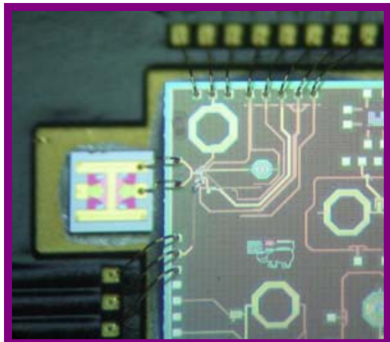
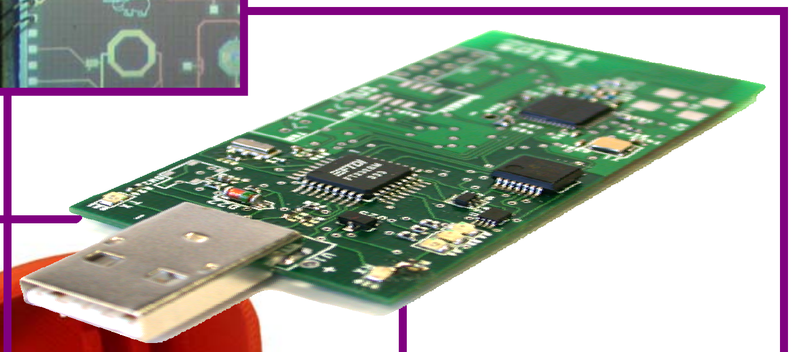
UC Berkeley's "Demand Response" Project

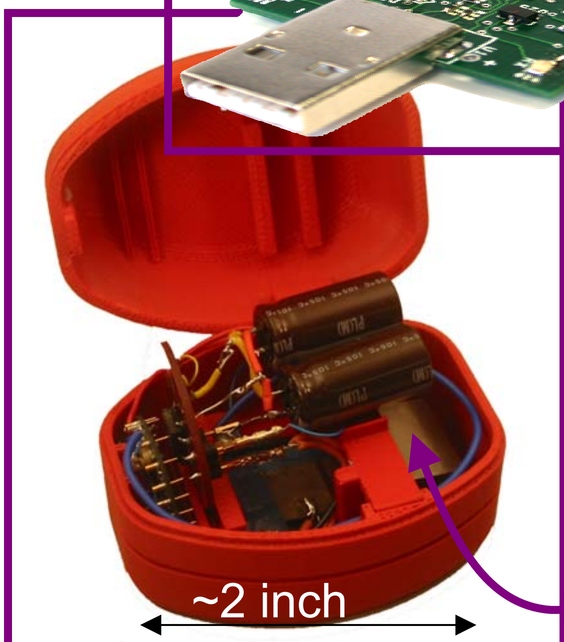
Paul Wright (Materials and Manufacturing)

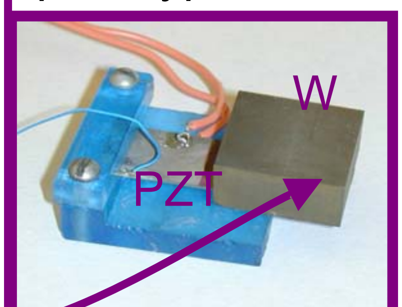
In collaboration with the multidisciplinary team of:

Edward Arens & Charlie Huizenga (Buildings),
David Auslander (Controls), David Culler (O/S),
Jan Rabaey (Radios), Richard White (Sensors)



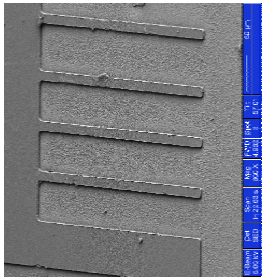


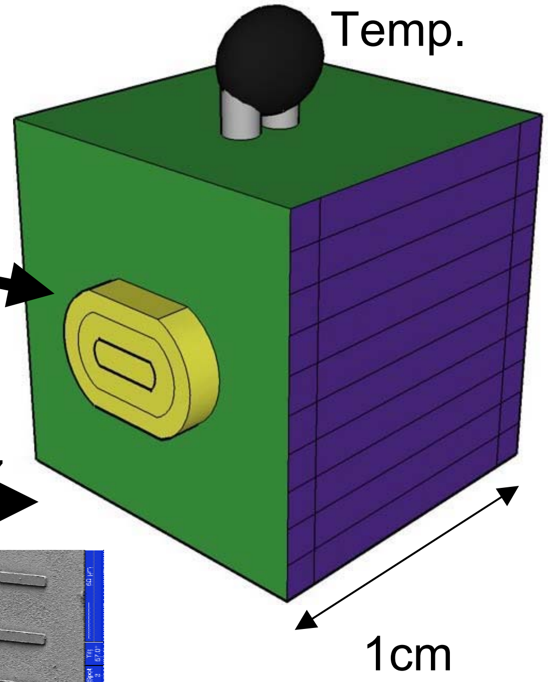




Today's prototypes

2005 2006 2007





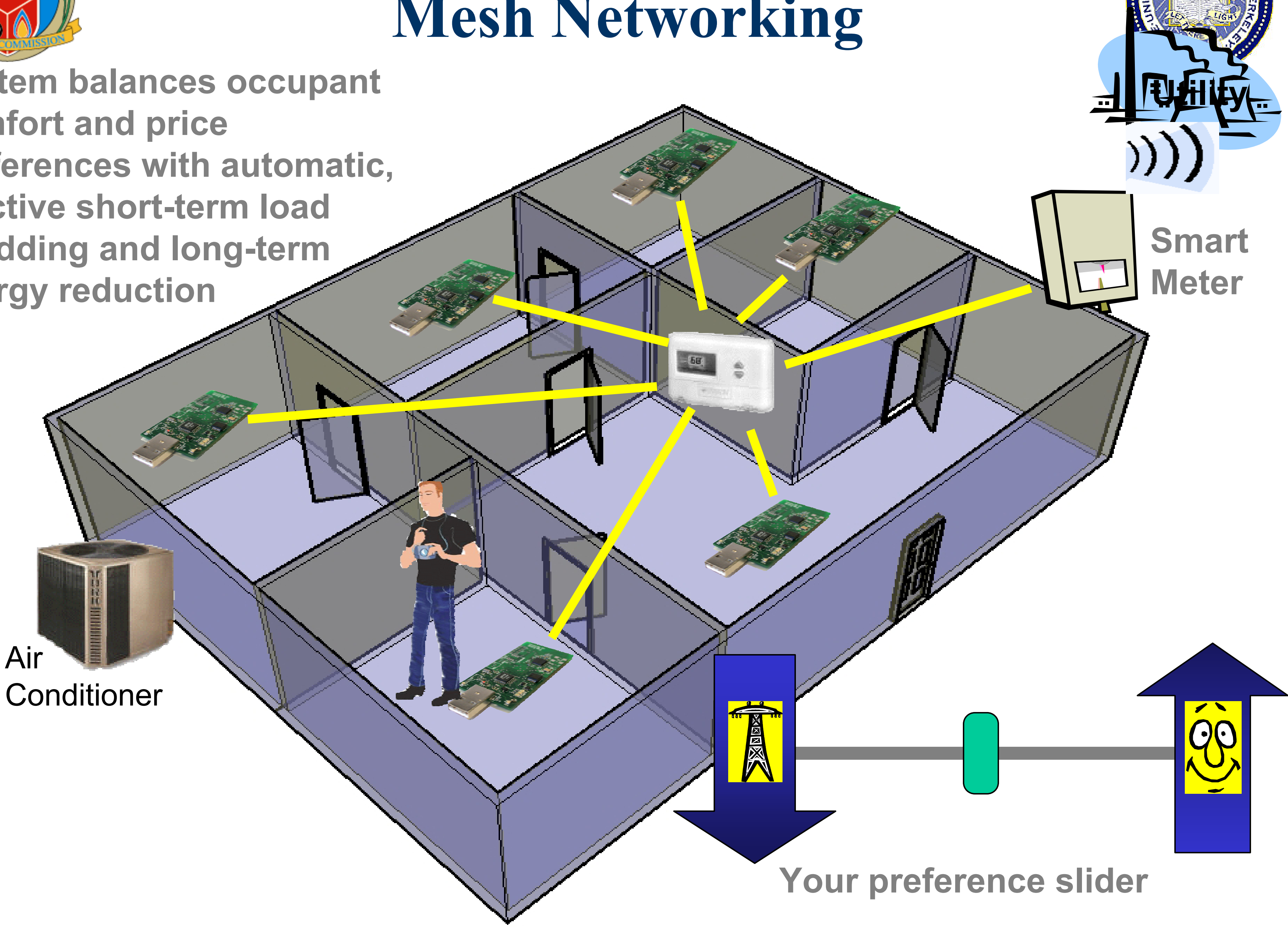
MEMS version in progress for 2007

Four Sub-Teams with a 10x10x10 mission

- **1. Communication - Pico Radio & TinyOS for networking of devices**
  - Low-power and low-cost radio platforms, supported by appropriate operating systems, for ad hoc sensor and actuator network applications.
- **2. Controls - Applications on a prototype of New Thermostat**
  - Easy-to-use “thermostat” that can act as an automatic proxy to optimize energy savings versus comfort under varying energy price conditions.
- **3. Sensors - Relation to New Meter (Voltage/Current)**
  - Low-cost wireless, passive and non-intrusive current and voltage sensing for application to the next generation meter and other devices.
- **4. Power Supply - Energy Scavenging (important for Temp Nodes)**
  - Infinite life power source that scavenges energy from the environment. Possible energy sources include solar, vibration, air flow, and hybrid.

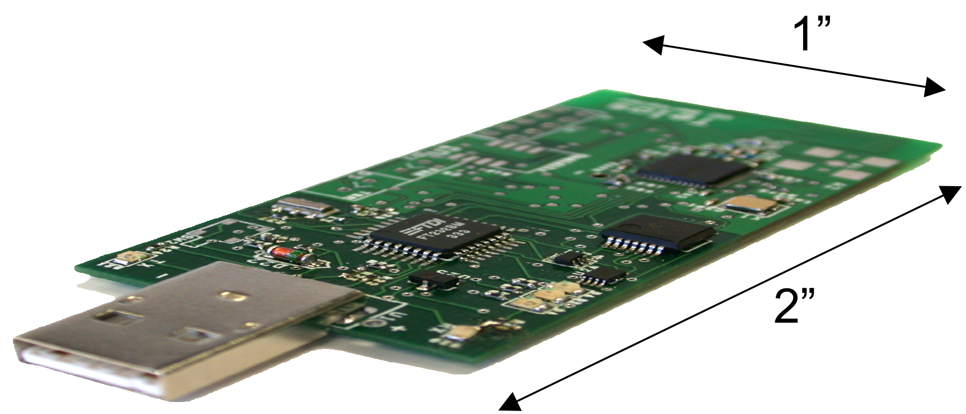
1. Communication with Mesh Networking

System balances occupant comfort and price preferences with automatic, reactive short-term load shedding and long-term energy reduction



TinyOS on Nodes (called ‘Motes’)

CPU	
Bus Speed	8 MHz
RAM	2 Kb
Program Space	60 Kb
External Flash	512 Kb
Serial Communications	DIO,SPI,I2C,UART
Current (active w/ radio on)	19 mA
Current (sleep)	2.4 μA
Voltage	2.0-3.6V
Radio	
Frequency	2400-2483 MHz
Data rate	250 kbps
Output Power	-25 to 0 dBm
Antenna	Microstrip Inverted-F
Humidity Sensor	
Humidity Accuracy	3.5% RH
Temperature Accuracy	0.5 °C
Electromechanical	
Battery	2xAA, 2/3A



Ultra Low Power Node {called ‘Telos’}

16-bit microcontroller has a sub 1mA sleep state and can rapidly wakeup from sleep in under 6ms.

Telos operates down to 1.8V to extract as much energy as possible from the battery source.

However!!
Need Much Low Power Radios

- **Why is low power necessary? - Volume is dominated by energy scavenging/storage devices**

Battery power density: 100μW/cm^3/year

Solar power density: (10μW/cm^2-10mW/cm^2)

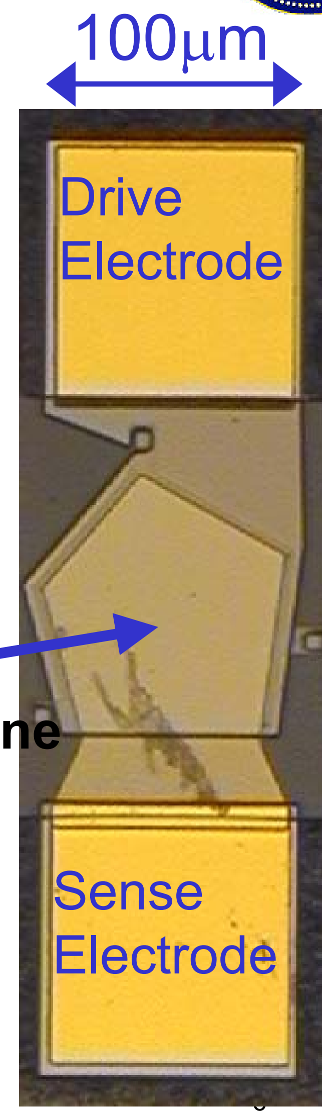
Vibrational power density: <300μW/cm^3

Power consumption determines sensor node volume.

For a 1cm^3 node, 1% DC, need $P_{transceiver}$ <1mW

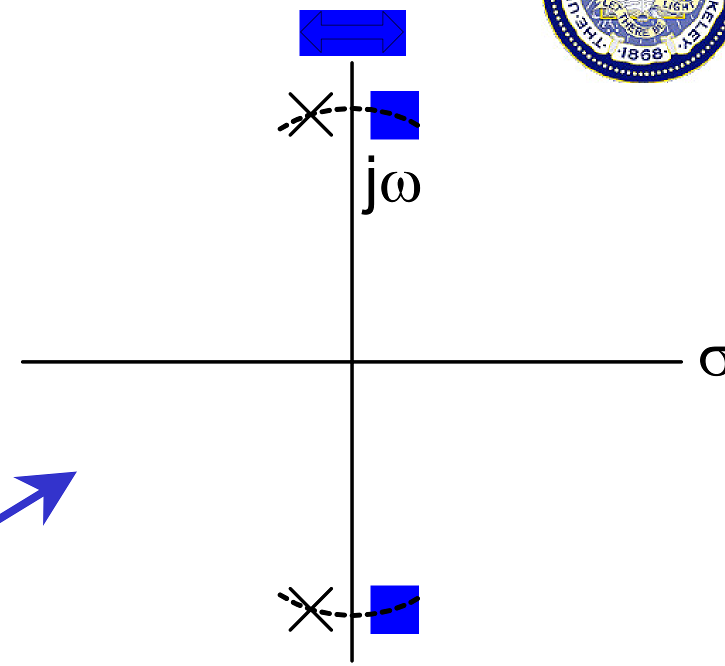
RF MEMS: A new opportunity

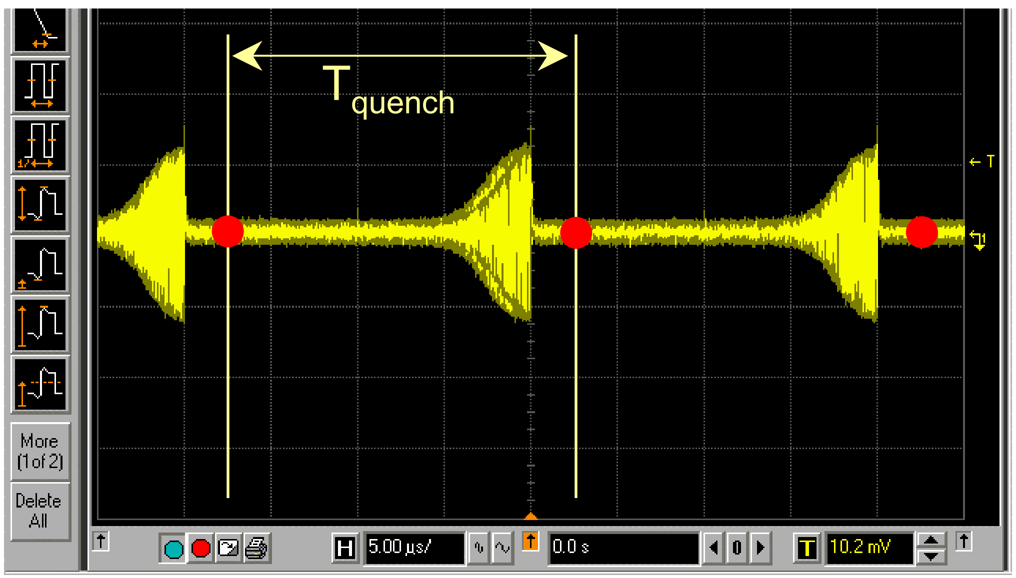
- **Substantial work in academia in RF MEMS (UC Berkeley, Michigan, etc.)**
- **Heavy industrial research in BAW resonators: (Infineon, Agilent, ST Microelectronics, etc.)**
- **Agilent FBAR resonators: building block of Tx filters and duplexers**
- **Active resonator area: AlN piezoelectric membrane. Isolation chamber bulk-micromachined under membrane**
- **Benefits:**
  - High Quality-Factor passive structures
  - Passive RF frequency reference
  - MEMS/CMOS co-design



Super-regenerative Receiver

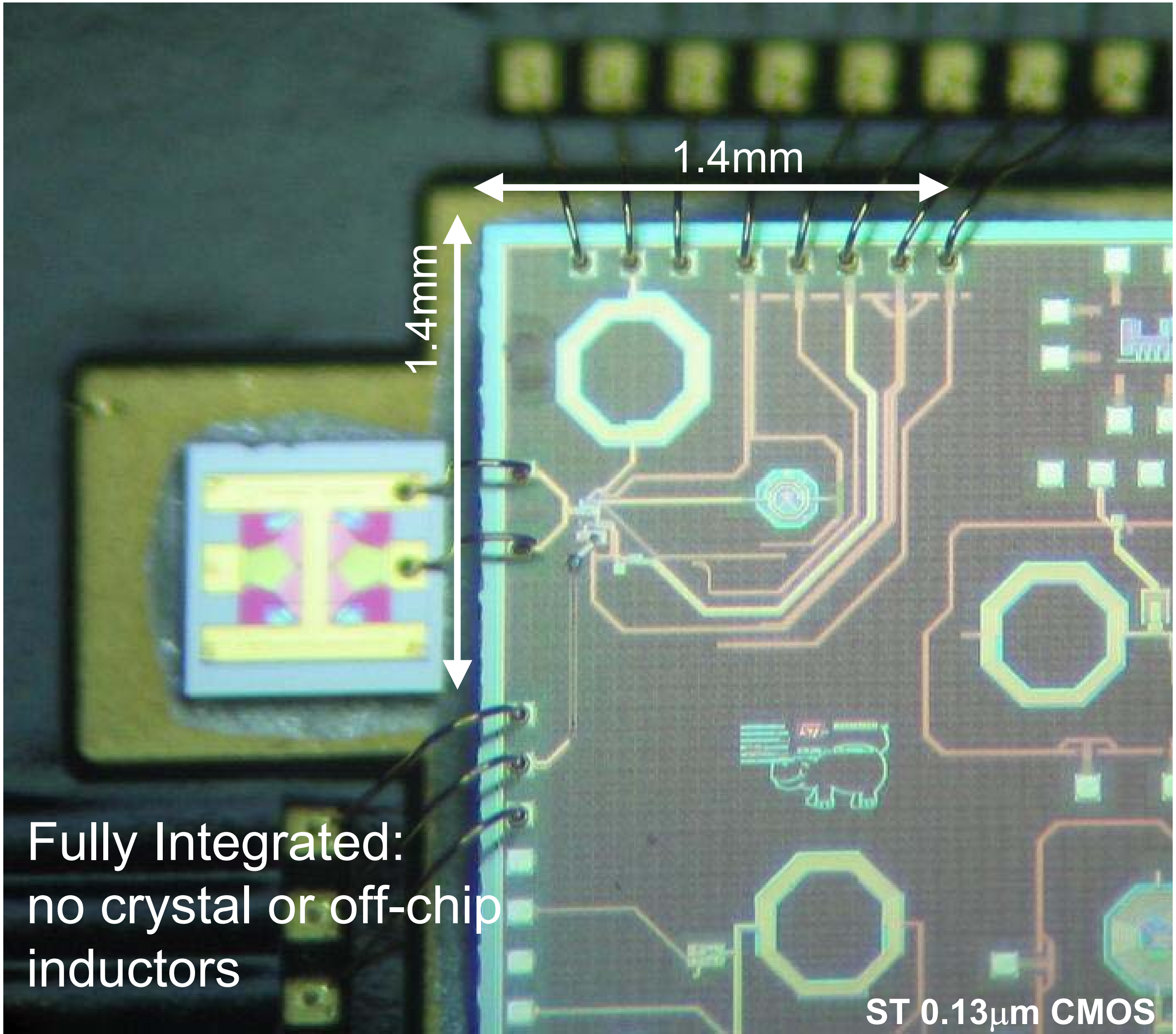
- Regenerative -- creates feedback loop around amplifier [a] between incoming frequency ~ and amplified frequency ~
- But delicate & potentially unstable so …
- SuperRegenerative -- Periodically start-up and quench oscillator in presence of RF signal every T_{quench}





- Sampling of input signal
- Detect area under oscillation envelope to demodulate signal

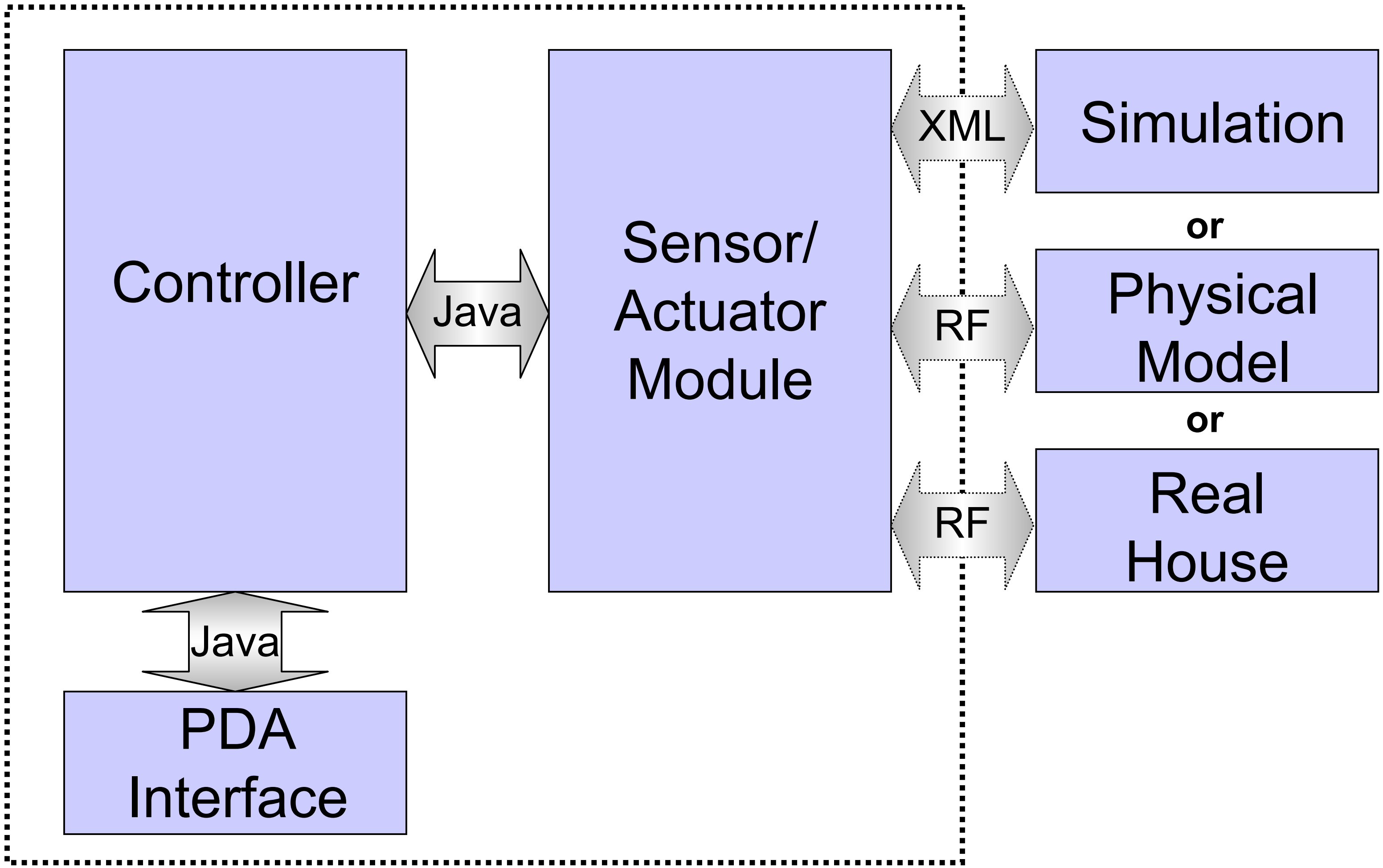
Receiver Implementation



Conclusions – SubTeam # 1

- The combination of RF MEMS/Super-regenerative CMOS architecture yields low power consumption and high integration…
- Arrays of MEMS resonators will ultimately allow simultaneous access to many bands for interference avoidance, fading immunity
- Using these techniques, a 1mW, fully integrated, 1mm^2 transceiver for wireless sensor networks is feasible and will enable much lower power ‘motes’

2. DR Thermostat and Controls Group DREAMS: Demand Response Electrical Adaptive Management System

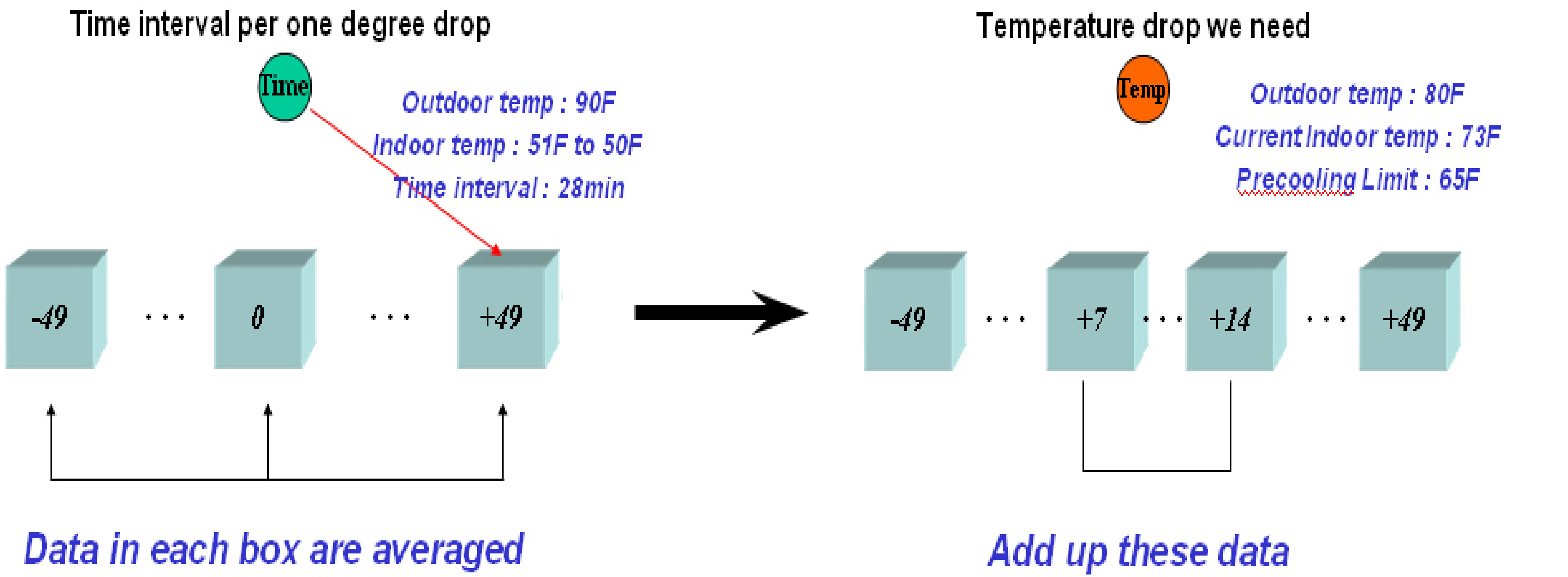


Controller (top left of previous slide)

Adaptive Precooling Strategy

Typical precooling strategies use a fixed cooling start time which can lead to overcooling or undercooling.

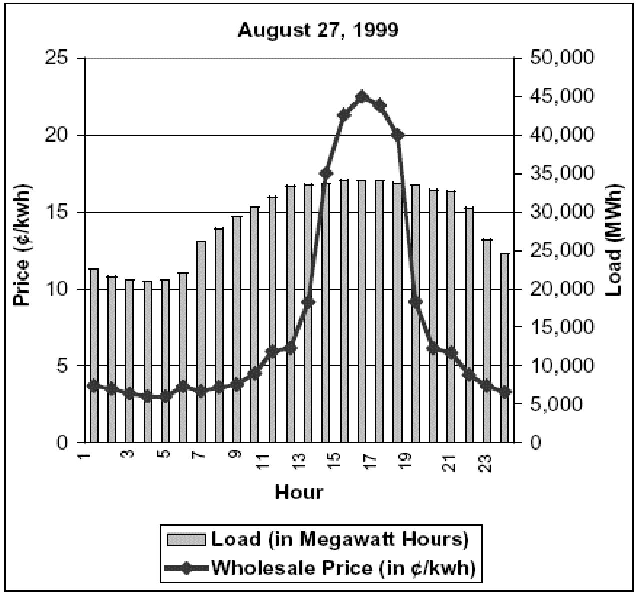
The Adaptive Controller DR precooling strategy uses a dynamic cooling starting time using a Learning Algorithm:

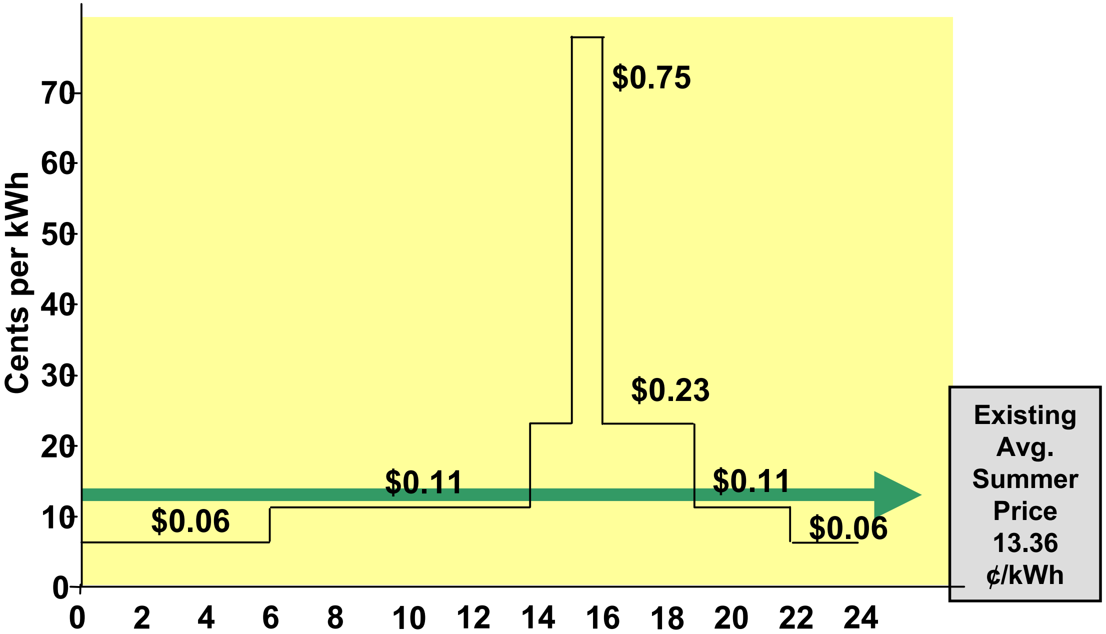


Dynamic Electrical Power Prices

Previously our inputs were rigid – E.g. price per price periods nonvariable
Next we will use dynamic prices for Thermostat control strategy

- **Price response to load, which is affected by weather and customer usage.**
- **Basic prices schedule changes with season.**
- **“Critical peak” price that can be dispatched during peak periods (high and medium price) for up to 50 hours each year, with day ahead notice.**





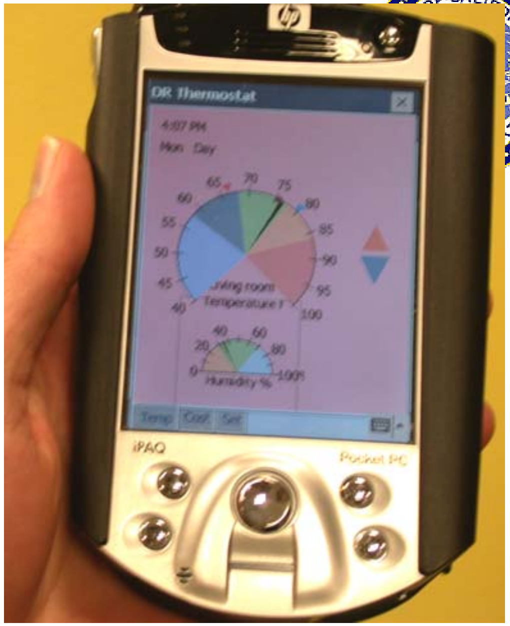
PDA InterfaceProxy

Currently Adaptive Controller runs on PDA

- Receives and displays indoor temperature for two indoor zones, outdoor temperature, and relative humidity from wireless motes
- Displays energy usage of loads, price, cost per day and per month
- Sends actuation signal to fan or “AC unit

Next steps:

- Usability testing
- Learning algorithms



Passive Proximity AC voltage and Current Sensing

Sub-Team 3: Dick White and Students EECS and BSAC

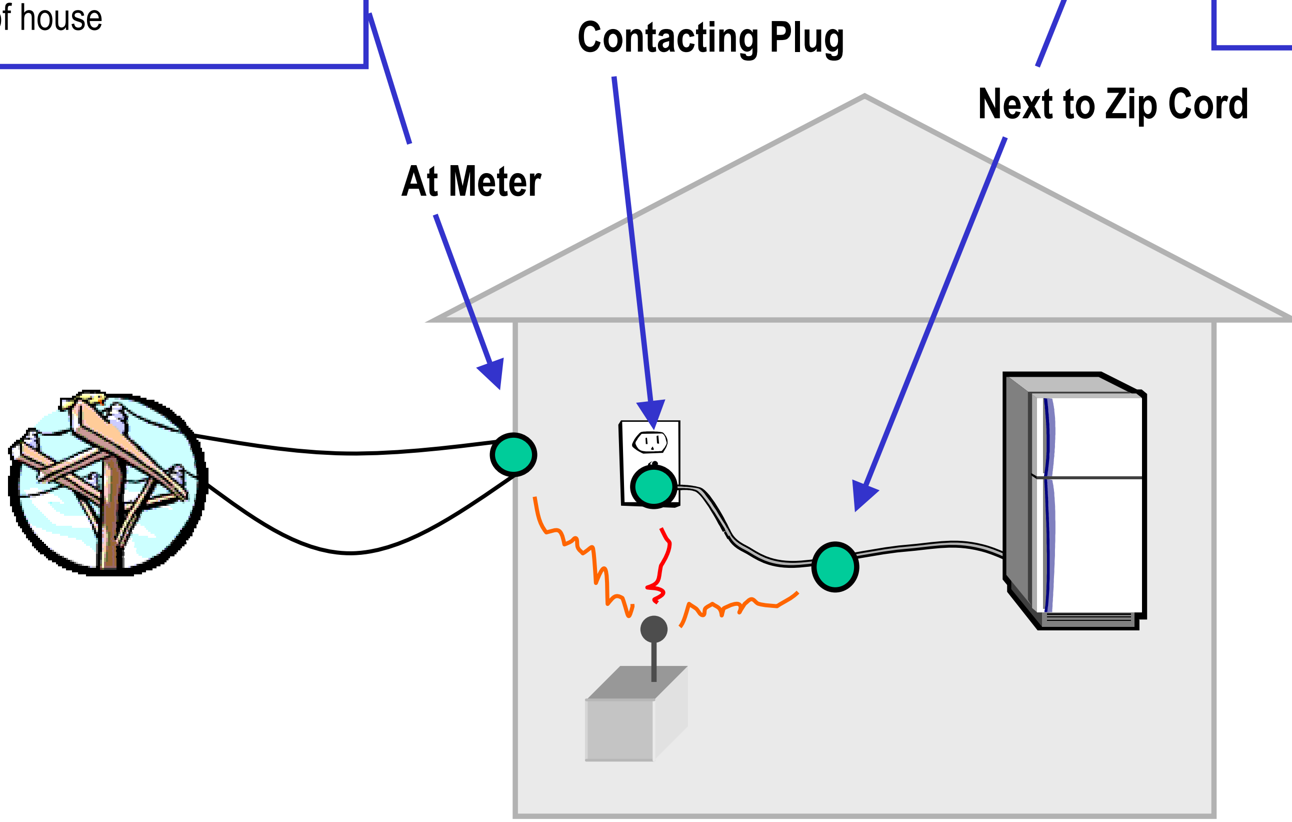
Electric Metering

Revenue Metering

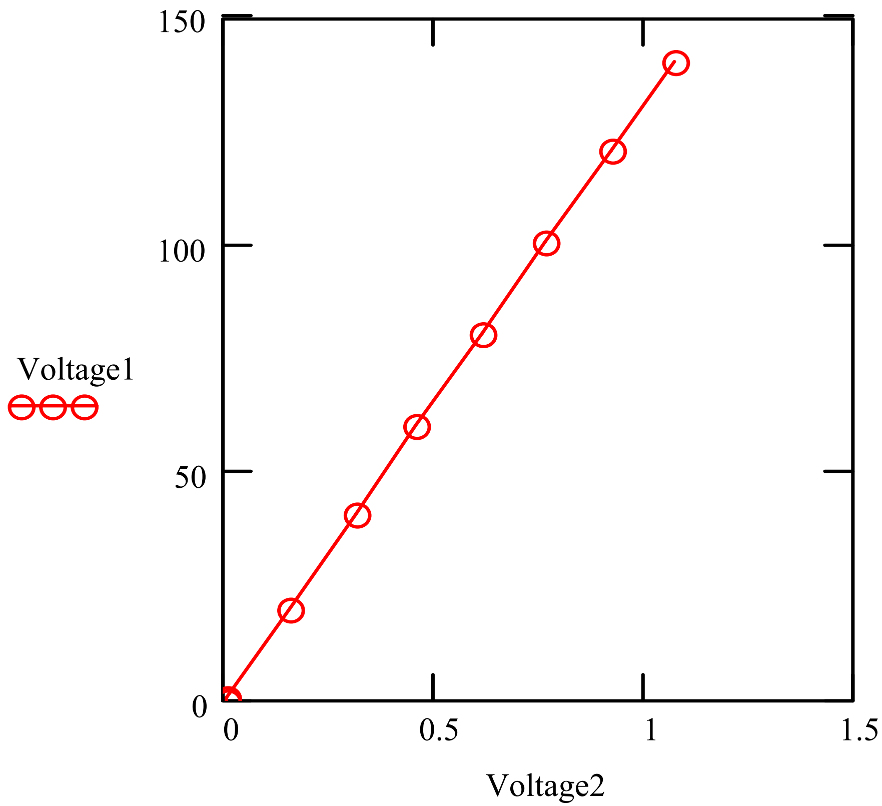
– measure power use (and time-of-use) of house

Sub-Metering

– measure and control power use and time-of-use of appliances

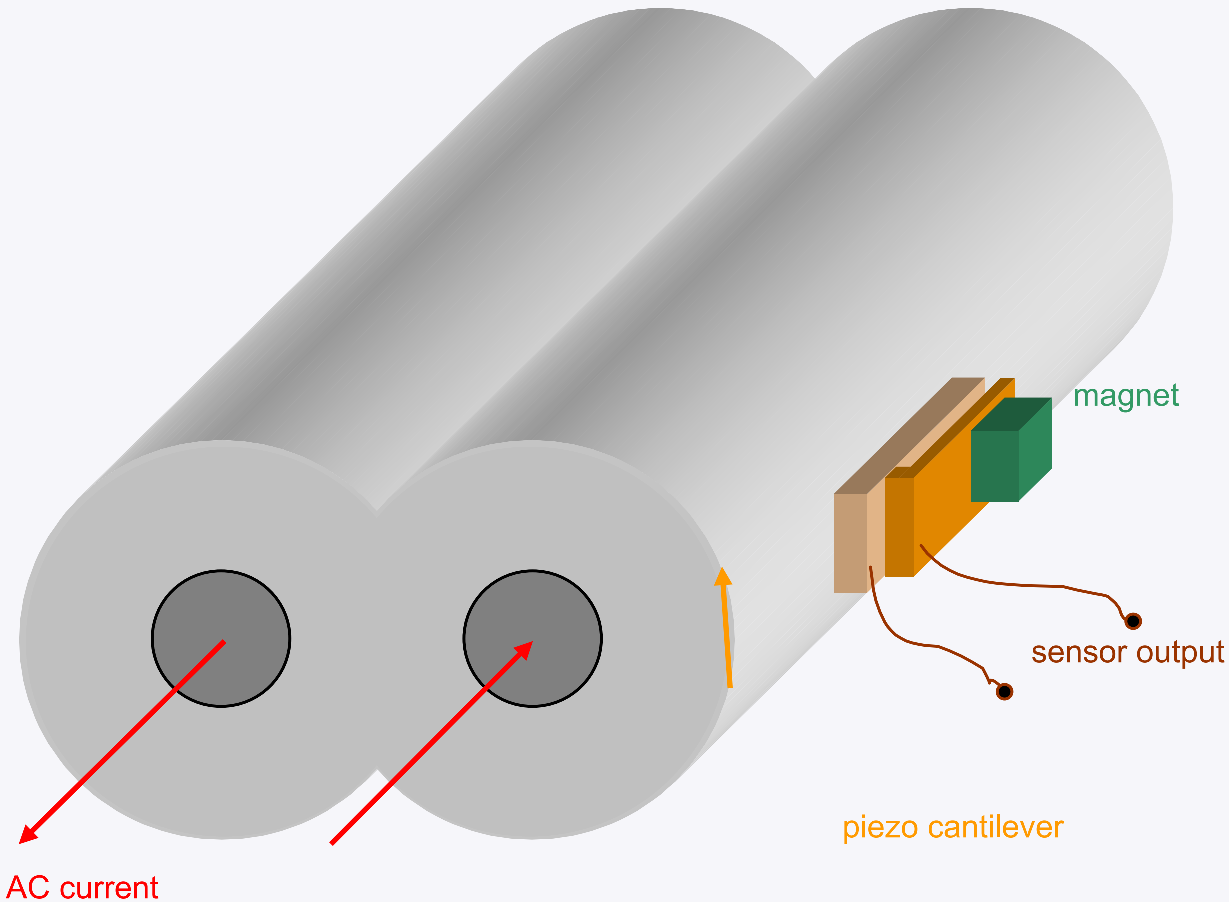


Linearity Test – Voltage Sensor



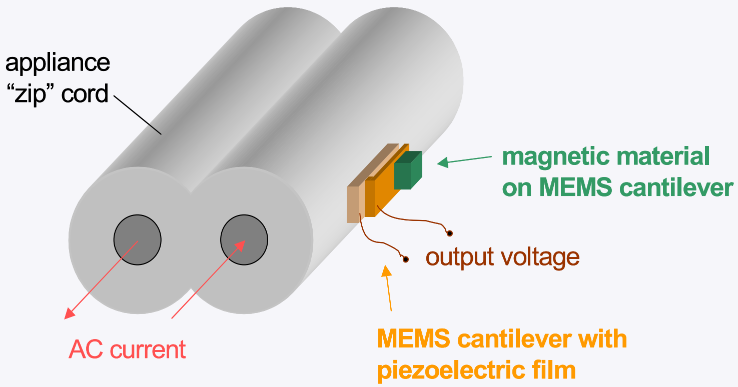
Measured on zip-cord with pickup from two 4-inch brass sleeves on insulated wires (HP 973A DMM)

Passive Proximity Measurement of AC Current



MEMS – noncontact measurement of AC currents

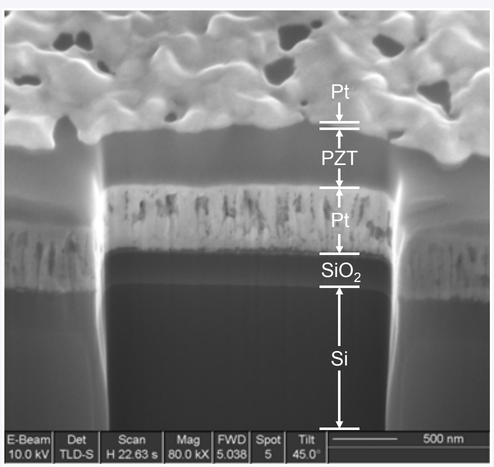
Proximity Measurement



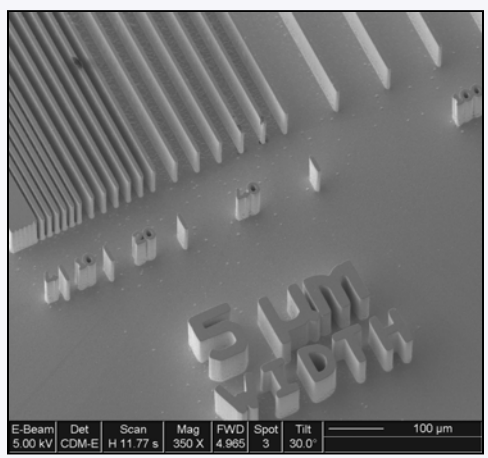
MEMS Advantage

arrays allow correction for position errors

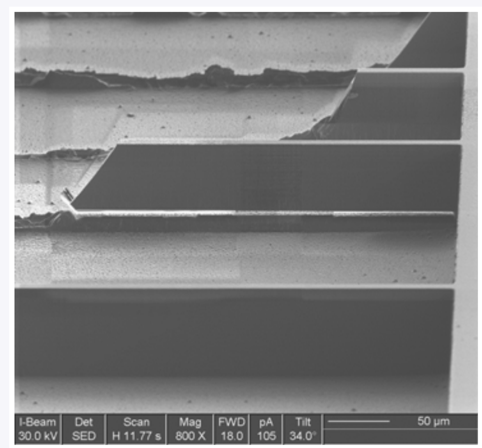
Microfab



thin films

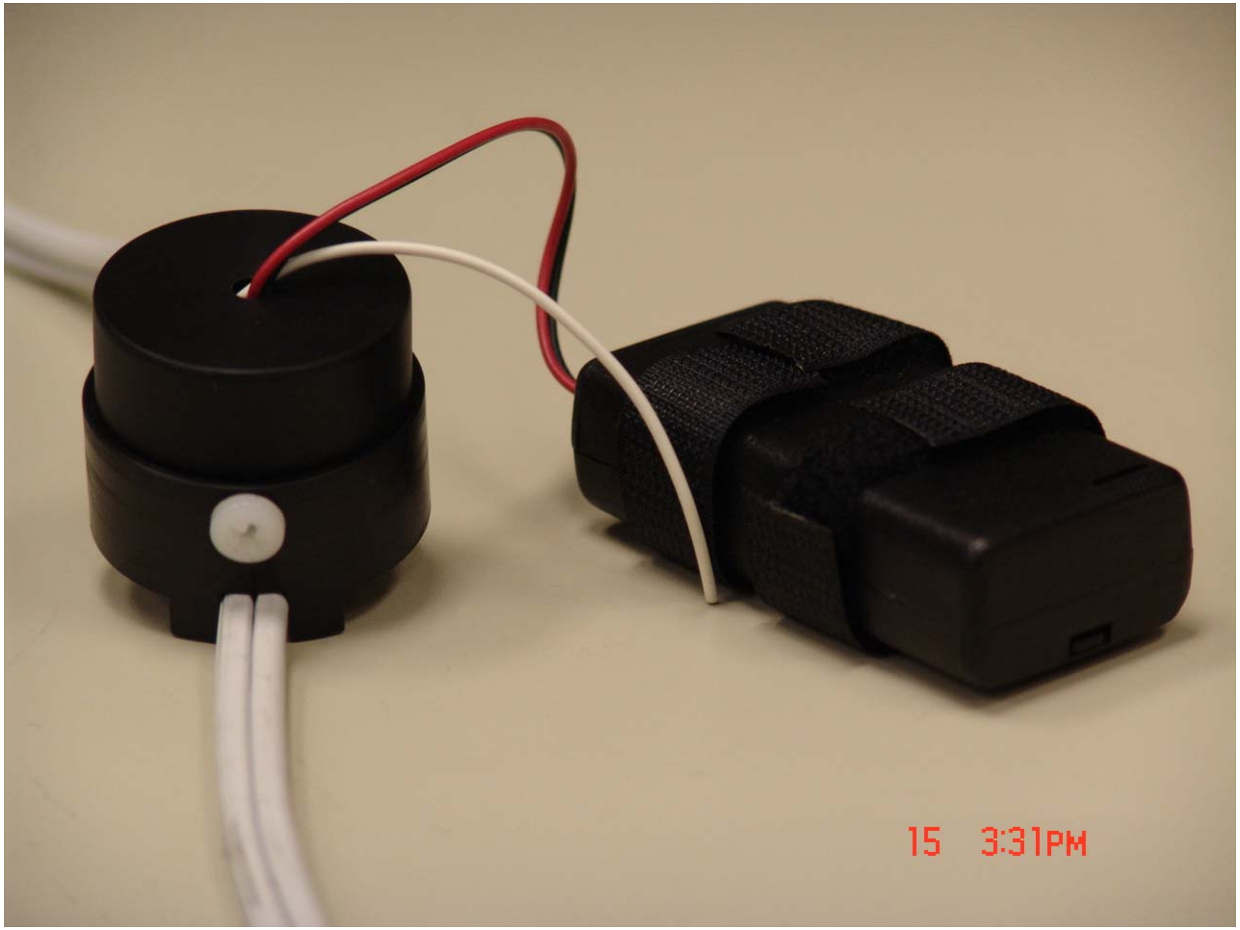


arrays of unreleased sensors



single cantilever released

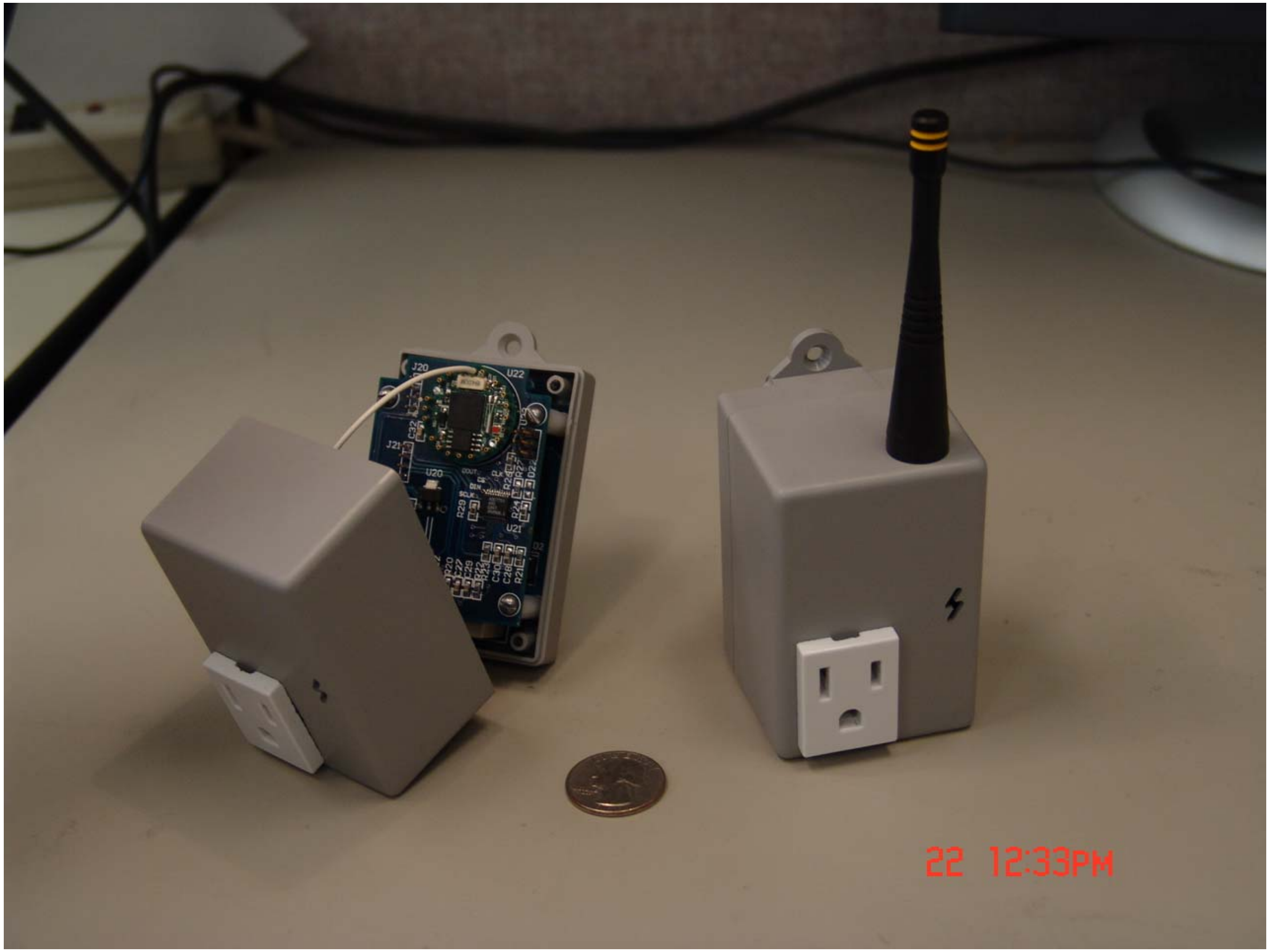
Wireless Current Sensor



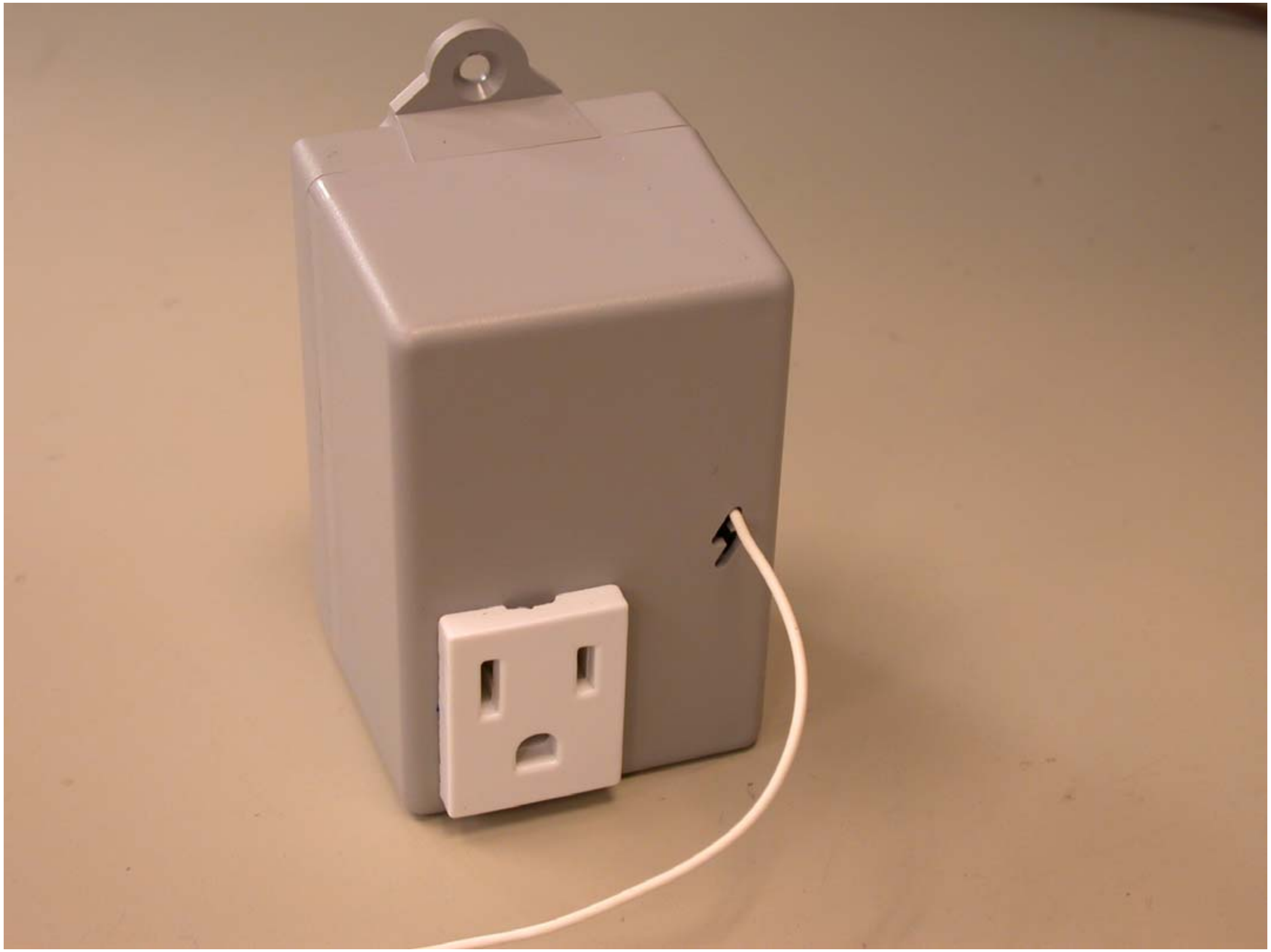
Piezo Sensor

Wireless Mote

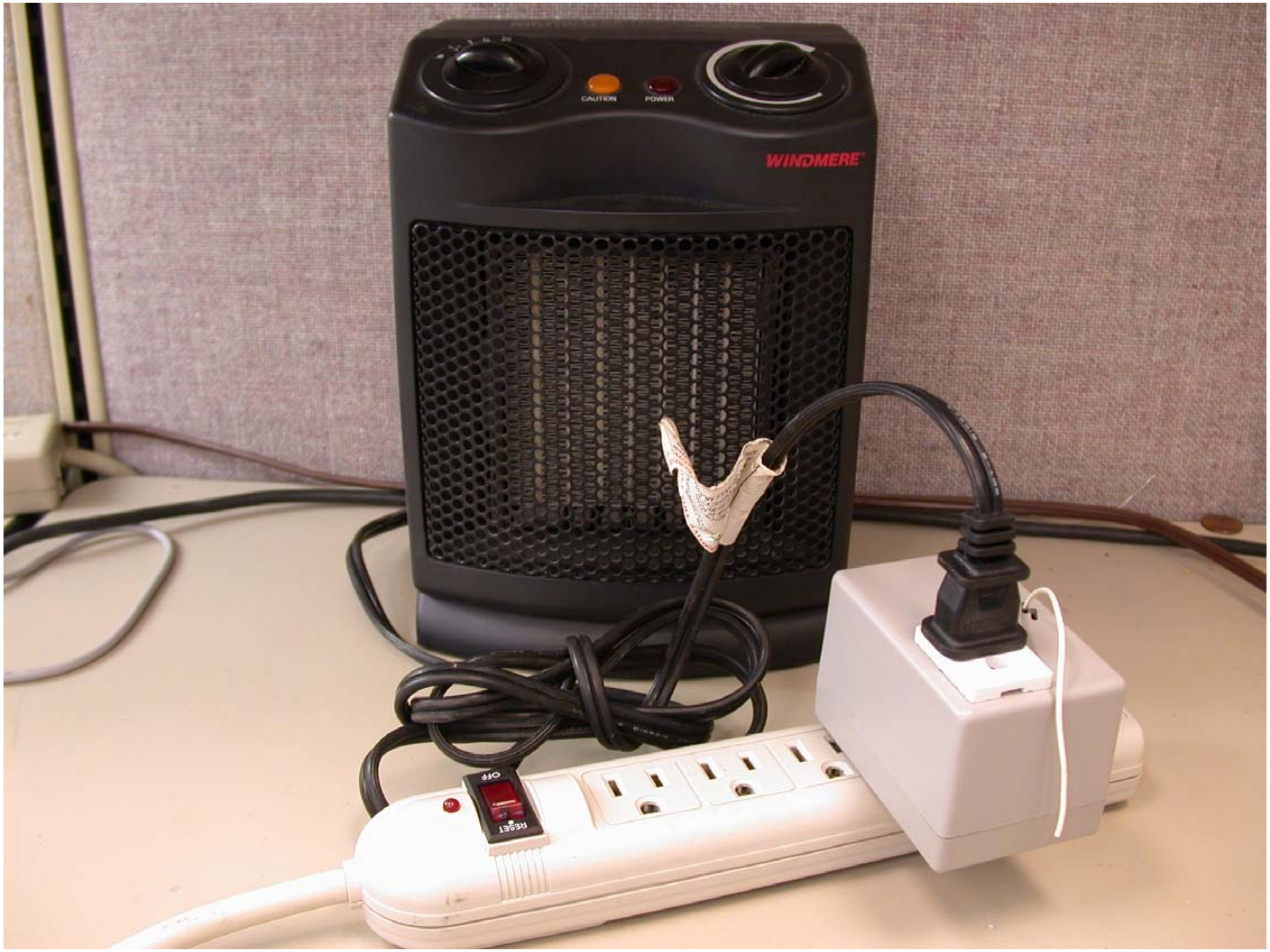
Wireless Metering Outlet



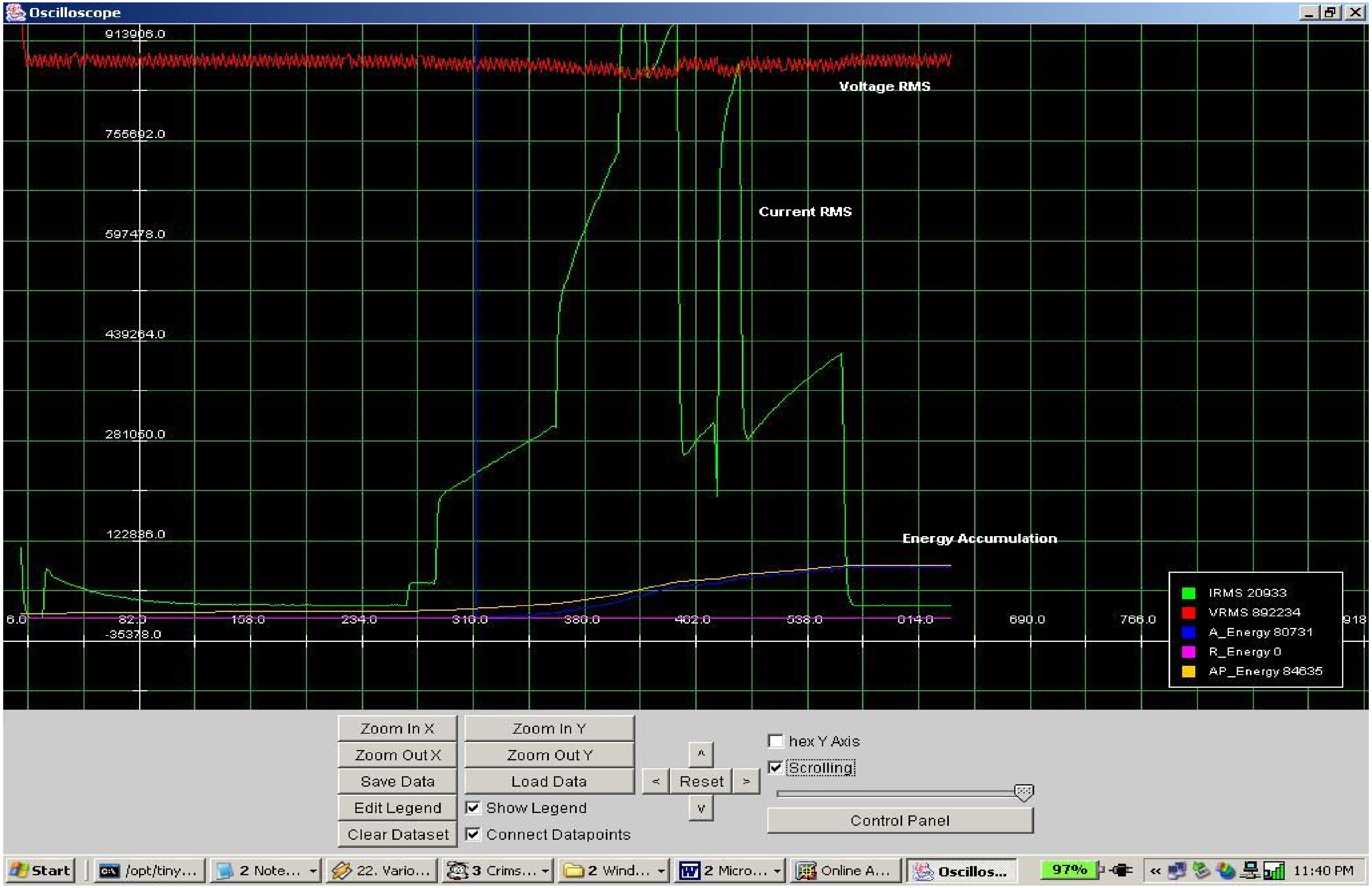
Chassis



Operation

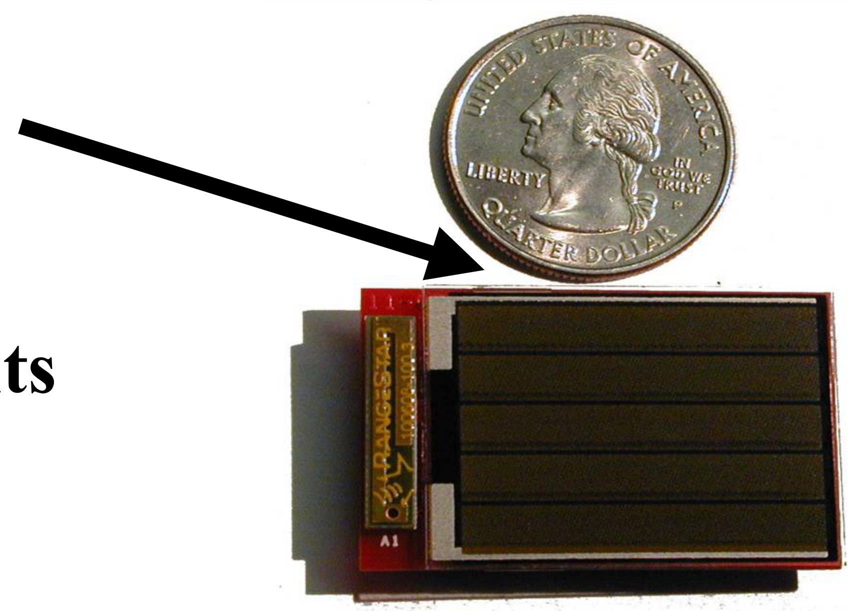


Metering Data



Sub-Team 4. Power Sources
Critical Enabling Technology to achieve "No replaceable batteries" on the nodes

- Possibilities include:-
- Photovoltaic (Solar)
- Vibrations
- Air Flow
- Temperature Gradients
- Pressure Gradients
- Human Power
    - MIT shoe-insert project
    - FreePlay wind-up products

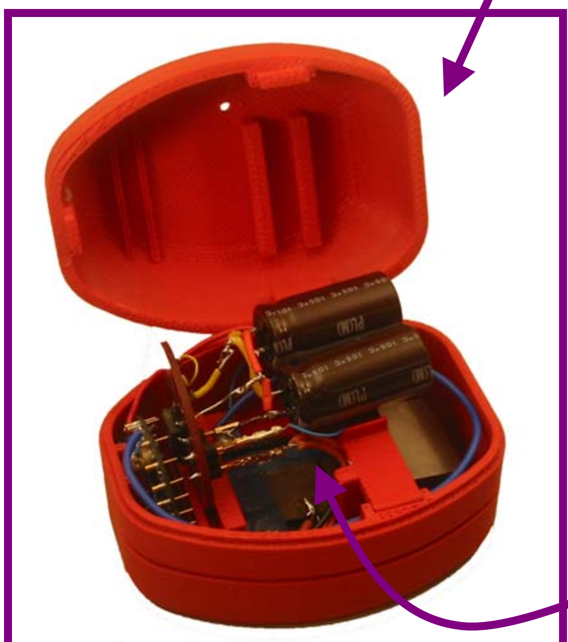


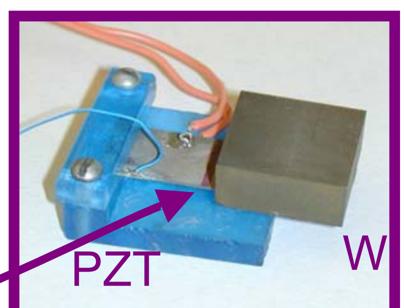
Power Sources:

Impact of 'MicroPower' on CA 'GigaPower' Challenges

Sources

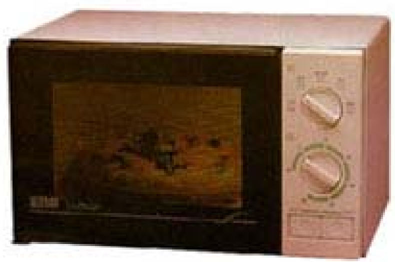
- HVAC ducts
- Raised Floors
- Motors
- Large windows
- Mount under wooden staircase





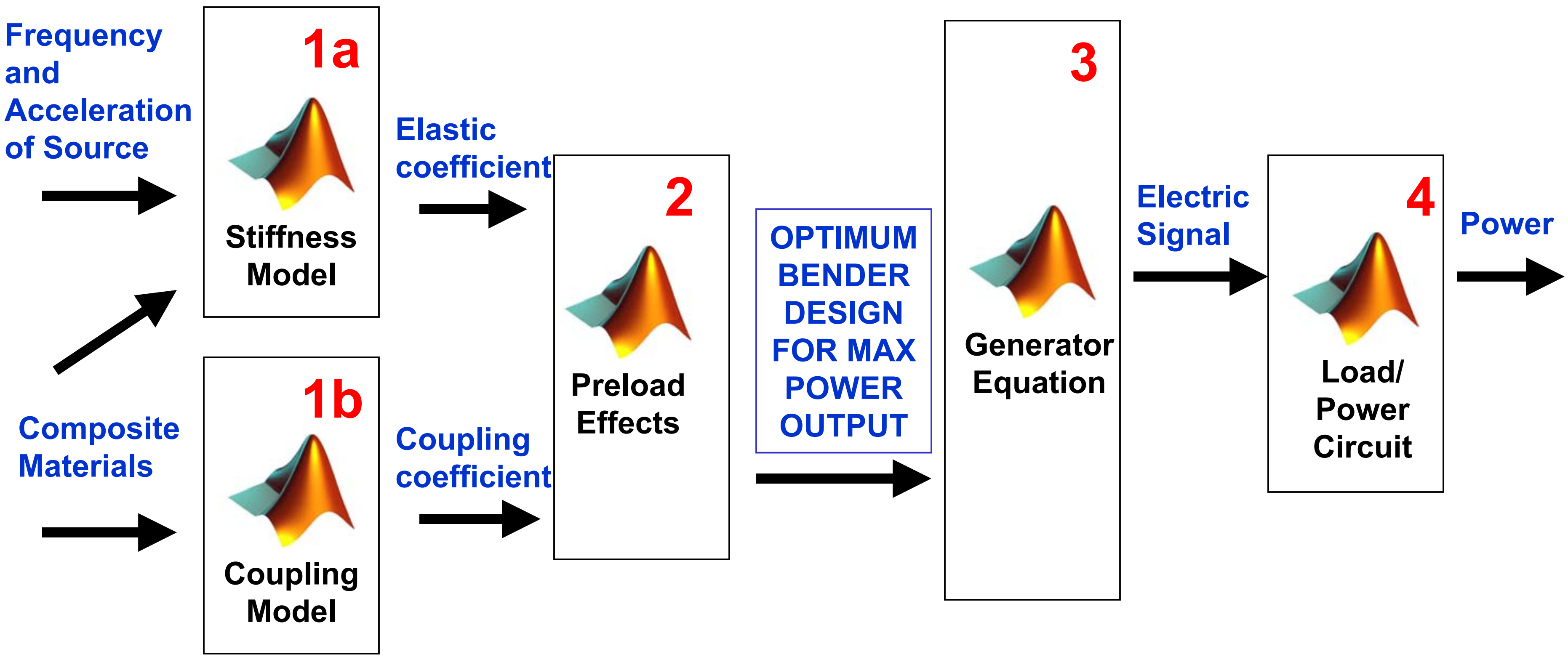
- **Three Rules for Design**
  - $P \sim M$
  - $P \sim A^2$
  - $P \sim 1/\omega$
- **PZT-shims with W-mass**
  - Early work ~ 800 $\mu W/cm^3$ at 5 m/s^2 (on a clothes dryer!)
- **Recent successes**
  - TinyTemp Node on stairs
  - MEMS piezo bender

Residential Vibration Sources



Vibration Source	Frequency of Peak (Hz)	Peak Acceleration (m/s^2)
Kitchen Blender Casing	**121**	**6.4**
Clothes Dryer	**121**	**3.5**
Door Frame (just after door closes)	**125**	**3**
Small Microwave Oven	**121**	**2.25**
HVAC Vents in Office Building	**60**	**0.2-1.5**
Wooden Deck with People Walking	**385**	**1.3**
Bread Maker	**121**	**1.03**
External Windows (size 2ftx3ft) next to a Busy Street	**100**	**0.7**
Notebook Computer while CD is Being Read	**75**	**0.6**
Washing Machine	**109**	**0.5**
Stairs leading to the Second Story of a Wood Frame Office Building	**28 to 100**	**0.2**
Refrigerator	**240**	**0.1**

DESIGN FLOW

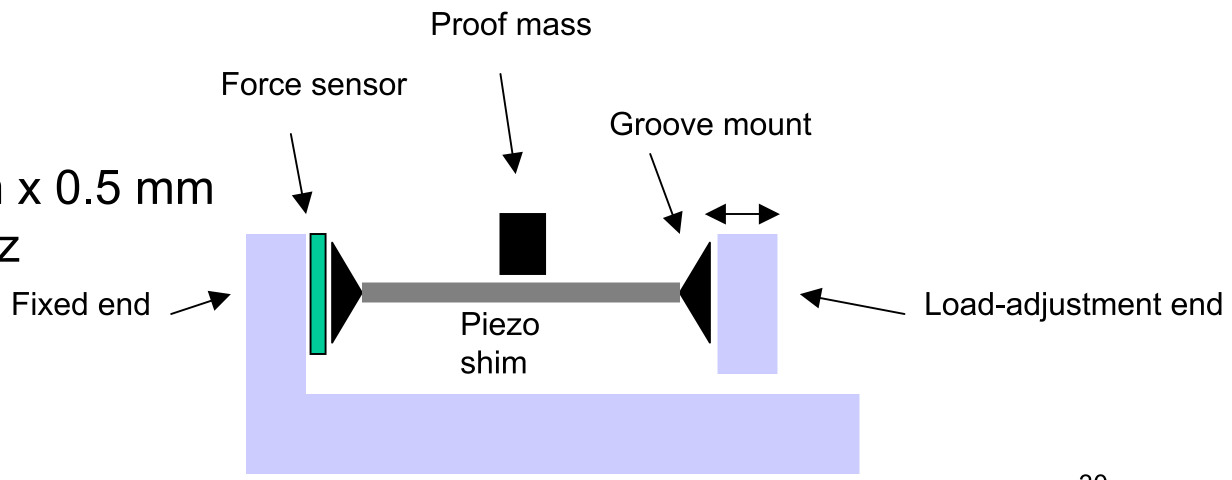


Frequency and Acceleration of Source
Composite Materials
1a
Stiffness Model
1b
Coupling Model
Elastic coefficient
Coupling coefficient
2
Preload Effects
OPTIMUM BENDER DESIGN FOR MAX POWER OUTPUT
3
Generator Equation
Electric Signal
4
Load/ Power Circuit
Power

In-progress tunable-resonance device design

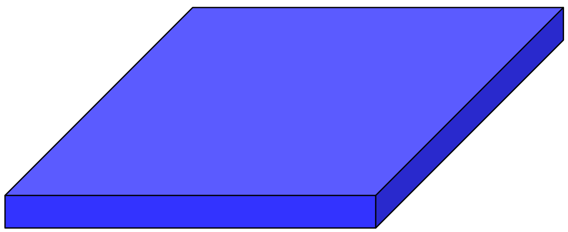
- Bracket fashioned from machined aluminum
- Load is applied by a setscrew assembly
- Proof mass is mounted using a tiny screw
- Resonance range can be adjusted by changing proof mass or shim thickness

Proof mass = 15 grams
Piezo shim = 32 mm x 13 mm x 0.5 mm
Unloaded resonance = 150 Hz



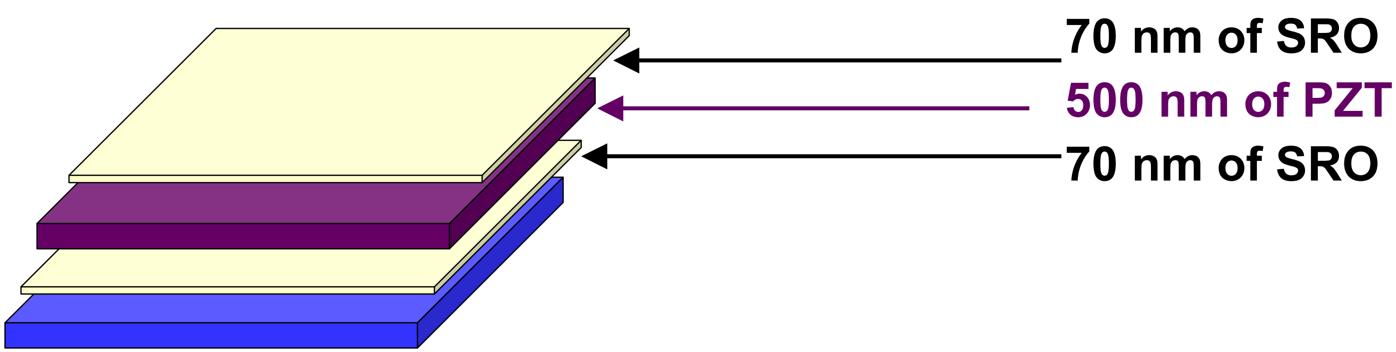
Microfabrication

- **Base layer of Si/STO ($SrTiO_3$) provided by Motorola**



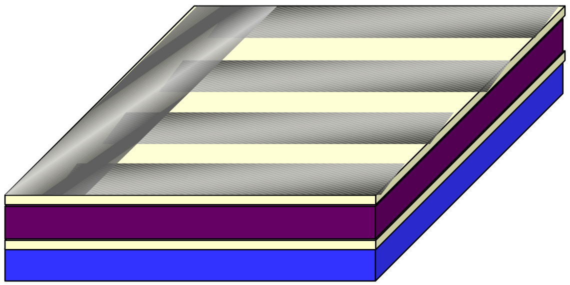
- Si provides ease of fabrication
- STO enables epitaxial growth

- **SRO ($StRuO_3$) PZT ($Pb_{1.15}Zr_{0.53}Ti_{0.47}O_3$) deposited via PLD**



Base layer (Silicon Wafer with $SrTiO_3$)

Deposition and patterning



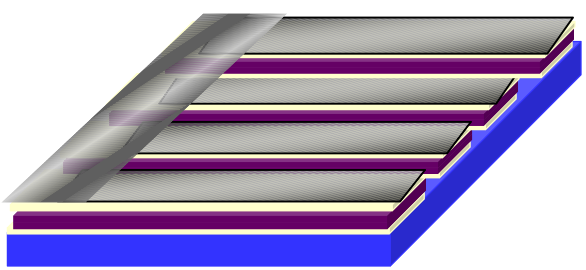
Edwards electron beam evaporator

* Ti: 10-15 nm (for adhesion purposes)

* Pt: 150-200 nm

→ Pt thickness will be varied to function as elastic layer

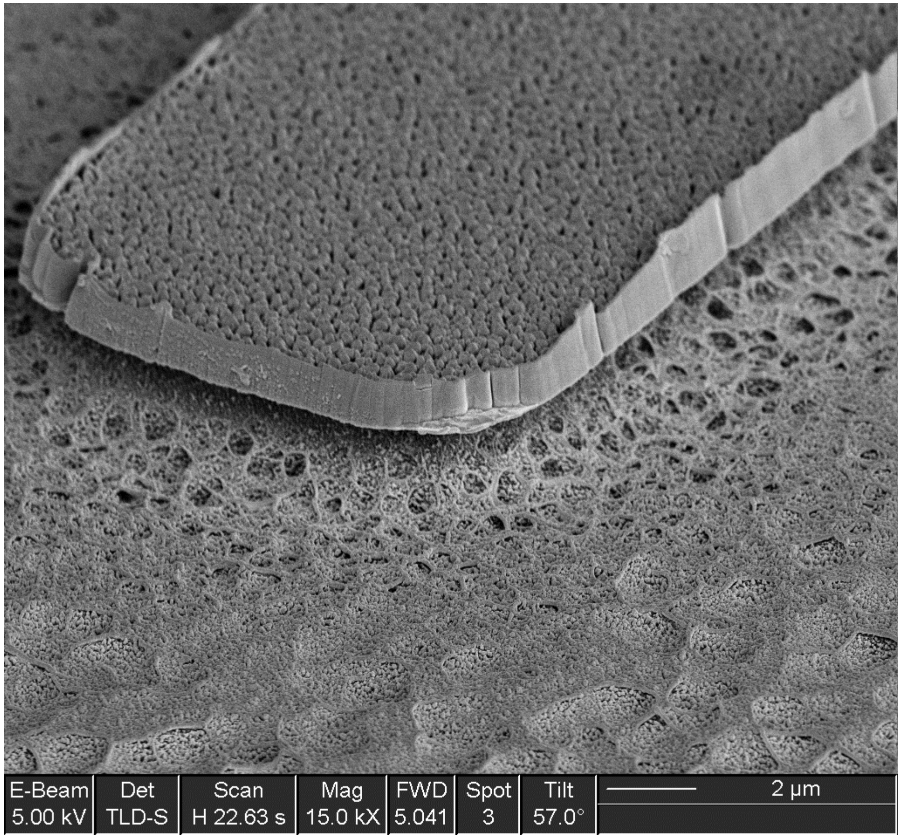
- **Initial etching**



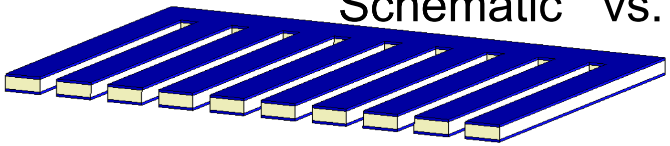
Ar Ion mill

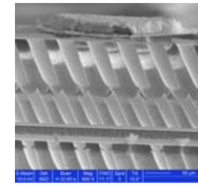
* 5 nm/min @ 0.25 mA

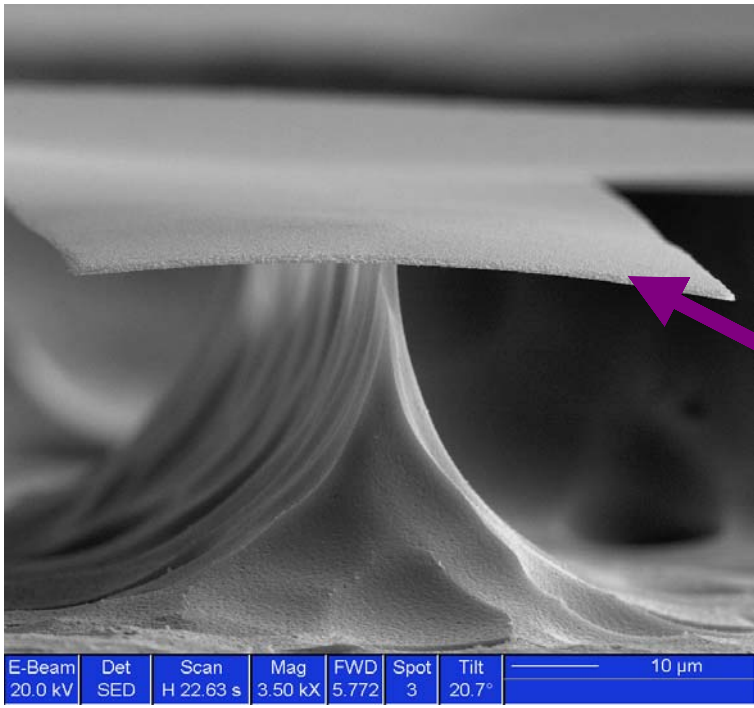
Just starting to be etched…



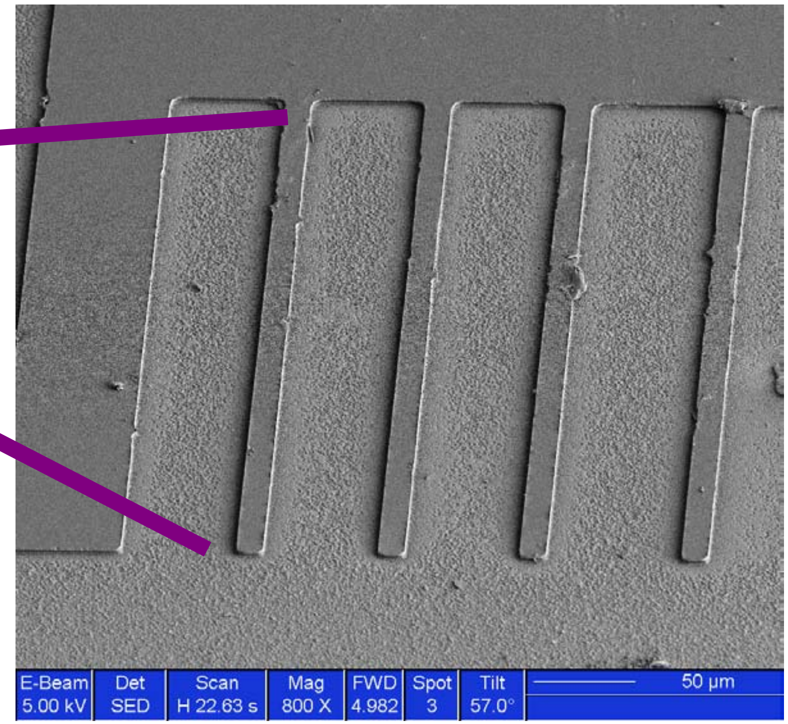
Schematic vs. Actual Device







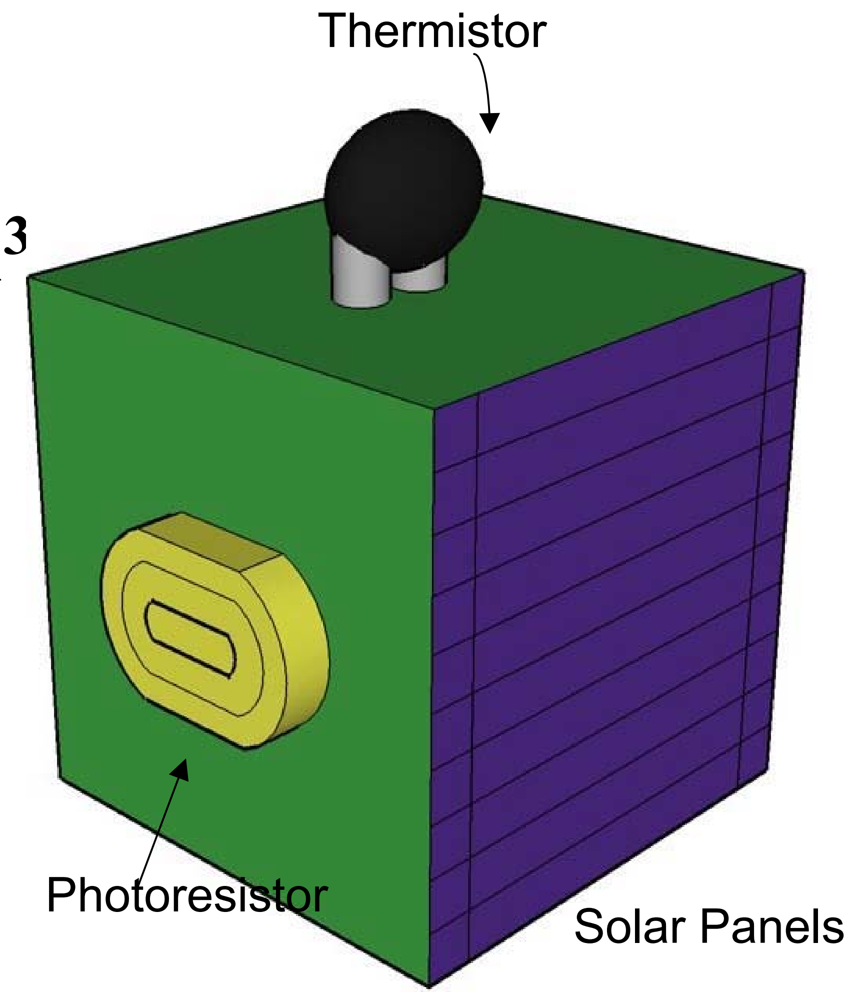
End-on view of one MEMS cantilever



View from above of MEMS cantilevers…

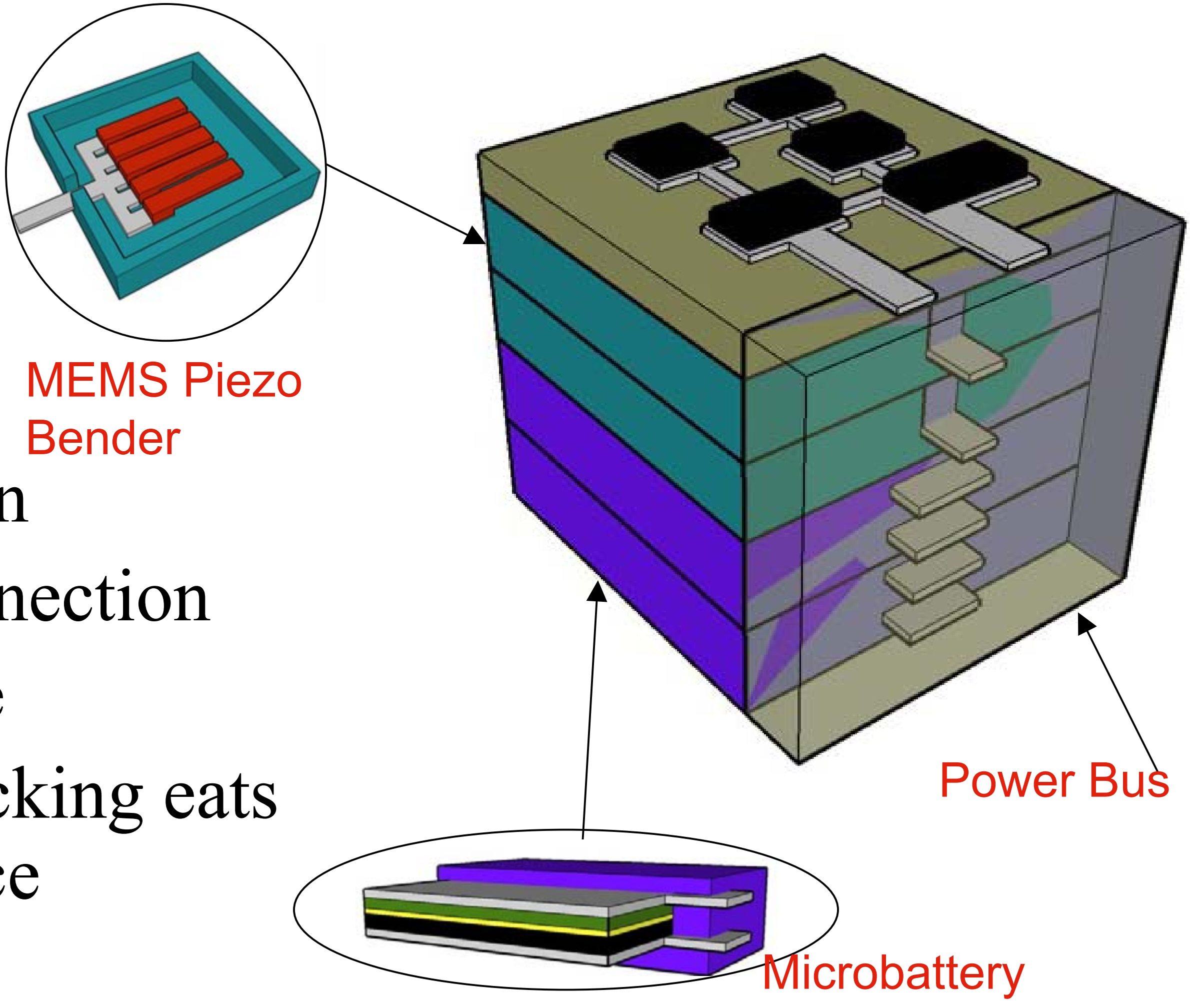
"Potential Breakthroughs"
"The PicoCube"

- **Early thinking about integrated device ~1 cm^3**
  - 3-D wiring
  - 4 sides with solar panels
  - 2 sides with sensors
  - On-board recharg. battery
  - On-board piezo electric generation



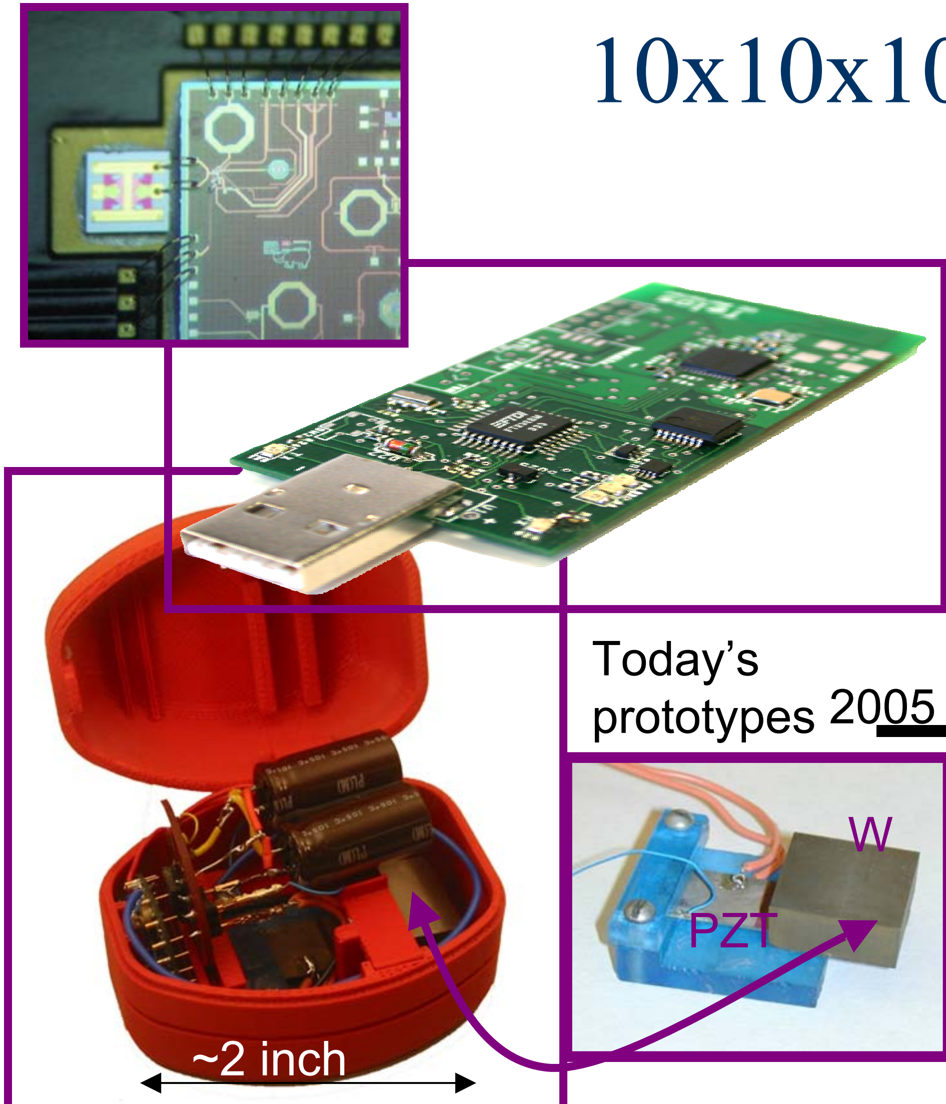
Step One

- ≥ 3 Separate Components
- 1 Bus
- Overall
  - + Modular Design
  - + Simplifies Connection
  - - Steals a surface
  - - Component packing eats significant space



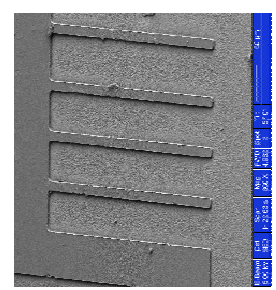
End/Summary/Questions

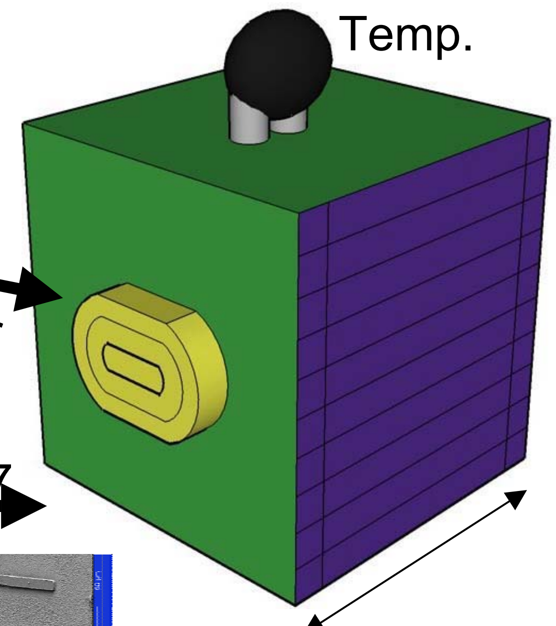
10x10x10 →



Today's
prototypes

2005 2006 2007





MEMS version in
progress for 2007