MEMS AC Current Sensor for use in DR

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Acknowledgement

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Agenda

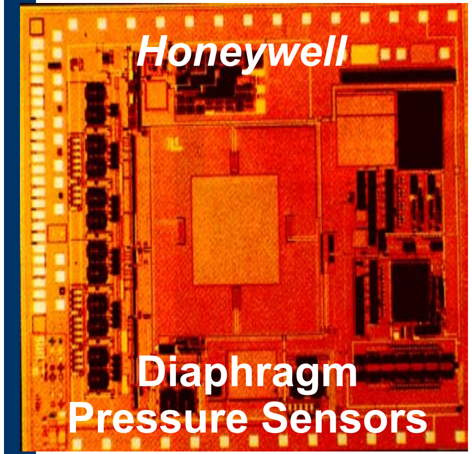
- Size domains for electric sensors
- MEMS (Micro-Electro-Mechanical Systems
- Passive, proximity-based electric sensors
- Current sensing at potentials < 600 volts
- Existing technologies
- Permanent magnets and piezoelectric materials

Size domains for electricity sensors

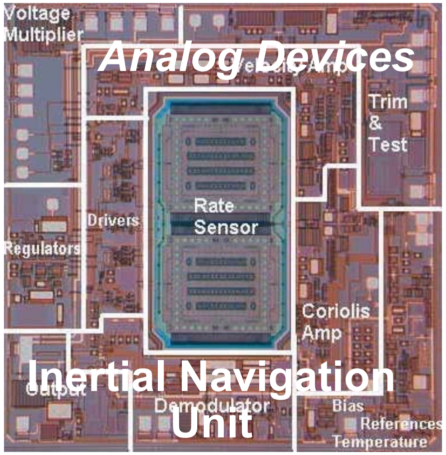
- Meter (m, little over a yard)
- Millimeter (mm, 10^{-3} meters)
  - Grain of sand = 0.2 to 2 mm diameter
- Micrometer (µm, 10^{-3} mm)
  - Human hair ~ 70-100 µm
  - Domain of electronics and MEMS
- Nanometer (nm, 10^{-3} µm)
  - Molecular bonds are tenths of nm
  - 1 Angstrom = 0.1 nm

MEMS Examples
(Dennis Polla -- DARPA

Microsensors

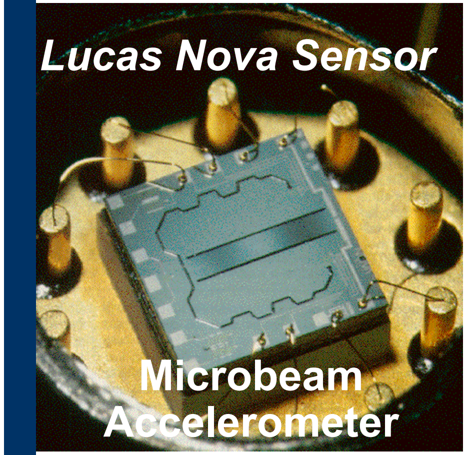

Honeywell

Diaphragm Pressure Sensors

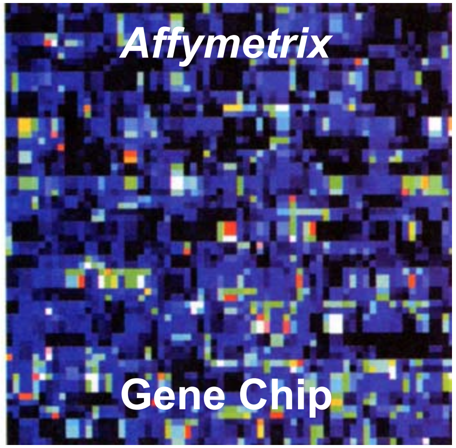


Analog Devices

Inertial Navigation Unit

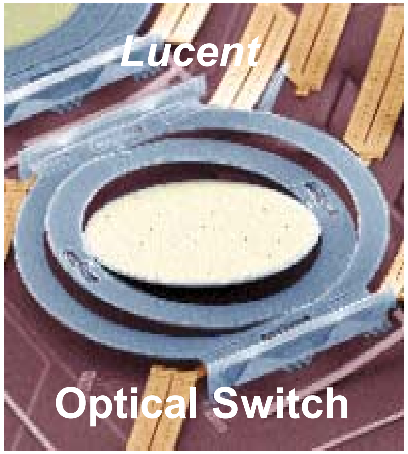

Lucas Nova Sensor

Microbeam Accelerometer

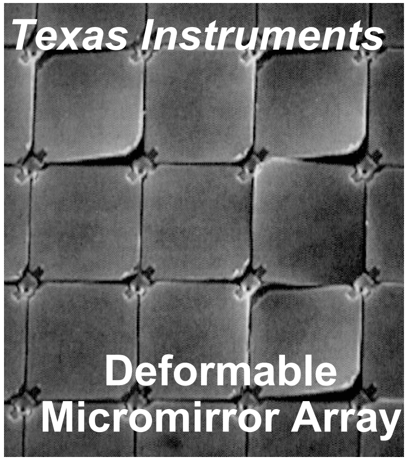

Affymetrix

Gene Chip

Microactuators

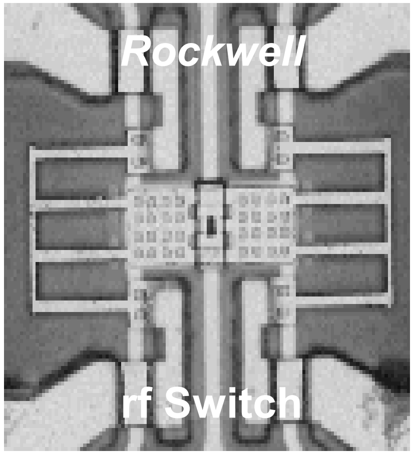

Lucent

Optical Switch


Texas Instruments

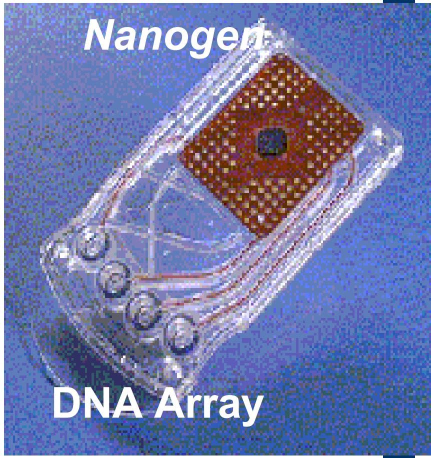
Deformable Micromirror Array

RF Electronics


Rockwell

rf Switch

Microfluidics


Nanogen

DNA Array

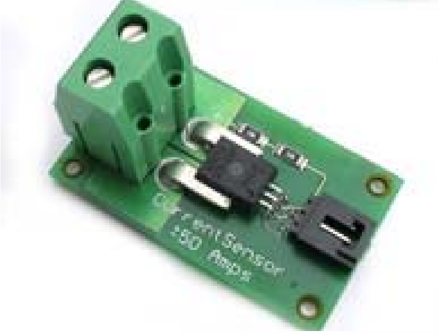
Current sensing at potentials <600 v

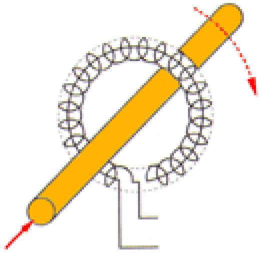
- **Design passive, proximity-based current sensors for homes and buildings**
  - Passive sensors require no external power, dramatically extend life of wireless sensor node
  - Proximity-based doesn’t require electrical connection or wraparound, doesn’t require precise alignment to conductor, potentially sensors will be integrated with CPU and radio on a single piece of silicon
- **Focus on currents in and around homes and other buildings (potentials less than 600 volts)**

Existing technologies

- **No MEMS current sensor on the market**
- **No passive (self-powered) sensor on the market that doesn't require wraparound**

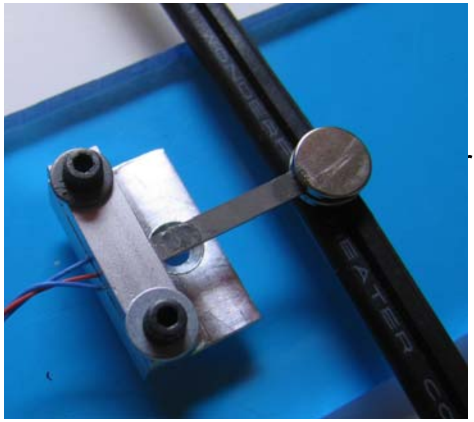
- **Kill-A-Watt™**
  - shunt resistor-based
  - in-line
- **Current Transformer**
  - self-powered
  - requires wraparound – impractical for many applications
- **Hall Sensor**
  - proximity-based
  - requires 10s of mW of power
- **Rogowski Coil**
  - voltage scales with square of linear dimension so small scales = small voltages
  - difficult to micro-fabricate a coil of many turns

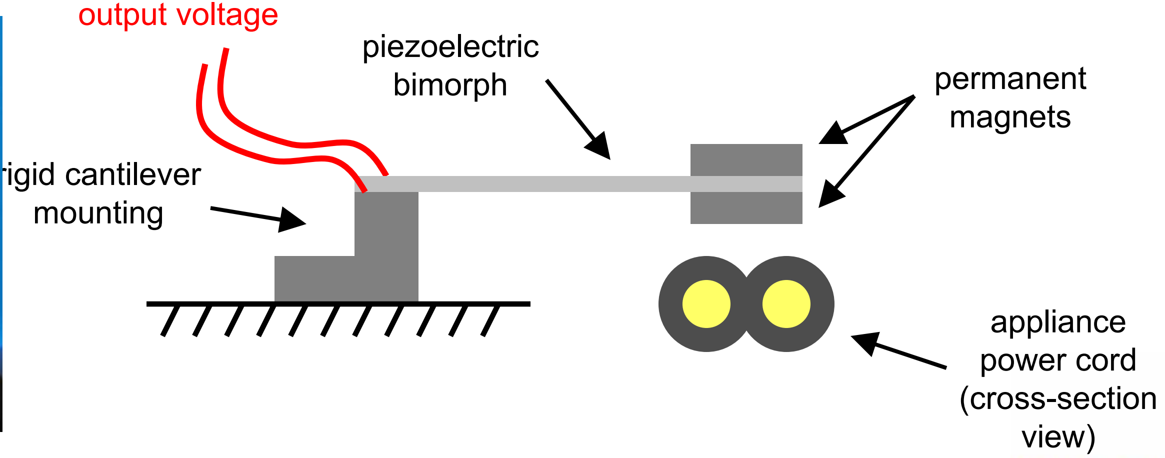




Basic Idea: Combine permanent magnet and piezoelectric materials in sensor

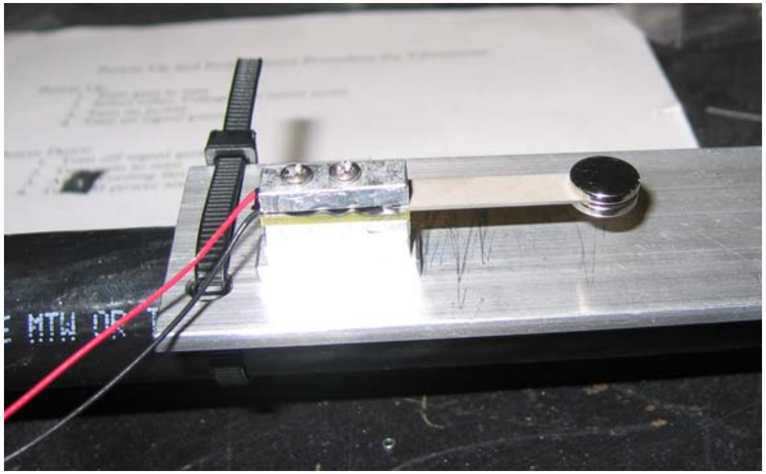
- Permanent magnets can couple to the magnetic fields surrounding AC current carriers
- Piezoelectric materials can transduce the forces on the permanent magnet to an output voltage

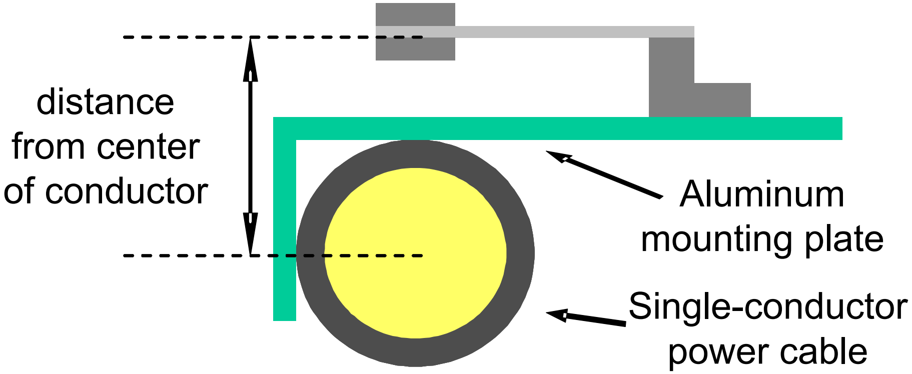




Initial mesoscale prototypes show promising behavior

Sensor mounted on a single-conductor power cable



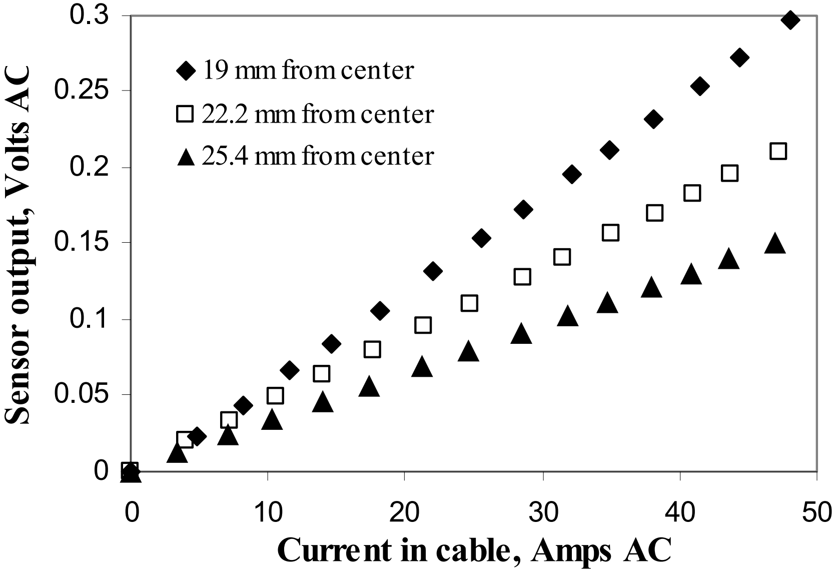


distance from center of conductor

Aluminum mounting plate

Single-conductor power cable

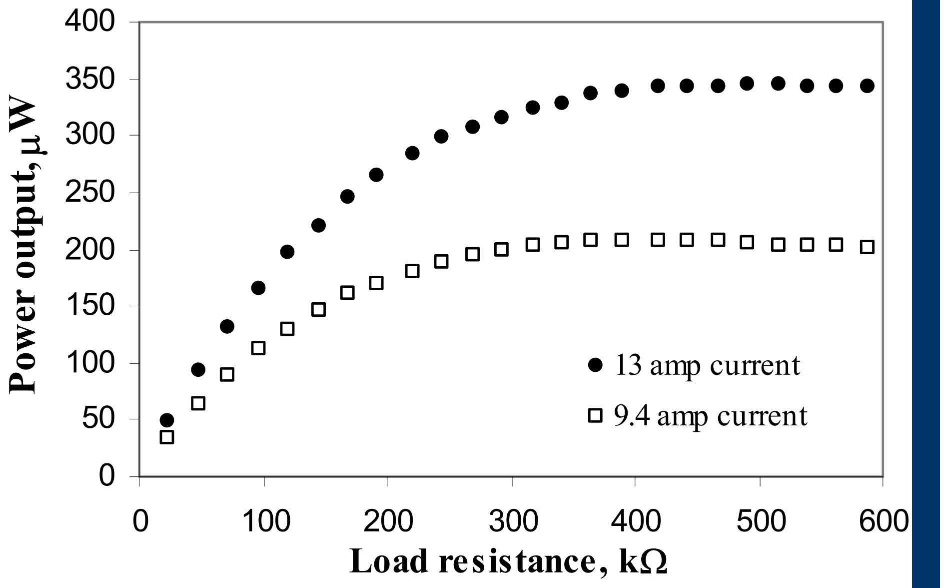
Current sensor response – varying distance from power cable



Can we power the sensor node without a battery?

- Device scavenged 350 microwatts from a standard 1500 W space heater appliance cord, sufficient to power a commercially-available wireless sensor node at a 1% duty cycle
- Tuned to 60 Hz resonance frequency for maximum coupling and power output

Energy-scavenging power output by sensor from space heater power cord



Publication:

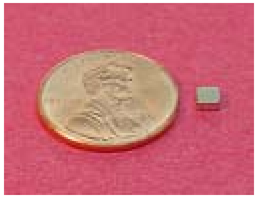
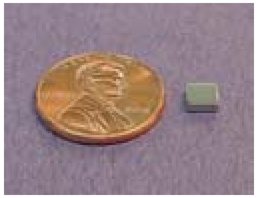
E. S. Leland, R. M. White, P. K. Wright "Energy scavenging power sources for household electrical monitoring," PowerMEMS 2006, November 29–December 1, 2006, Berkeley, California

Current sensor design questions

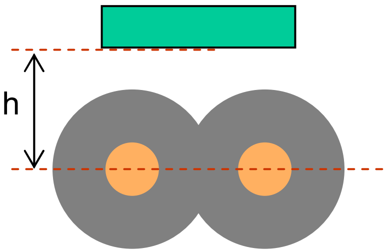
- **How sensitive will the current sensor be? (in V/A)**
  - How do I calculate the forces on a permanent magnet in a magnetic field?
  - How does force on the magnet translate to voltage out of the piezoelectric bimorph transducer?
- **How well will this sensor's performance scale downward to smaller sizes?**

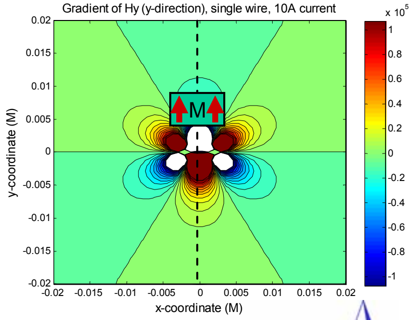
So how big are these forces?

You can feel them!

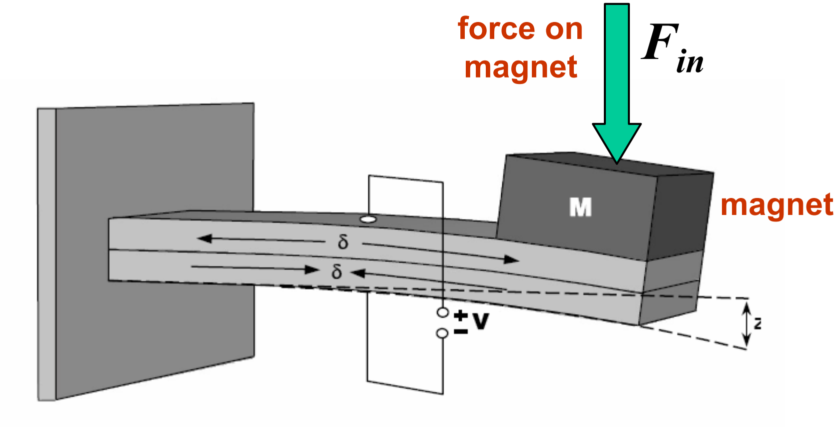
NdFeB magnets (from K & J magnetics www.kjmagnetics.com)		
Dimensions (mm)	**3.2 x 3.2 x 1.6**	**4.8 x 4.8 x 1.6**
Mass (g)	**0.12**	**0.27**
Br (T)	**1.3**	**1.35**
	MATLAB simulation results	
Force/Current (mN/A) h = 2 mm	**0.446 = 3.8 x gravity at 10 A**	**0.792 = 3 x gravity at 10 A**
Force/Current (mN/A) h = 3 mm	**0.254 = 2.2 x gravity at 10 A**	**0.468 = 1.8 x gravity at 10 A**
Force/Current (mN/A) h = 4 mm	**0.150 = 1.3 x gravity at 10 A**	**0.293 = 1.1 x gravity at 10 A**

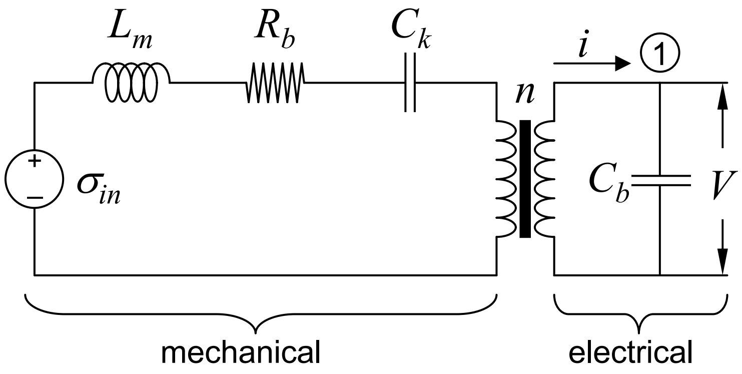
magnet centered above zip-cord





Force on the magnet generates voltage in piezoelectric element





Using electro-mechanical equivalents, applying Kirchhoff's Voltage Law to the left and Kirchhoff's Current Law to the right:

KVL:

$$T_{in} = T_m + T_b + T_k + T_t$$

$$T_{in} = L_m \ddot{S} + R_b \dot{S} + \frac{1}{C_k} S + nV$$

KCL: $i_1 = C_b \dot{V}$

To determine equations of motion, we need to find equivalent expressions for T_{in}, L_m, R_b, C_k, n, i, C_b

S. Roundy, P. Wright, "A piezoelectric vibration based generator for wireless electronics," *Smart Materials and Structures*, vol. 13 (2004) pp. 1131-1142

Simulations indicate micro-scale versions should produce measurable voltages

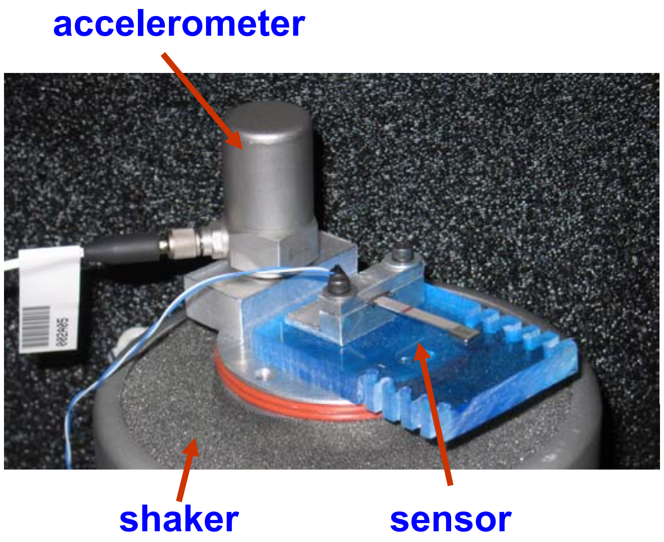
	PZT					Aluminum Nitride	
	prototype bimorph	sputtered film	1 mm PZT MEMS	500 μm MEMS	200 μm MEMS	500 μm MEMS	200 μm MEMS
cantilever l x w (μm)	**25 x 3.1 mm**	**5 x 1 mm**	**1000 x 100**	**500 x 100**	**200 x 50**	**500 x 100**	**200 x 50**
magnet l x w x t (μm)	**3.2 x 3.2 x 1.6 mm**	**1 x 1 x 1 mm**	**100 x 100 x 100**	**100 x 100 x 100**	**50 x 50 x 50**	**100 x 100 x 100**	**50 x 50 x 50**
shim thickness (μm)	**127**	**25**	**1**	**1**	**1**	**1**	**1**
shim material	**steel**	**steel**	**Pt**	**Pt**	**Pt**	**Pt**	**Pt**
resonance (Hz)	**166**	**560**	**281**	**927**	**7760**	**1140**	**9560**
sensitivity (mV/A)	74.6	12.5	1.91	0.911	0.0921	**10.6**	**1.08**

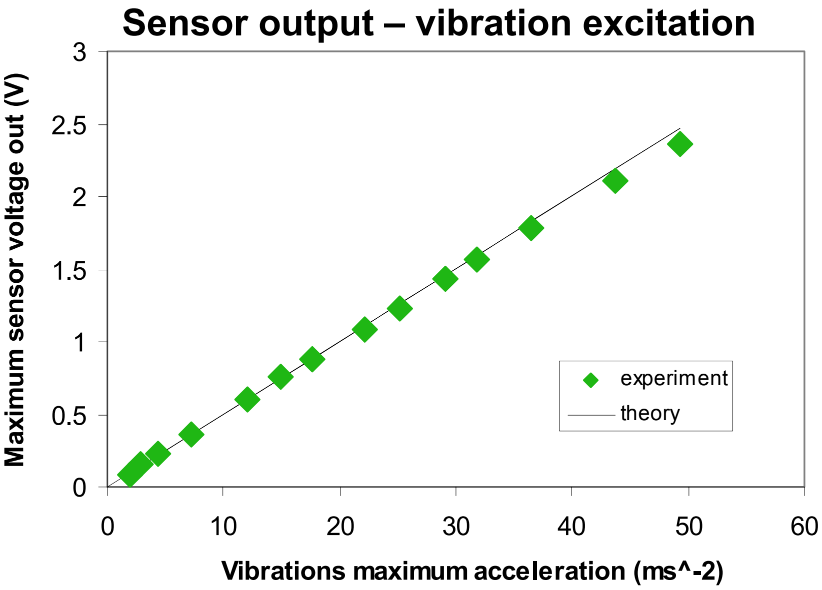
With sensitivities 10x those of PZT, model results suggest AlN is worth a closer look as an active material.

Notes: Prototype bimorph had two PZT layers, all others have only one active layer. PZT properties: d_{31} = -141 pm/V, ε_r = 1800, density = 7800 kg/m^3, c_p = 66 GPa. AlN properties: d_{31} = -7.5 pm/V, ε_r = 9, density = 3200 kg/m^3, c_p = 135 GPa. NdFeB properties: density = 7500 kg/m3, B_r = 1.3 T for the leftmost two beams, 0.5 T for the rest. Steel properties: c_p = 200 GPa, density = 7800 kg/m^3. Pt properties: c_p = 171 GPa, density = 21450 kg/m^3.

Analysis and experiment in agreement for mesoscale current sensor

1. **Analysis of device output expressed as $V_{out} = F_{in}(d_{31})$ when apply mechanical force F_{in} to sensor whose piezo-material is characterized by constant d_{31}. Put sensor device on shake table with known acceleration, measure output and find effective d_{31} by curve fitting**





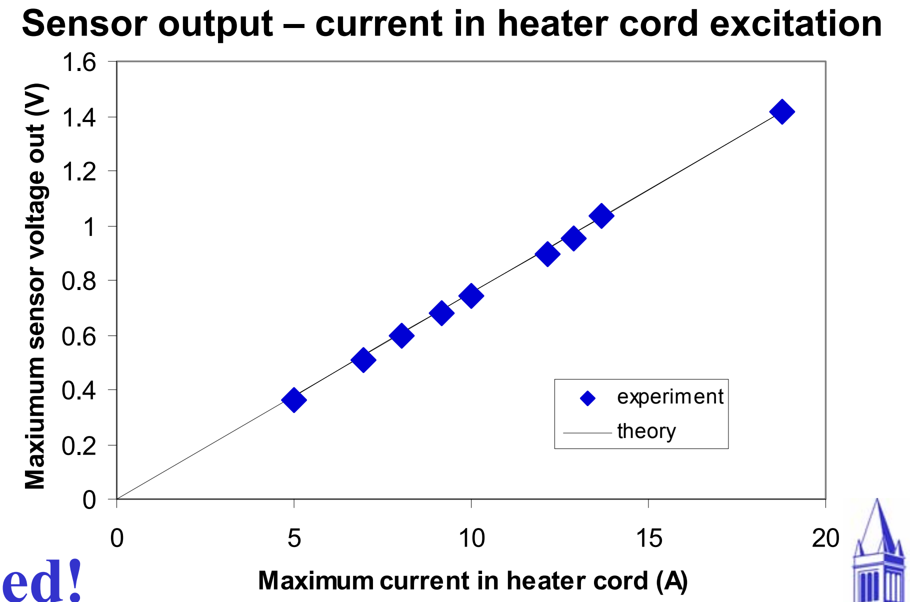
Analysis and experiment in agreement for mesoscale current sensor (continued)

2. **Measure sensor response to current *I*, compare with predictions from current sensor analysis using the value of d_{31} obtained from shake table experiment.**

Force on cantilever produced by current *I* is

$$F_{in} = I\beta$$

$$V_{out} = I\beta K(d_{31})$$


Sensor output – current in heater cord excitation

Excellent agreement observed!

Major design take-aways

- **Current sensor output voltage is linearly proportional to current, as predicted by theory and demonstrated by experiment**
  - Magnetic force is proportional to current
  - Voltage out proportional to force
- **Magnetic force proportional to magnet volume, remanence**
- **Theoretical models suggest micro-scale devices should be feasible**

Research plan going forward

- Fabricate Aluminum Nitride (AlN) cantilever devices in the UCB Microlab
- Characterize AlN cantilevers to verify voltage/force model at the micro-scale
- Identify most promising method to fabricate micro-magnets

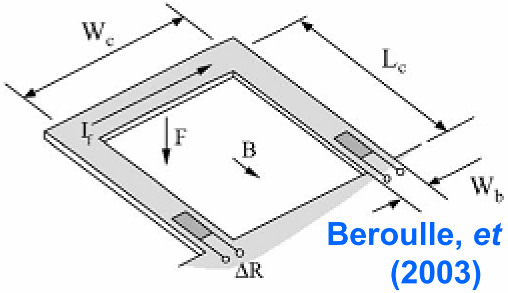
Literature review

Measuring current

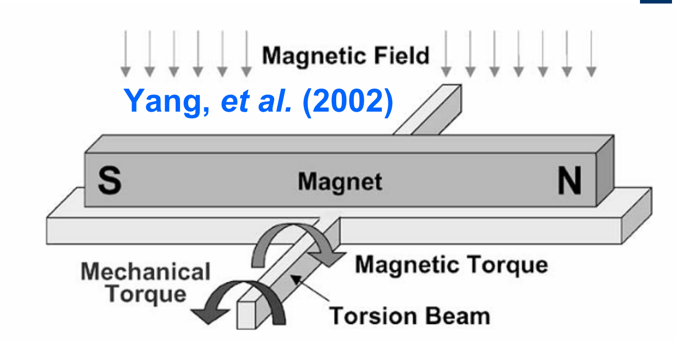
- C. Xiao, *et al.*, "An Overview of Integratable Current Sensor Technologies," *Proc. 38th IAS Annual Meeting* (2003) pp. 1251-1258
- P. Ripka, "Current Sensors using Magnetic Materials," *Journal of Optoelectronics and Advanced Materials*, vol. 6 no. 2 (2004) pp. 587-592

MEMS magnetometers

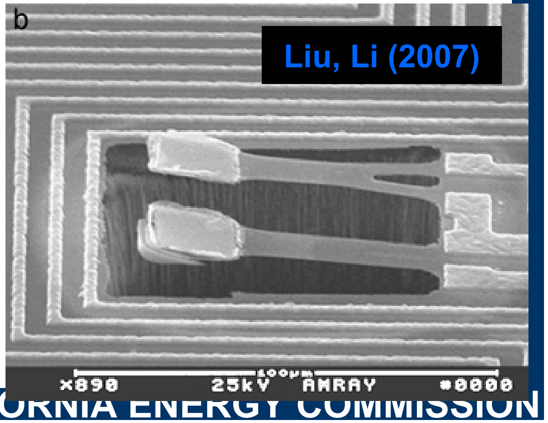
- Beroulle, *et al.*, "Monolithic piezoresistive CMOS magnetic field sensors," *Sensors and Actuators A*, vol. 103 (2003) pp. 23-32
- H.H. Yang, *et al.*, "Ferromagnetic micromechanical magnetometer," *Sensors and Actuators A*, vol. 97-98 (2002) pp. 88-97
- J. Liu, X. Li, "A piezoresistive microcantilever magnetic field sensor with on-chip self-calibration function integrated," *Microelectronics Journal*, vol. 38 (2007) pp. 210-215



Beroulle, *et al.* (2003)



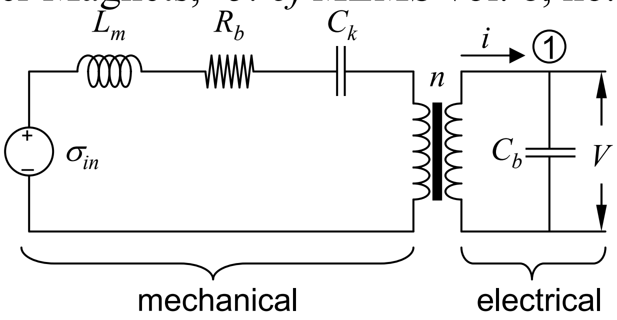
Yang, *et al.* (2002)



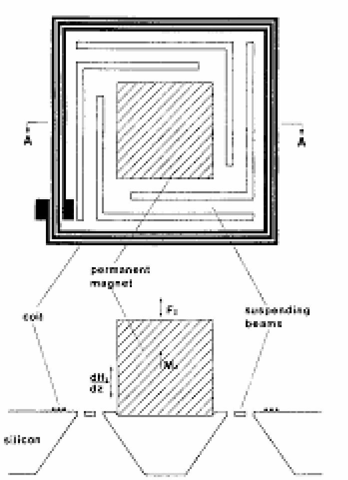
Liu, Li (2007)

Literature review, continued

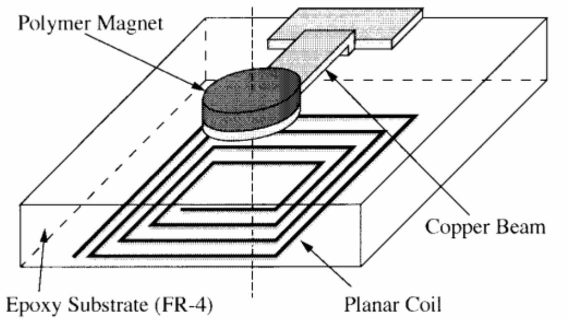
- **Piezoelectric cantilever output**
  - S. Roundy, P. Wright, “A piezoelectric vibration based generator for wireless electronics,” *Smart Materials and Structures* vol. 13 (2004) pp.1131-1142
  - S.N. Chen, *et al.*, “Analytical modeling of piezoelectric vibration-induced micro power generator,” *Mechatronics* vol. 16 (2006) pp. 379-387
- **Magnetic microactuators/sensors**
  - B. Wagner, W. Benecke, “Microfabricated actuator with moving permanent magnet,” *Proc. MEMS ’91* (1991) pp. 27-32
  - Lagorce, *et al.*, “Magnetic Microactuators based on Polymer Magnets,” *J. of MEMS* vol. 8, no. 1 (1999) pp. 2-9



Roundy, Wright (2004)



Wagner, Benecke (1991)

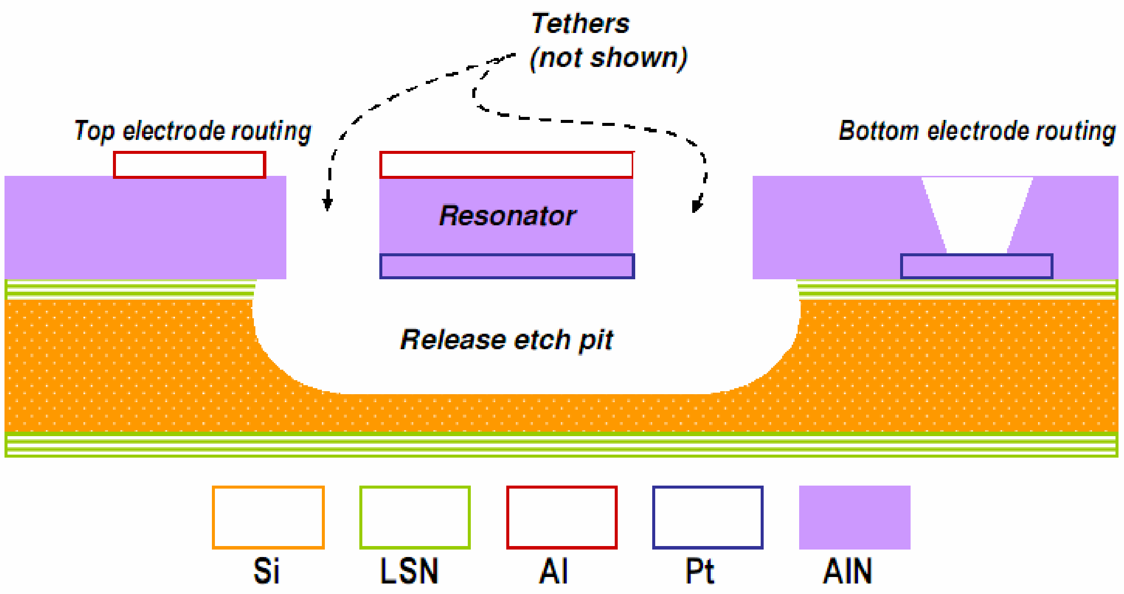


Lagorce, et al (1999)

Why not use Hall sensors?

- **Allegro 1392 Hall sensor**
  - 9.6 mW average power during operation, 75 μW sleep
  - Assume duty cycling of 120 samples/sec, 1 millisecond/sample
  - Average power 1.2 mW, ten times the target average power for a sensor node

AlN devices in the UCB Microlab



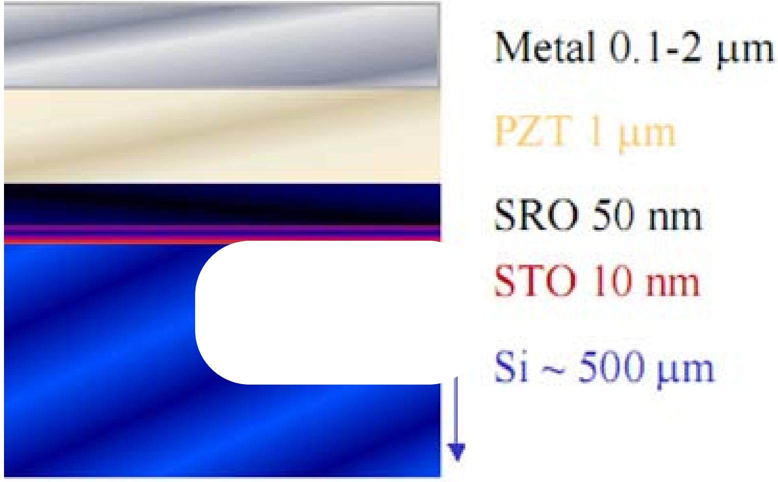
- LPCVD low-stress nitride
- Sputter deposition, pattern, and liftoff of Pt electrode
- Sputter deposition of AlN film
- Deposition, patterning, and Cl_2 RIE of Al top electrode
- Open via to bottom electrode using hot phosphoric acid
- AlN patterning using LTO “hard mask” and Cl_2 RIE
- XeF_2 release etch

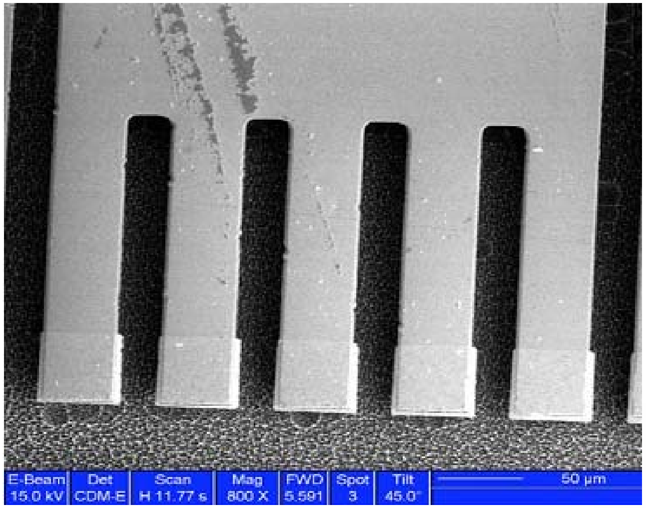
I’ll have to include an elastic support layer, as I’ll be fabricating a “31” mode cantilever. SOI substrate is one option.

P. Stephanou, “Piezoelectric Aluminum Nitride MEMS Resonators for RF Signal Processing,” *PhD Dissertation,* University of California, Berkeley (2006)

PZT cantilevers in the Microlab

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)

Possibilities for magnet fabrication

Screen/direct printing of magnetic powder/polymer composites

- L. Lagorce, M. Allen, “Magnetic and Mechanical Properties of Micromachined Strontium Ferrite/Polyimide Composites,” *J. of MEMS* vol. 6 no. 4 (1997) pp. 307-312
- C. Ho, *et al.*, “Dispenser Printed Electrochemical Capacitors for Power Management of Millimeter Scale Lithium Ion Polymer Microbatteries for Wireless Sensors,” *Proc. PowerMEMS 2006*, November-December 2006, Berkeley, California, pp. 219-222

Electroplating CoNiMnP, NiFe, Permalloy

- T. Liakopoulos, W. Zhang, C. Ahn, “Electroplated Thick Film CoNiMnP Permanent Magnet Arrays for Micromachined Magnetic Device Applications,” *Proc. MEMS ’96* (1996) pp. 79-84
- J. Judy, R. Muller, H. Zappe, “Magnetic Microactuation of Polysilicon Flexure Structures,” *Journal of MEMS* vol. 4 no. 4 (1995) pp. 162-169

Is NdFeB possible? Is it worth the trouble?

- B. Pawlowski, *et al.*, “NdFeB thick films prepared by tape casting,” *J. Magnetism and Mag. Mat’ls* vol. 265 (2003) pp. 337-344
- P. McGuiness, *et al.*, “100-µm-thick Nd-Fe-B magnets for MEMS applications produced via a low-temperature sintering route,” *J. Magnetism and Mag. Mat’ls* vol. 305 (2006) pp. 177-181