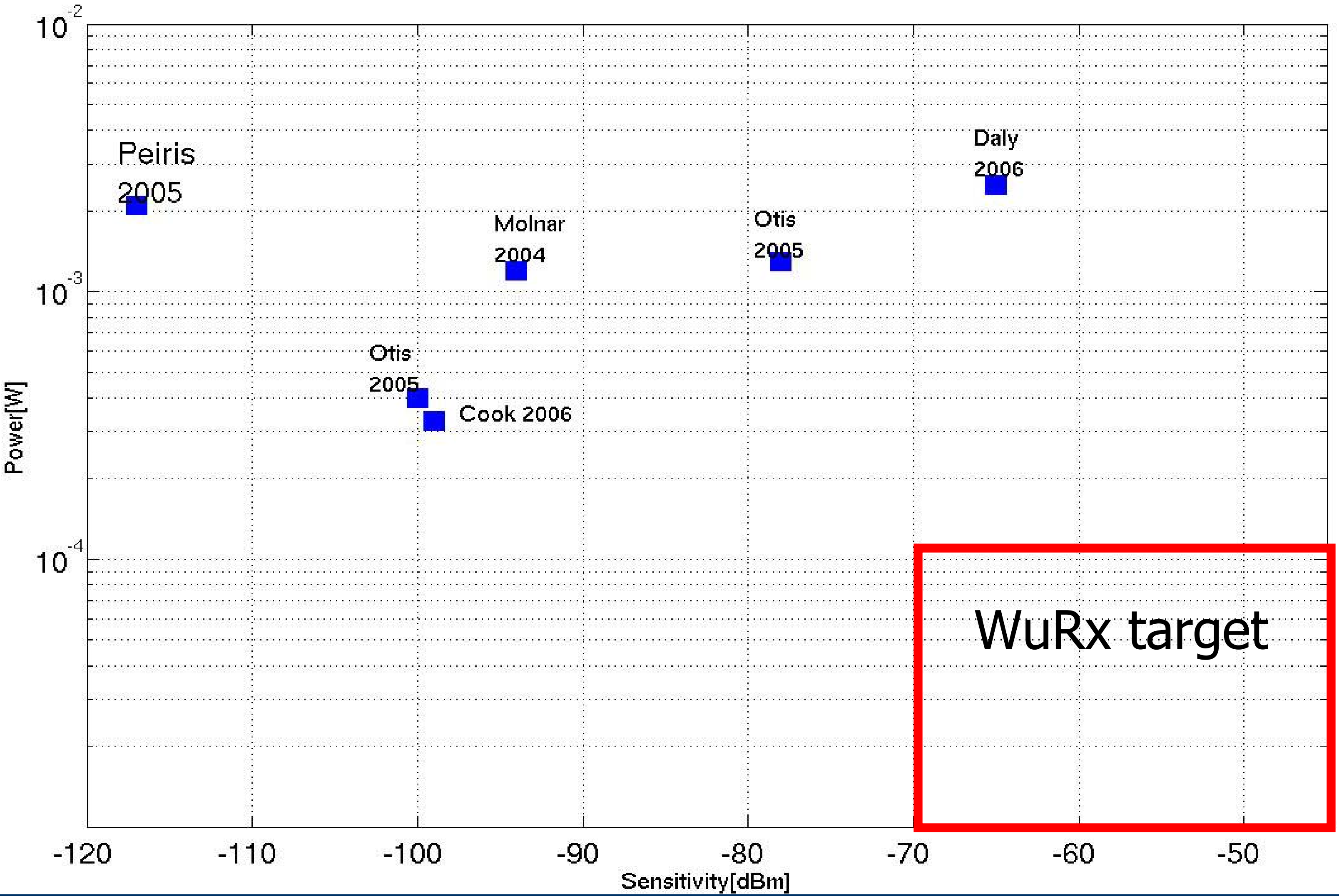
Silicon Prototype

BAW wirebonded directly to CMOS for prototyping

Fully integrated prototype in 90nm standard CMOS; no on-chip inductors



Low Power Design Space



Micro-Power Wireless

Main result:

"Reactive radios" represent a new paradigm in wireless transceivers:

- **Low power**
- **Low cost**
- **Low duty-cycle**

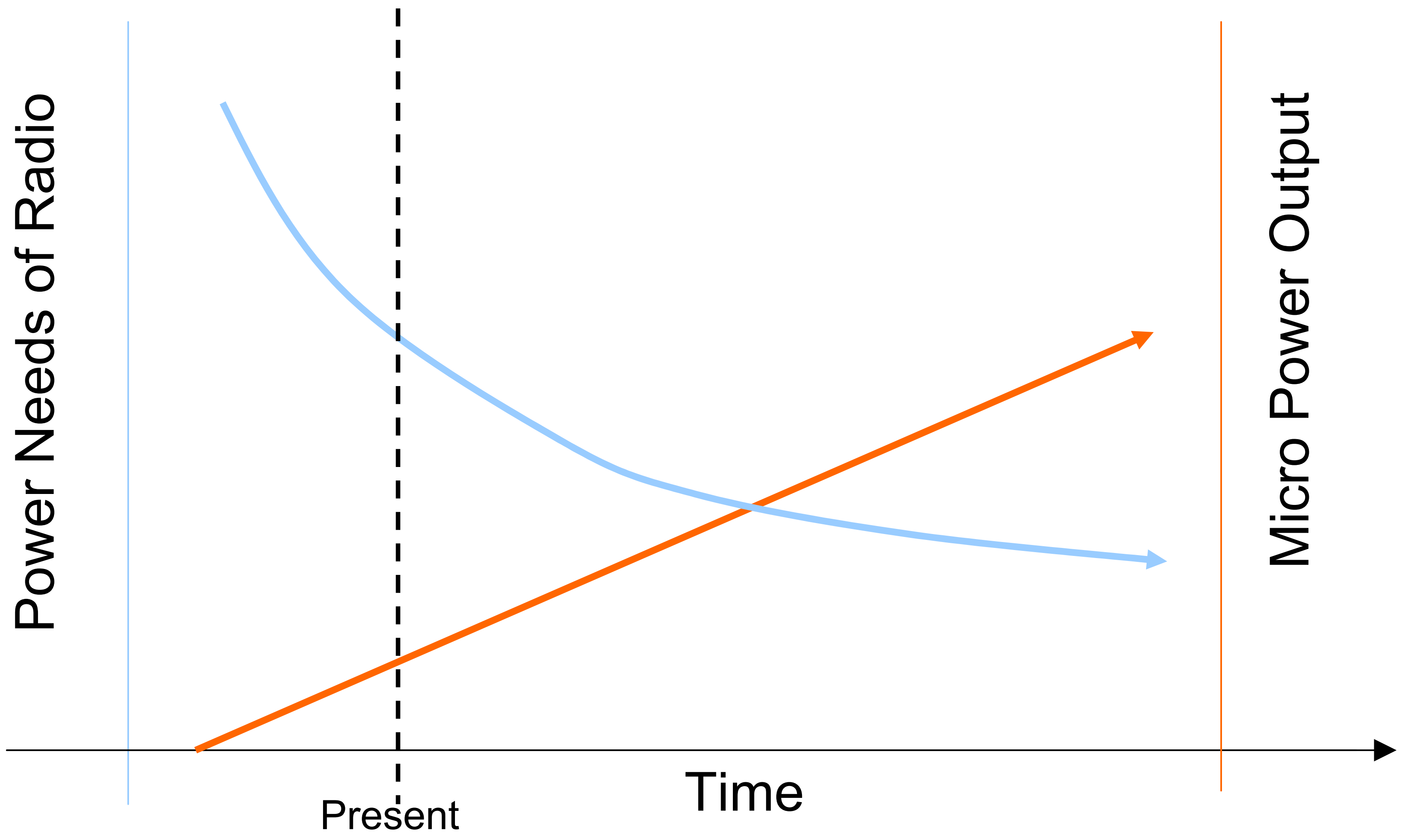
2. Micro-scale energy scavenging

Main result:

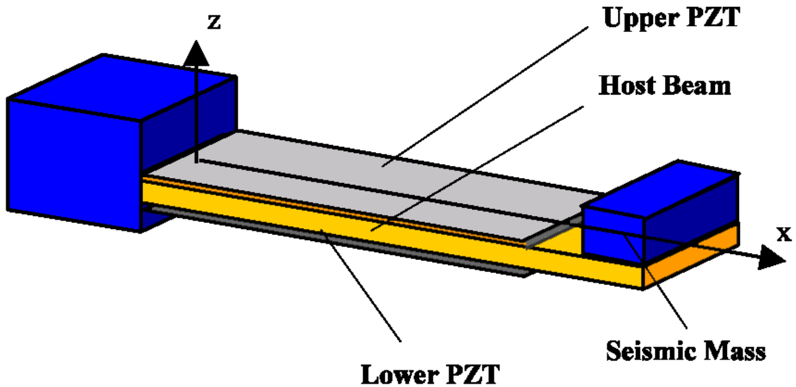
"Energy can be scavenged to power nodes"

- **MEMS scale is viable**
- **Lower duty-cycles allow more flexible systems**

Radios *vs* Scavengers



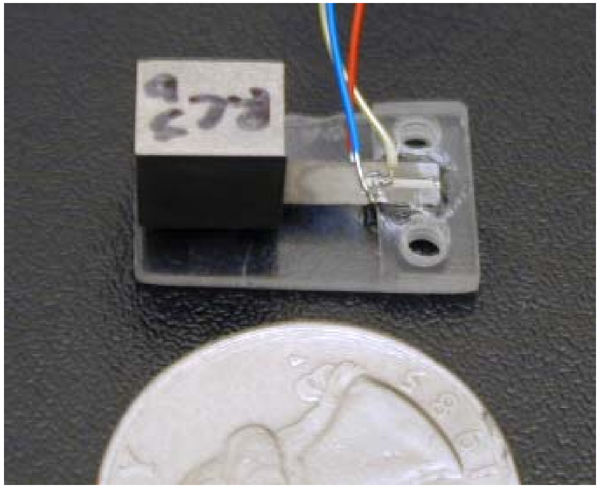
PZT cantilevers at the macro-scale



Piezoelectric Material -$PbZr_xTi_{1-x}O_3$

- **High piezoelectric coefficient**
- **Large range of solid solubility**
- **Well characterized properties in the bulk as well as thin film form**

40 mm x 3.5 mm, 2 g mass

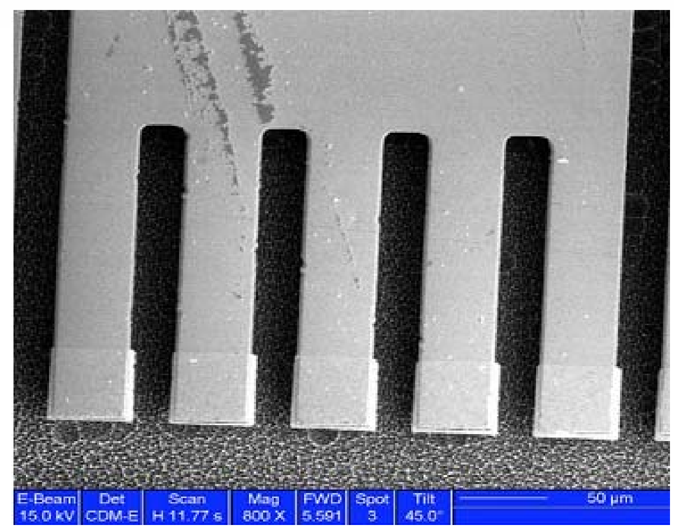


Heterogeneous Bimorph

- Two layers (piezoelectric, elastic)
- Proof mass
- Constitutive equations readily solved
  - adaptable to empirical modifications
  - adaptable to analytical modifications

PZT cantilevers in the micro-lab

1. Single crystal silicon wafer coated with 10 nm $SrTiO_3$ (STO, from Motorola, Inc.)
2. Deposit $SrRuO_3$ (SRO) bottom electrode using pulsed laser deposition (PLD)
3. Deposit PZT ($PbZr_{0.47}Ti_{0.53}O_3$)using PLD
4. Deposit top electrode/elastic layer (Pt with Ti adhesion layer) using e-beam/thermal evaporation
5. Define cantilever structures using photolithography
6. Etch down to Si substrate using ion mill
7. Release cantilever structures using isotropic XeF_2 etch



E. Reilly, E. Carleton, P. Wright, "Thin Film Piezoelectric Energy Scavenging Systems for Long Term Medical Monitoring," *Proc. IEEE Body Sensor Networks 2006* (2006)

Cost reduction @ MEMS scale

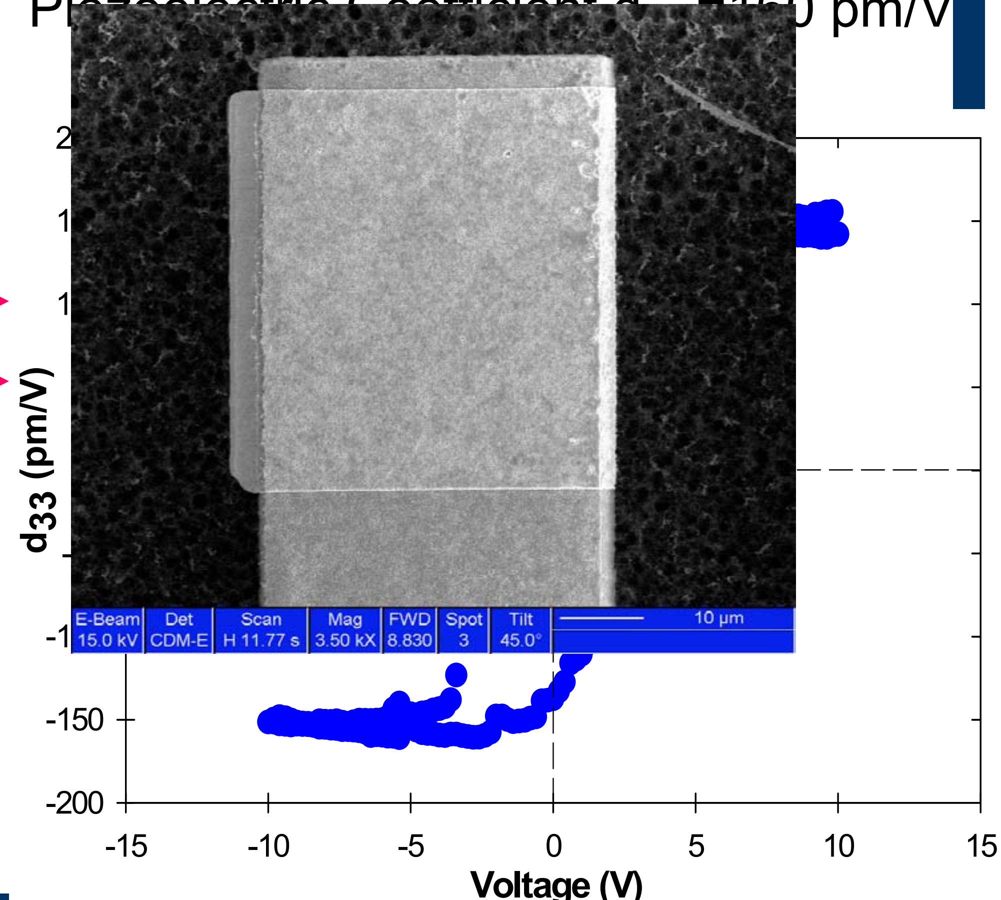
Piezoelectric and Elastic Layers

- Maximizing piezoelectric functionality on Si substrate for ease of integration

- Reduction of residual growth stresses through neutral Ar bombardment

typical value range

- Addition of proof masses to drive deflection and lower resonant frequencies



Main Results for MEMS Power Supply

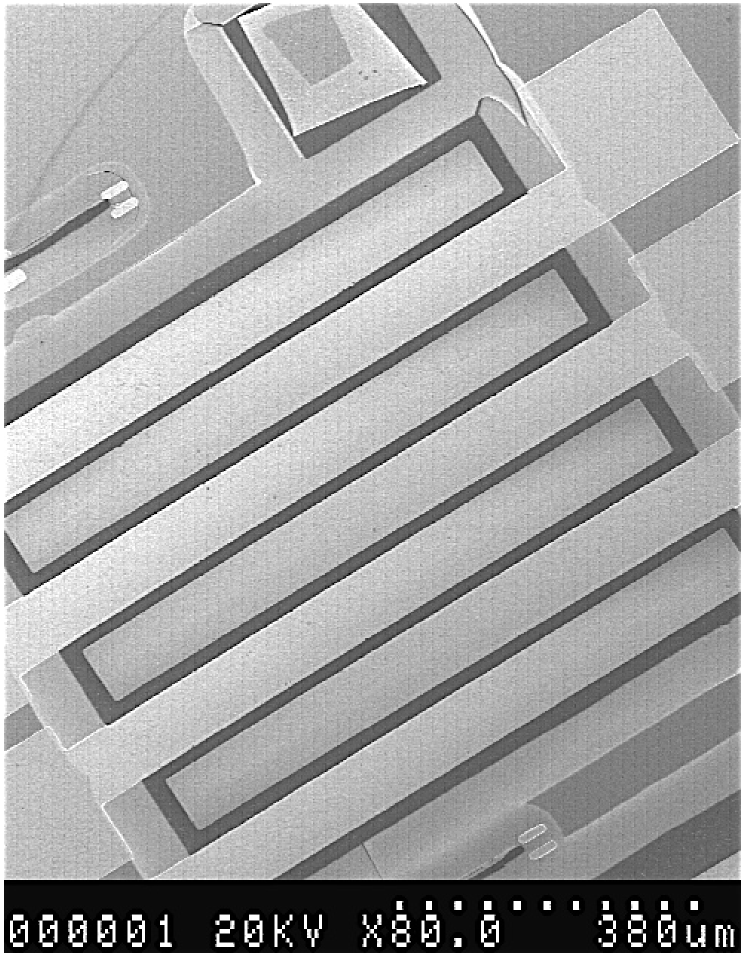
-Interdigitated electrode design to maximize packing efficiency

-Operating frequency range from 250-2500 Hz

-Mathematical modeling suggests power outputs between 80-200 $\mu W/cm^3$

-Output power and mechanical efficiency (Q factor) currently being explored

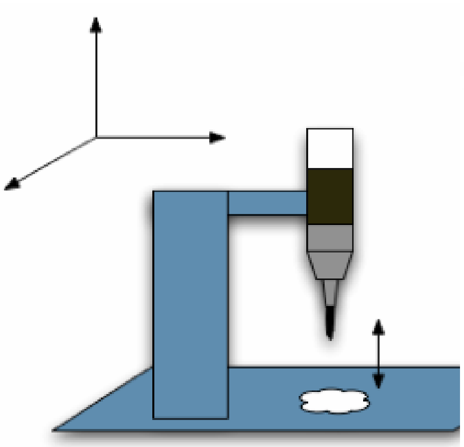
-Fabrication technique expansion to full 4” wafer (*Lindsay Miller)*

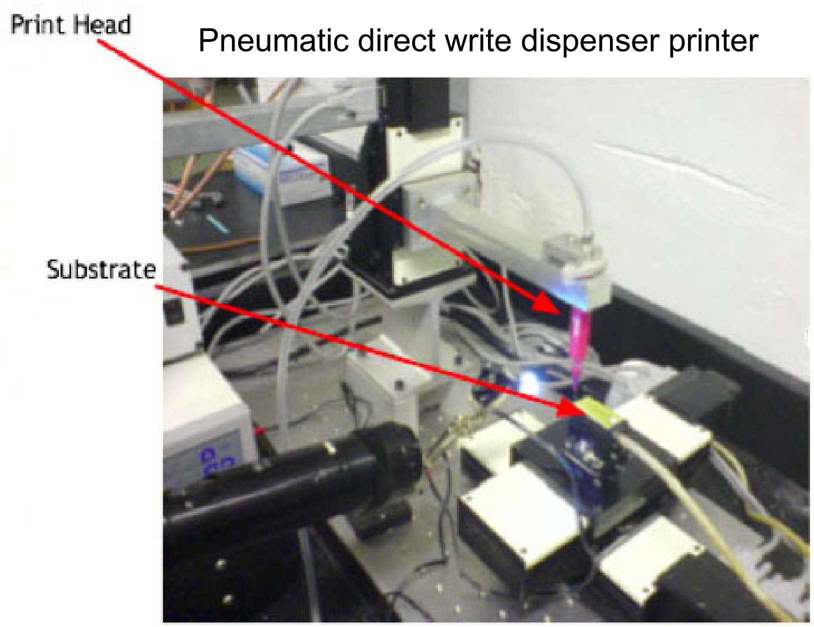


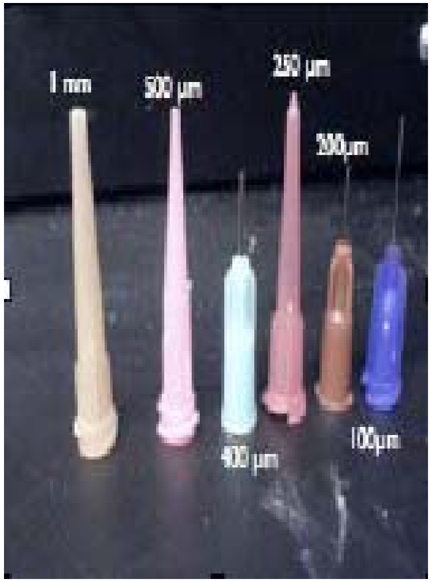
3. Micro-scale storage

- **Main Result: Thick film batteries provide adequate capacity in a small footprint**
- **Printing batteries atop circuit boards allows for**
  - Package reduction
  - Matching chemistries and capacities for subsystems, minimizing the overhead for power conditioning
- **Printable electronics includes batteries, capacitors, more...**

Additive Deposition (Printing) of Micro Power Devices



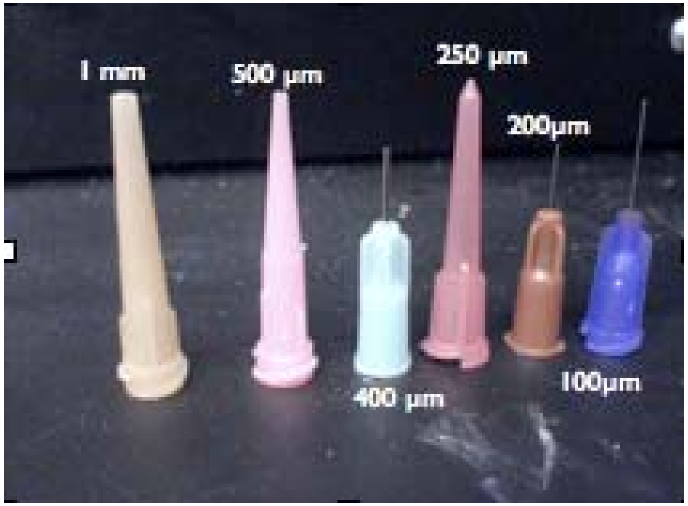




- **deposition of micro batteries and capacitors**

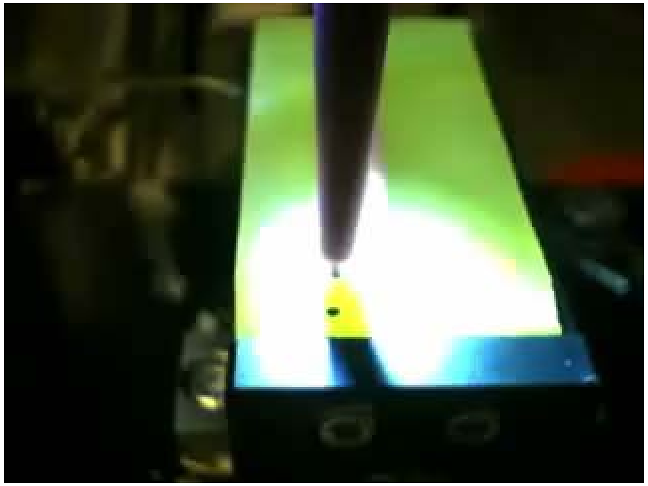
New equipment prototyped for DR project

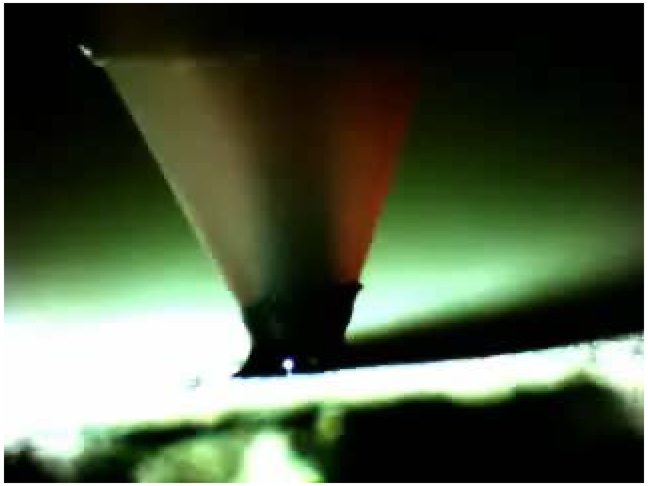
- **A pneumatic dispenser printer**
  - 100 µm feature sizes* (and shrinking)
  - 5 µm to 500 µm thicknesses
  - Rasters any image
  - Cheap, Scalable
  - Handles a wide range of viscosities



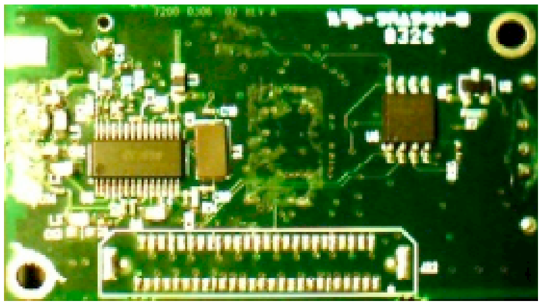
*Human hair ~ **100 µm**

Printing Carbon

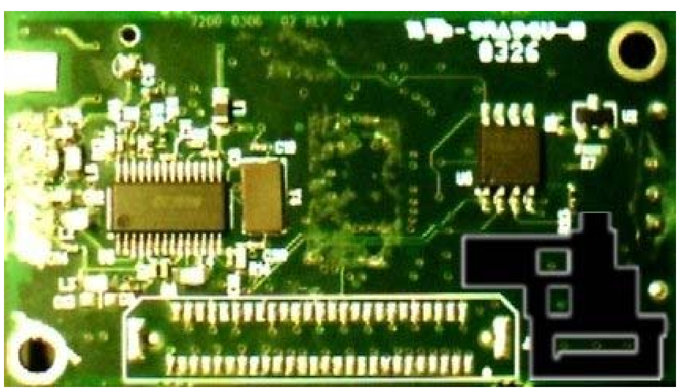




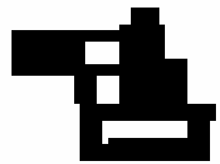
Goal: Print Anywhere



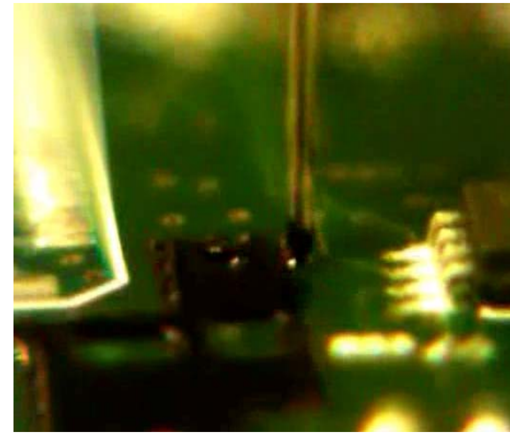
Select Area



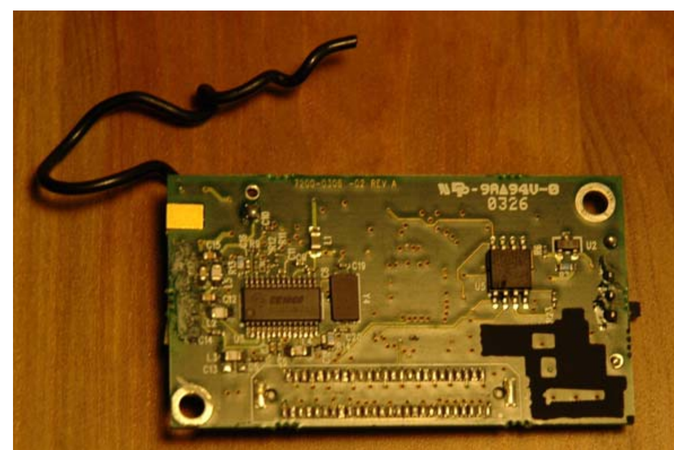
Send to Printer



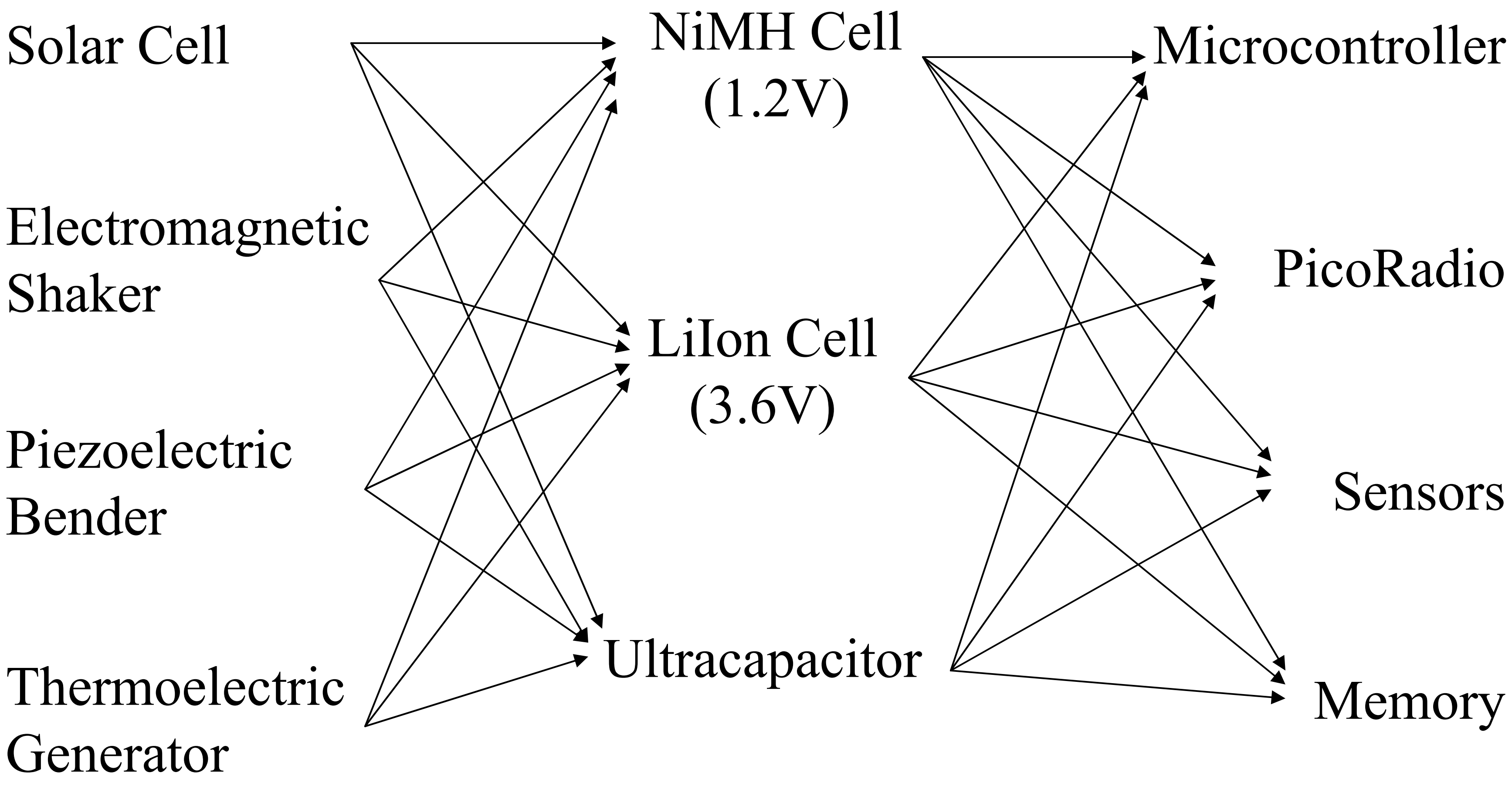
Print



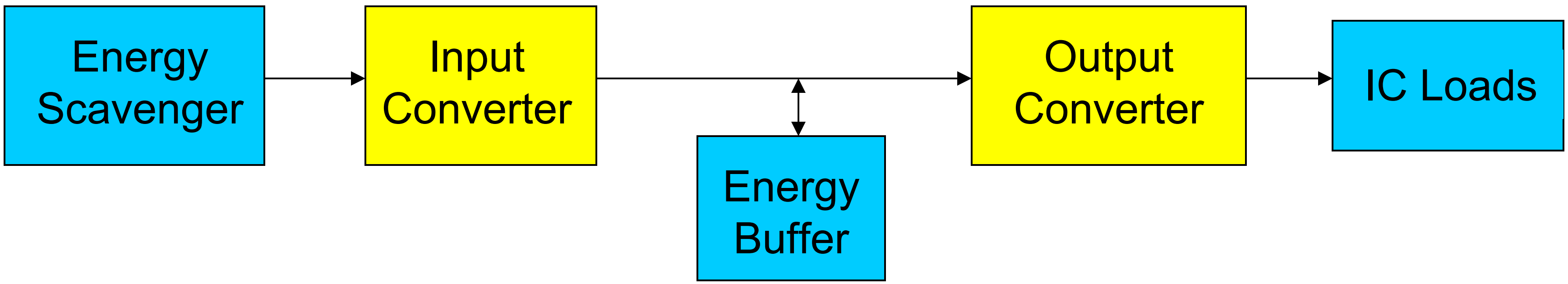
Dry



Power Interfaces



Energy Flow



- **Two equally-important energy strategies:**
  - Take what you can get
  - Use sparingly
- **Efficient conversion** and **optimal power harvesting is key to good performance**

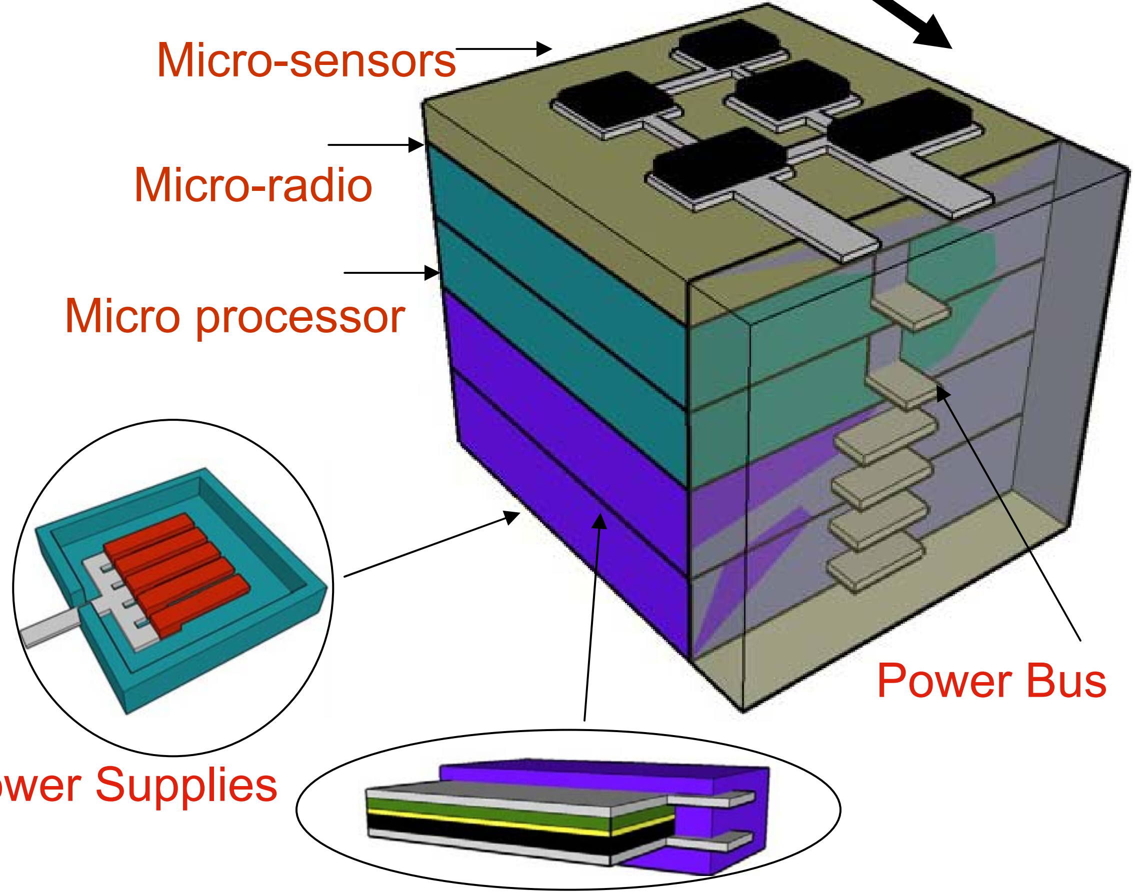
Main results of storage work

- **A viable method for printing Li-Polymer-Ion batteries has been developed**
  - Method is material and substrate independent
  - Printing at standard temperatures and pressure
- **Capacitors as well as batteries**
- **Storage needs can be customized for each level of a device (such as in the PicoCube)**

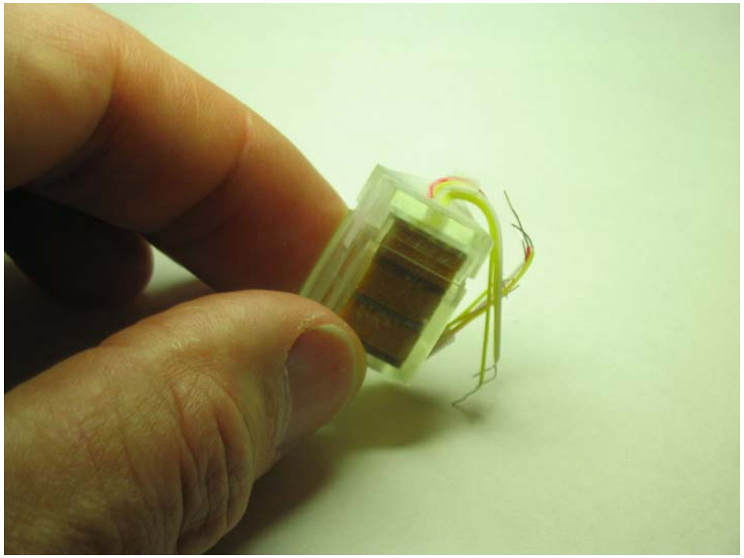
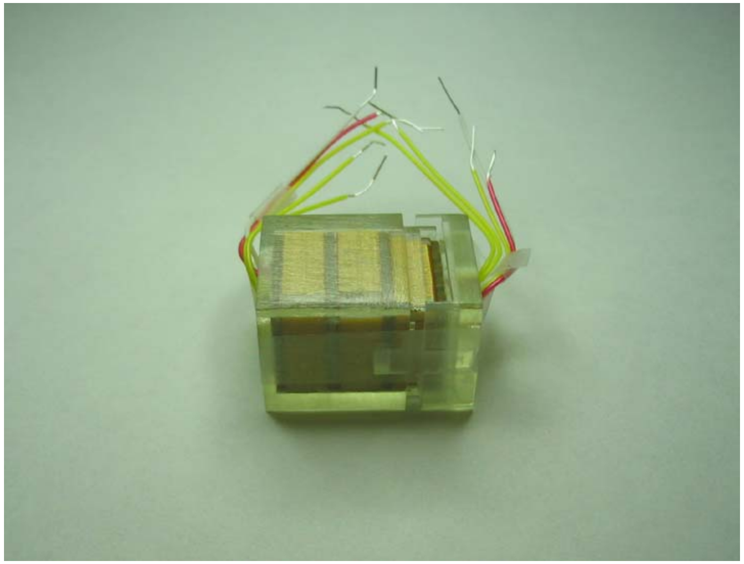
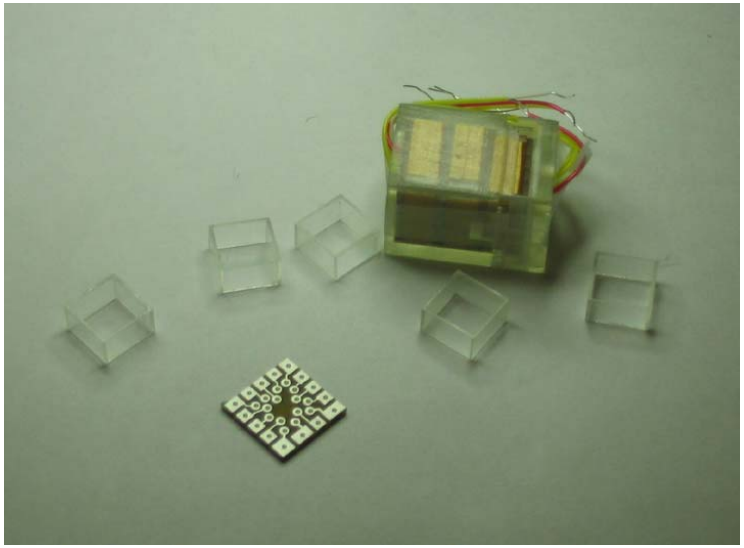
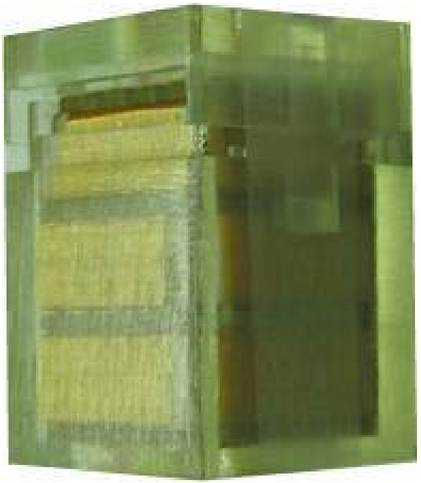
The way forward: Micro-integration by the millions = "super cheap"

Software applications run on the Hardware platforms

- Control logic
- Learning algorithms
- Automation
- Distributed throughout all computers in the system

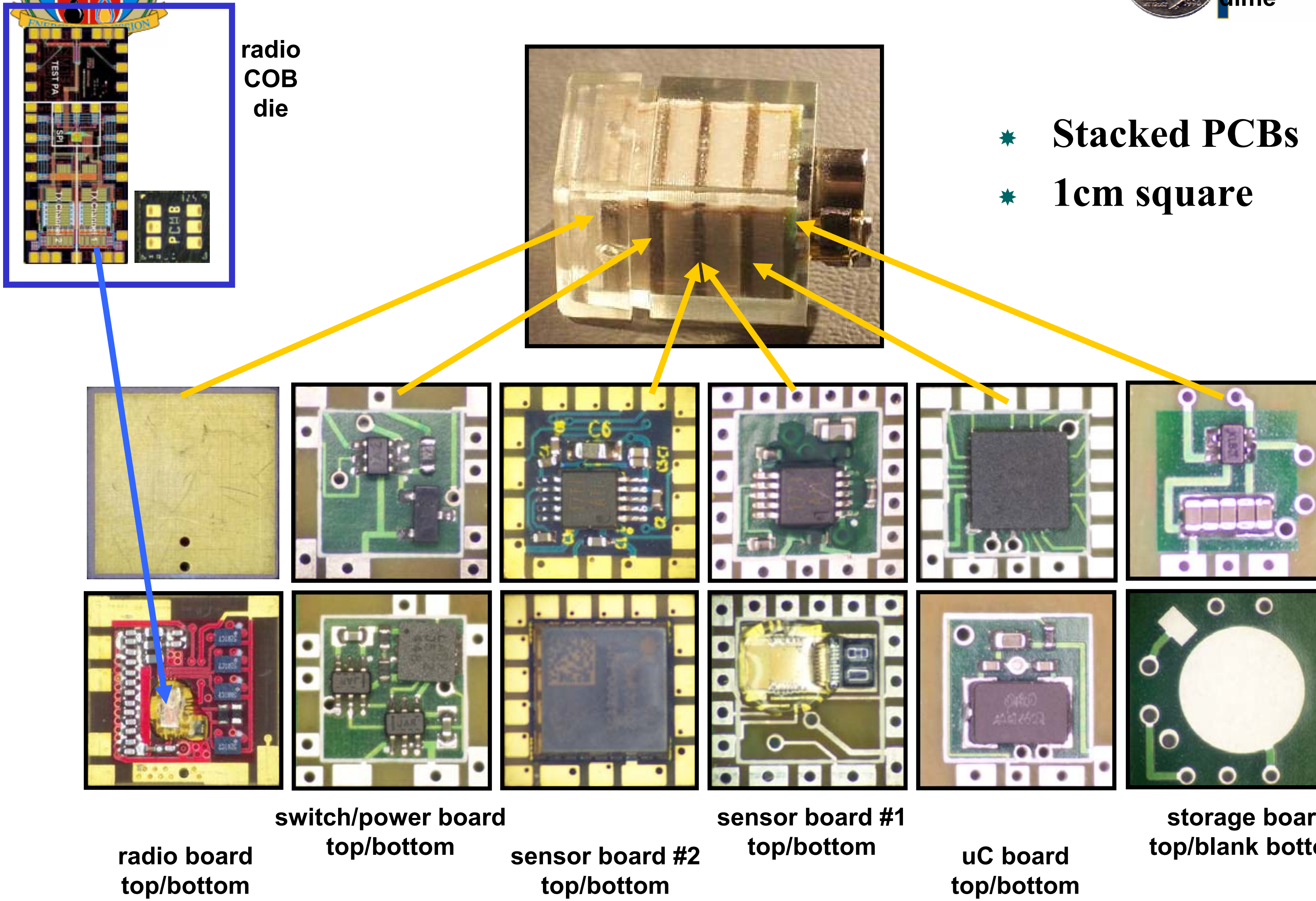


4. Beginning Micro-integration:
PicoCube January 2007

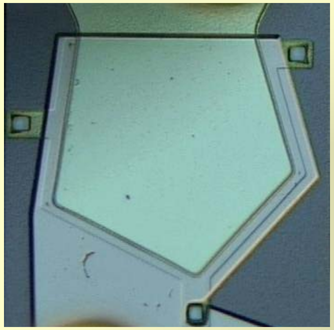
Micro-integration

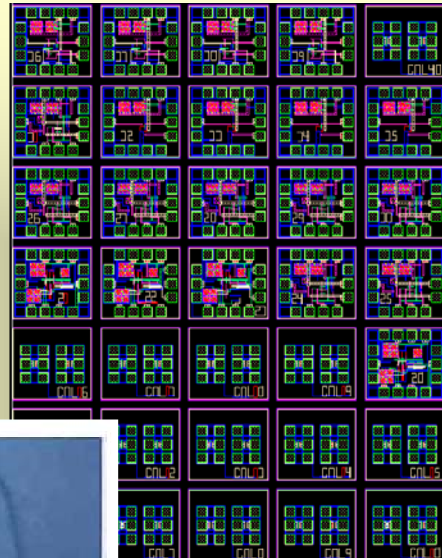
- Stacked PCBs
- 1cm square



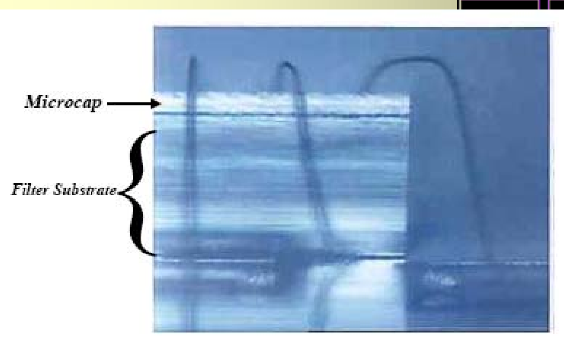
Graphic used for the hands-on part of the demo..

Further Minimization/Packaging





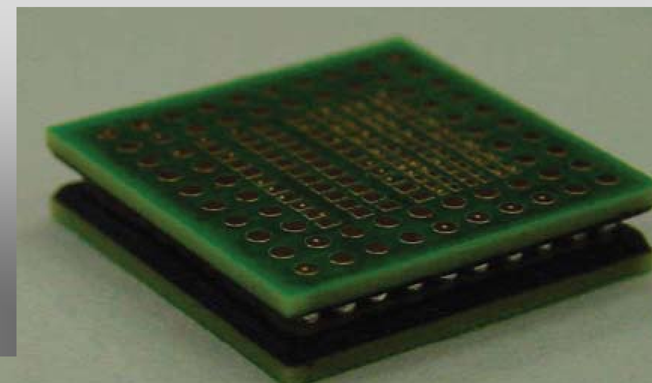
Micro-encapsulation allows co-design/packaging of FBAR resonators and CMOS circuitry

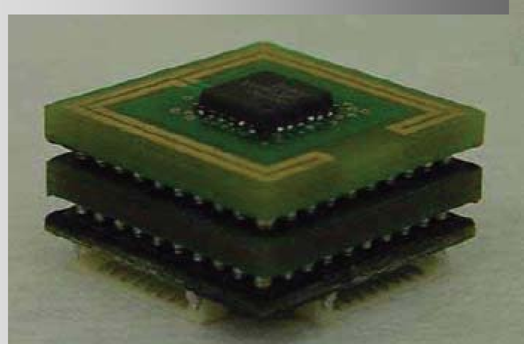


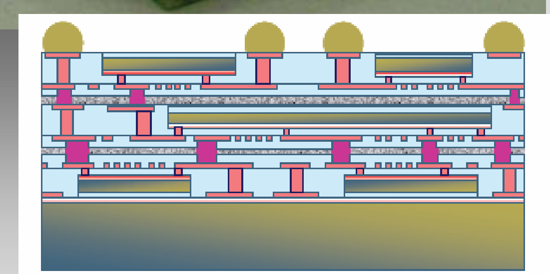
Joint project with Avago and UW

J. Richmond, M. Mark, N. Pletcher

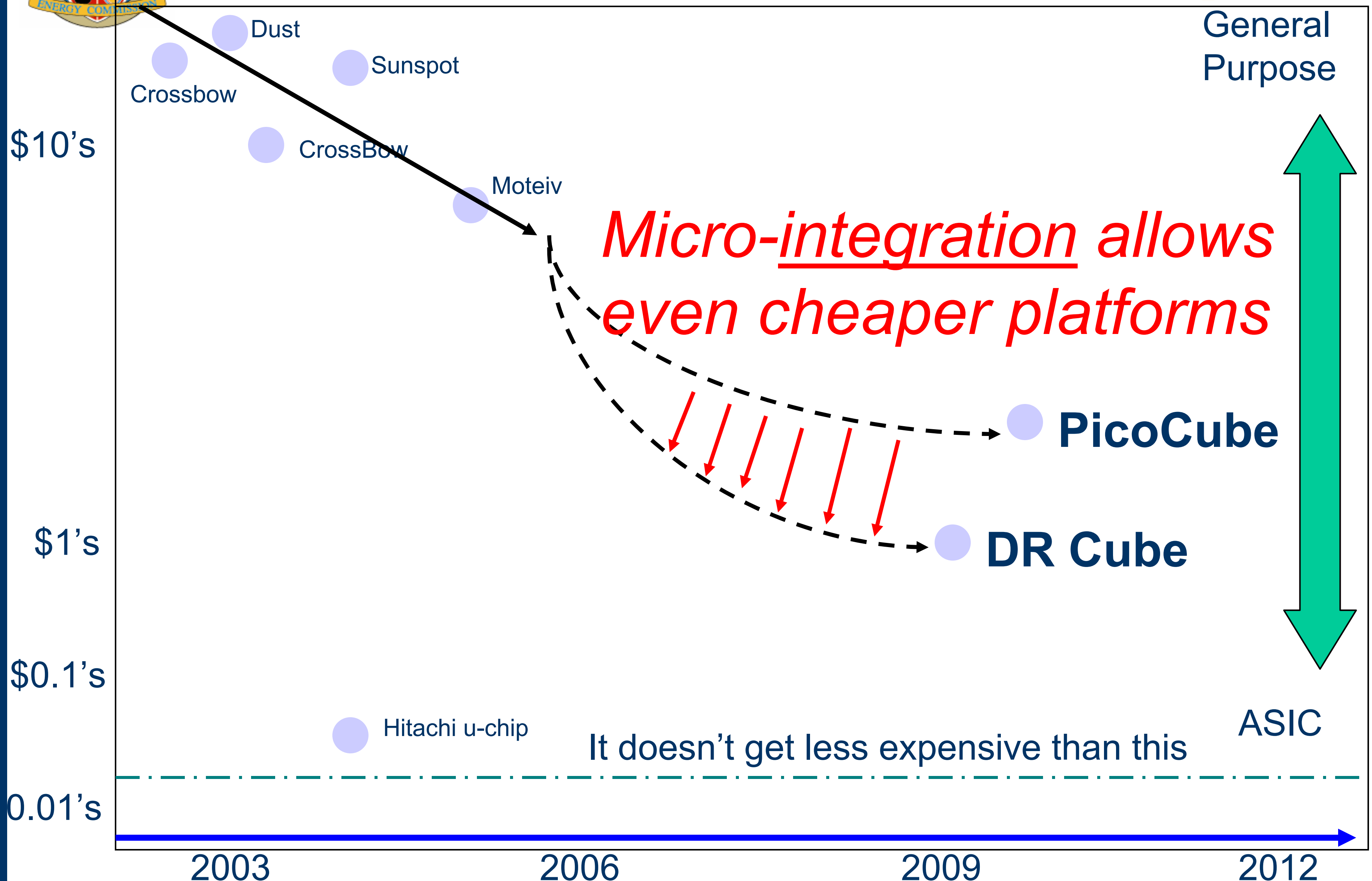
Exploring joint project with IMEC on 3D integration





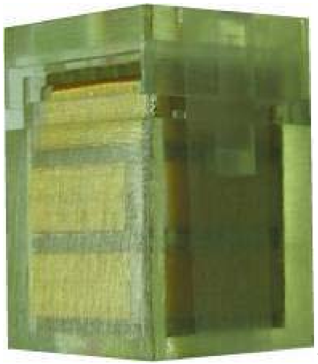


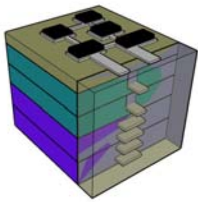
Pico Cube 2006 >> DR cube 2009



Summary: Micro-integration of Hardware, Software, & Applications

- **10x cost reduction, 10x capability increase**
- **Macro to micro UCB research**
  - Micro-computers
  - Micro-radios
  - Micro-sensors
  - Micro-power supplies
  - DR software applications
  - <$2 BOM per platform





2007 > 2009

- **Micro-integrated platform for meters, thermostats, temperature-nodes. Enables control and learning.**

Today's "Take-away"
The way forward

- 1. Make DR technologies significantly less expensive and thus more appealing to customers (integrated/seamless)
- 2. Accelerate innovations in the electricity sector by integrating technologies into "packages" that don't exist in marketplace
- 3. Package technology in forms/footprints that meet energy/DR requirements
- 4. Radios, Computation, Sensors, Scavengers, Storage