MEMS Energy Harvesting: Enabling Wireless Sensor Networks for Demand Response Applications

ETD Workshop

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Lindsay Miller, Nathan Emley, Padraic Shafer

In case you're about to check email for 20 minutes, remember these 4 points:

- MEMS energy harvesting is enabling technology for wireless sensor nodes
  - Provides replenishable power
  - Achieves size reductions
  - Reduces required maintenance
- Current prototype has made good progress, culminating in successful actuation of energy harvesting device
- 1-10 $\mu W/cm^3$ power output predicted from device
- First prototype costs ~ $16/chip,
  predicted to fall to ~ $1/chip with mass production

Motivation for Energy Harvesting

Goal: Use demand response to achieve energy efficiency & cost savings for consumer & utility

→ WSNs in commercial and residential buildings (& manufacturing sites) could meet these goals.

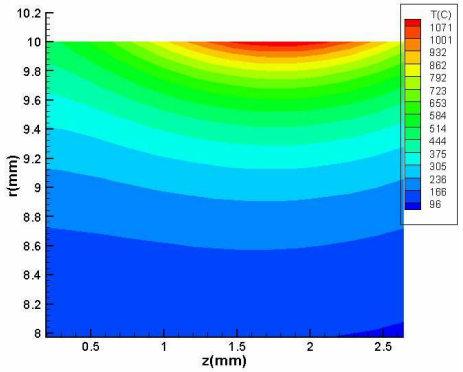
→ Current WSN nodes are limited:
→Bulky
→High-maintenance
→Expensive

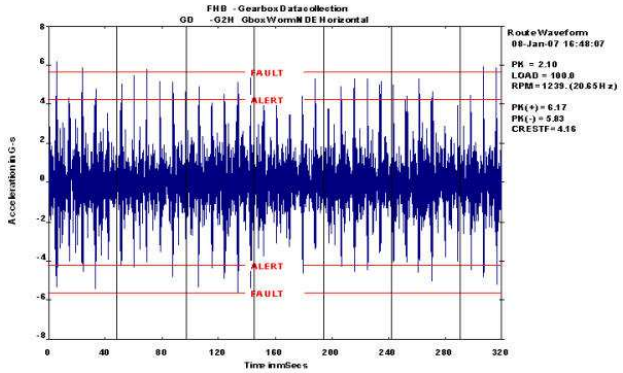
solution: → MEMS Energy harvesting is

→Small size
→Low maintenance
→Potential cost savings

Many Ways to Harvest Energy…

- Solar
- Wind
- Fluid flow
- Pressure gradient
- Temperature gradient
- **Vibration – buildings, machinery, appliances**





Piezoelectric Energy Harvesting

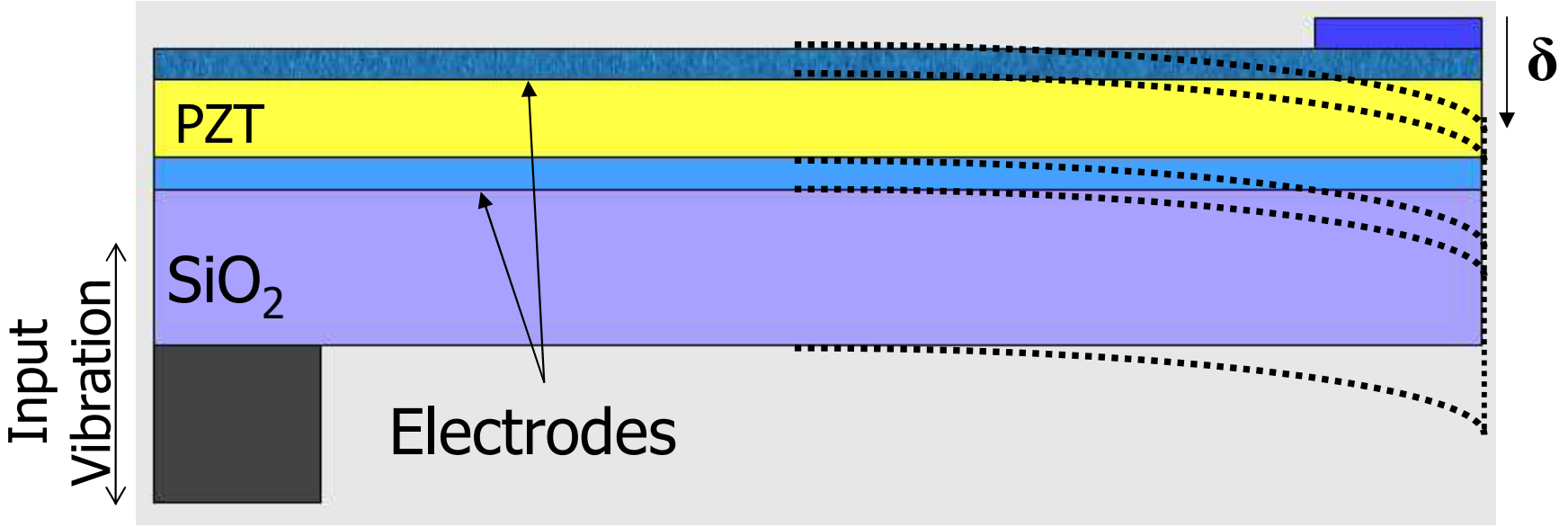
Piezoelectric **Actuator**: Deflects when a voltage is applied

Piezoelectric **Sensor**: Produces voltage when deflected (energy harvesting)

Power ~ Strain^2

$$P = \frac{1}{R}\left[\frac{c_p d_{31} t_p S_1}{\varepsilon}\right]^2$$

P = power
S = strain
d_{31} = piezo coefficient
c_p = elastic modulus
t_p = thickness
R = resistance
ε = permittivity

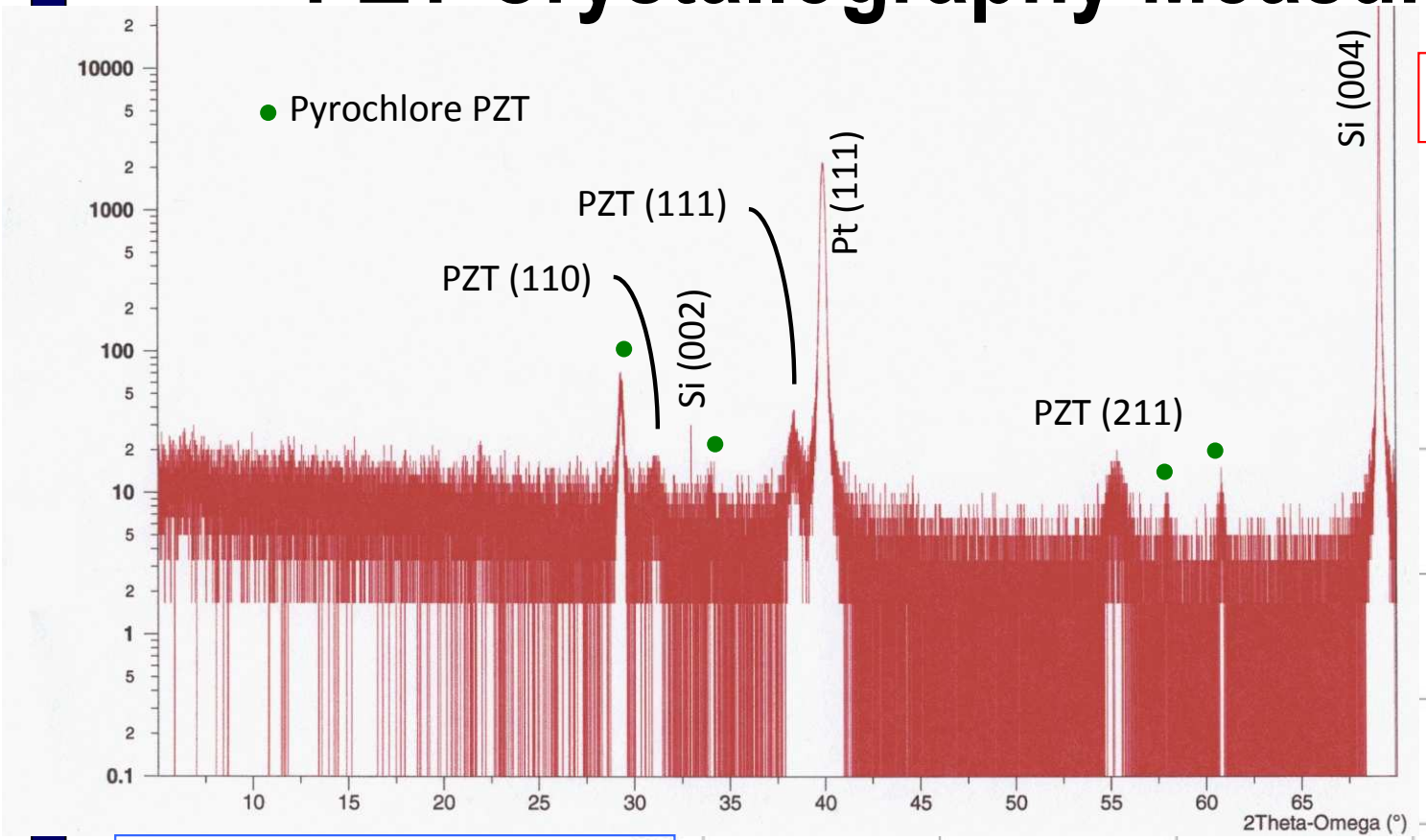


Progress on Vibration Energy Harvesting

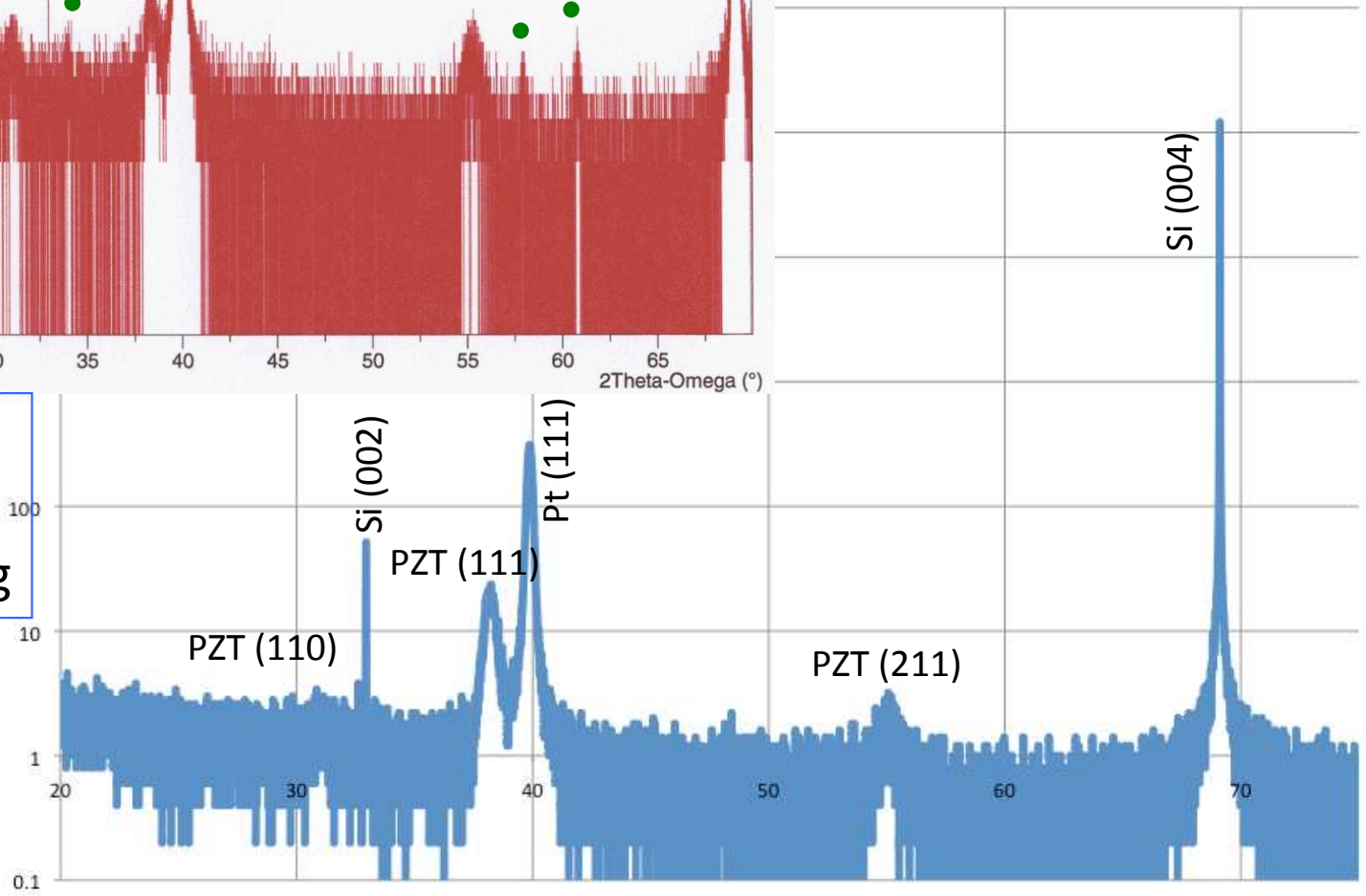
- Sol-gel PZT film improvements
- Successful fabrication of devices with sol-gel PZT active layer
- Successful actuation of those devices
- Manufacturing scale-up: chip to wafer scale
- Next: measure voltage output of devices

PZT Crystallography Measurements

First generation



Third generation:
- reduced pyrochlore
- better (111) ordering



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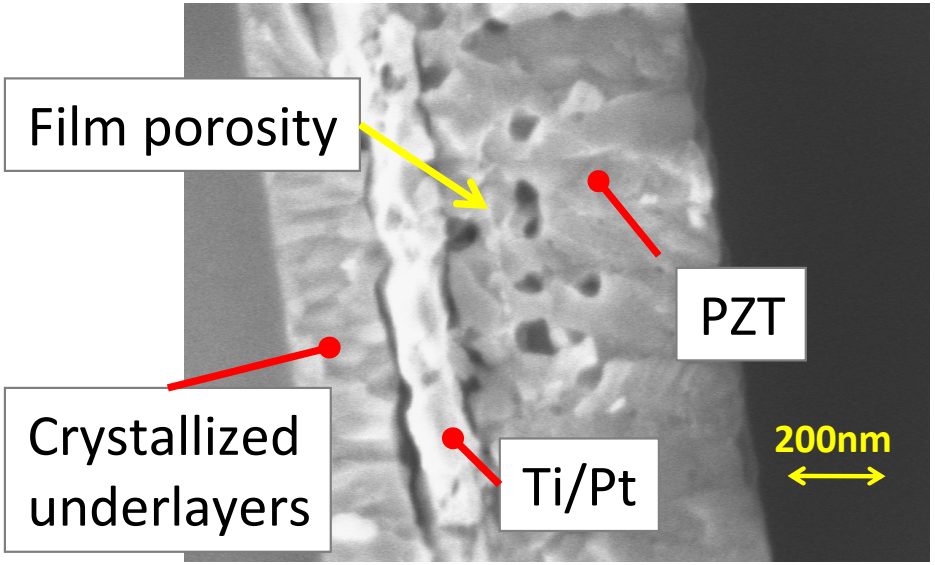
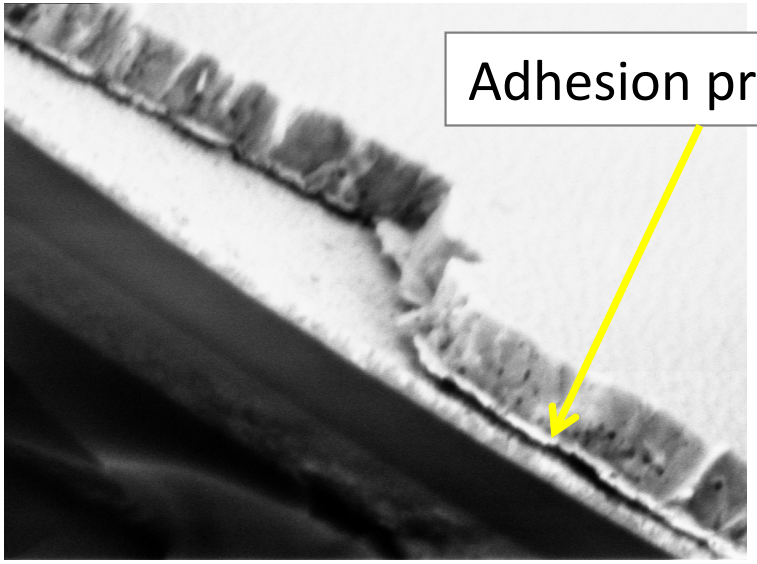
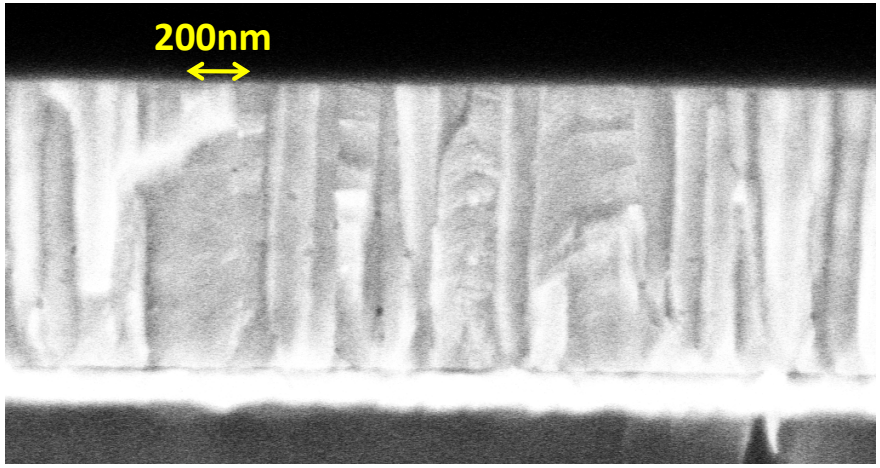
PZT Morphology

Initial films were porous and unknown crystallized layers lead to film delamination.





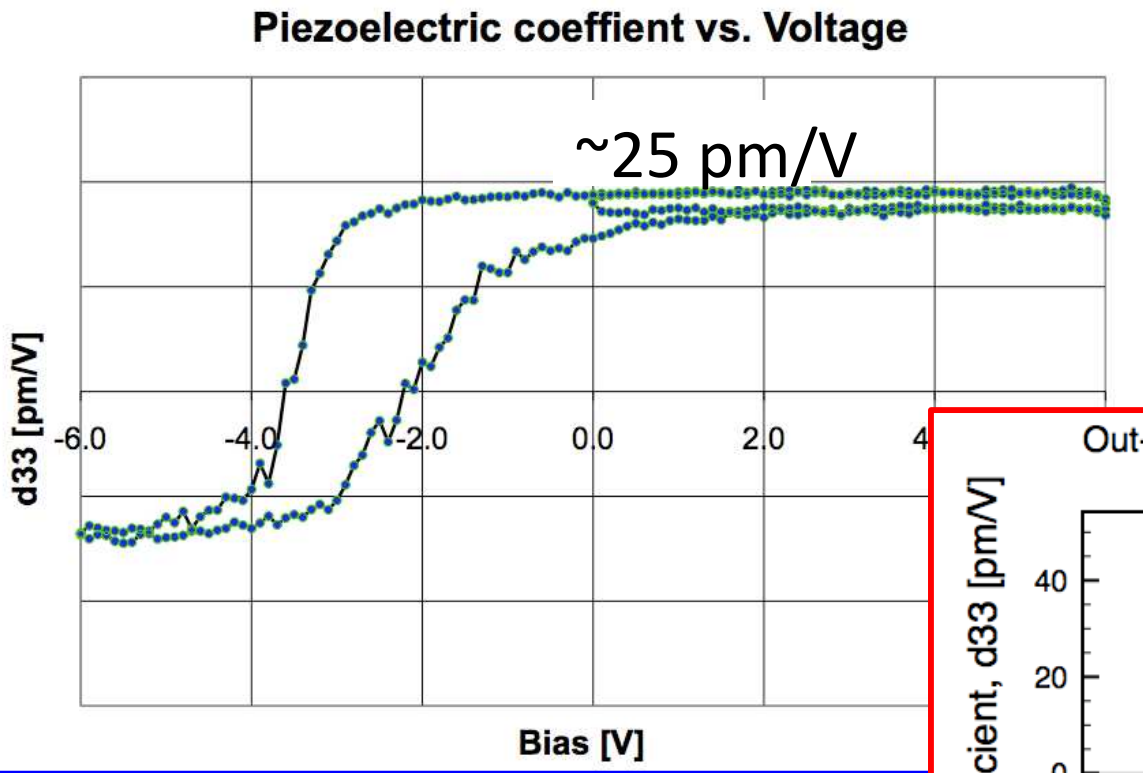
Careful control of substrate cooling after pyrolysis and slower ramp times during crystallization lead to much improved PZT morphologies.



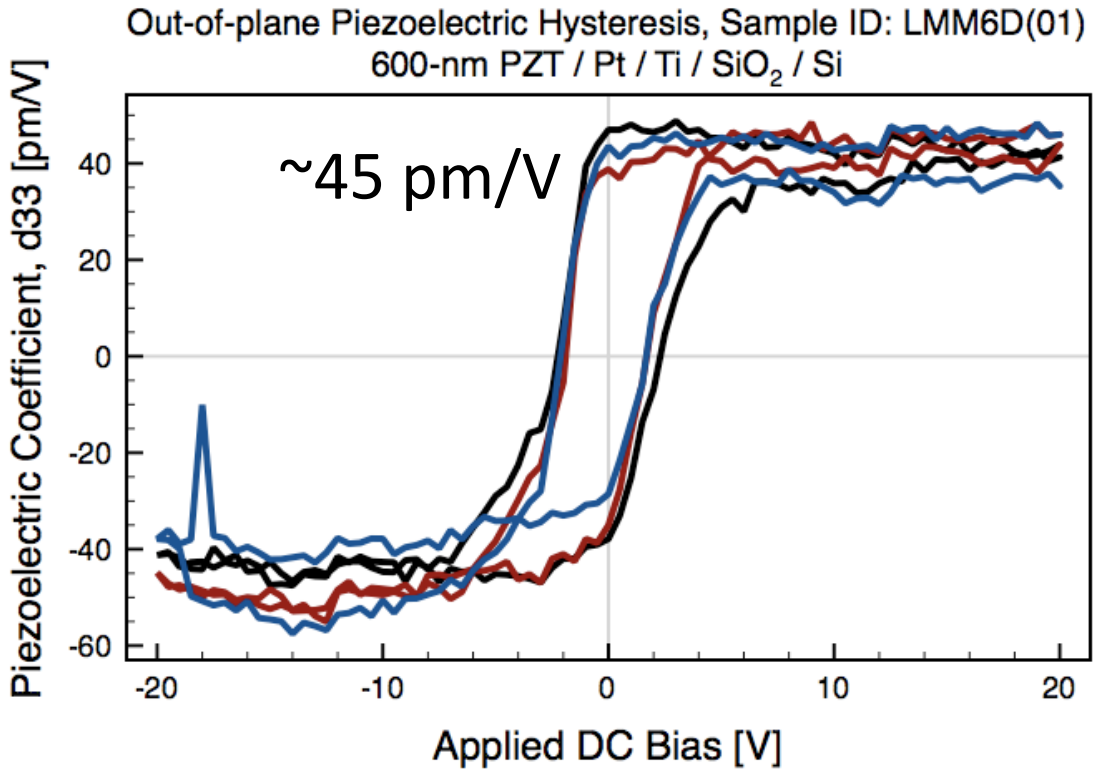
- Reduced porosity with no unknown layers
- Good, contiguous columnar growth between subsequent PZT spins.

PZT Piezoelectric Measurements

- Increased piezoelectric response with improved PZT



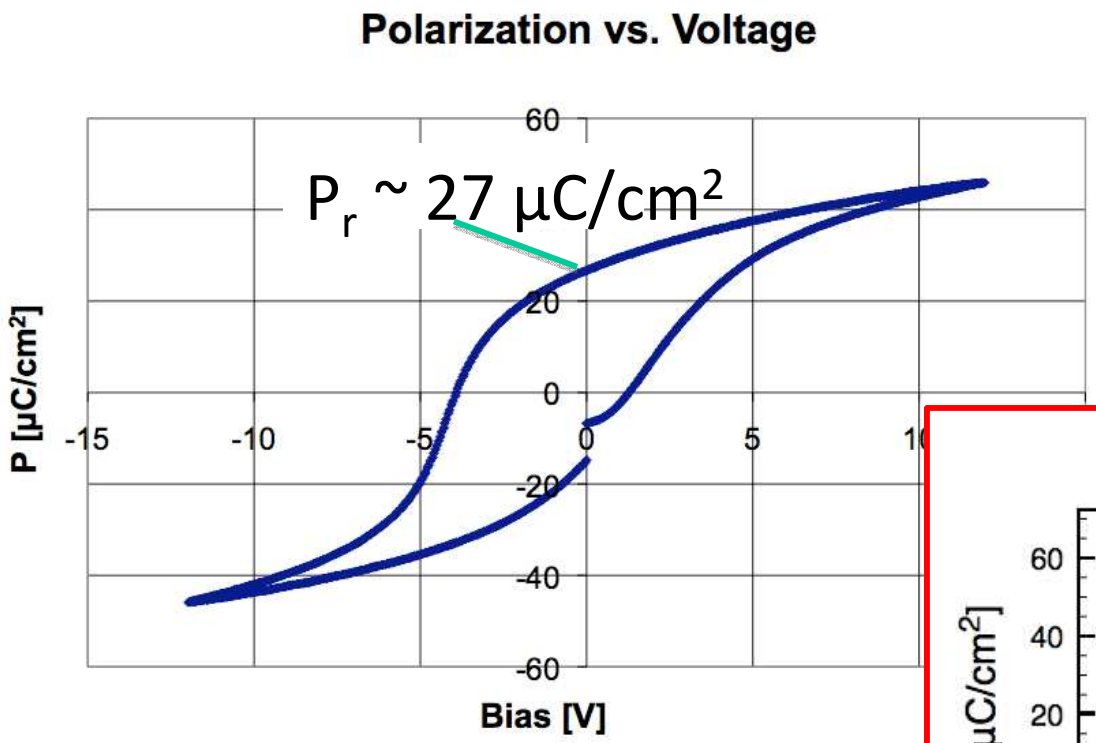
First generation:
- Low d_{33}
- Asymmetric and offset hysteresis



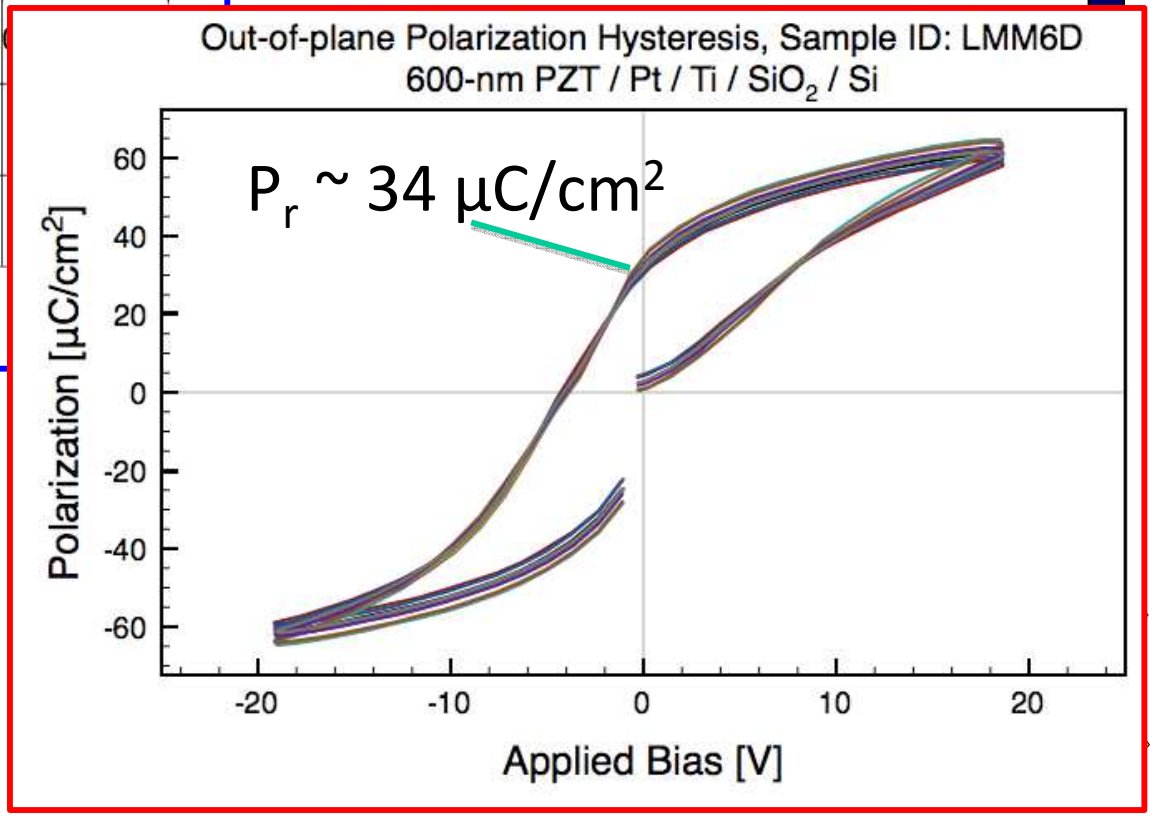
Third generation:
- Higher d_{33}
- Much more symmetric hysteresis
- Consistent response between scans

PZT Ferroelectric Measurements

- Increased ferroelectric behavior with improved PZT processing.

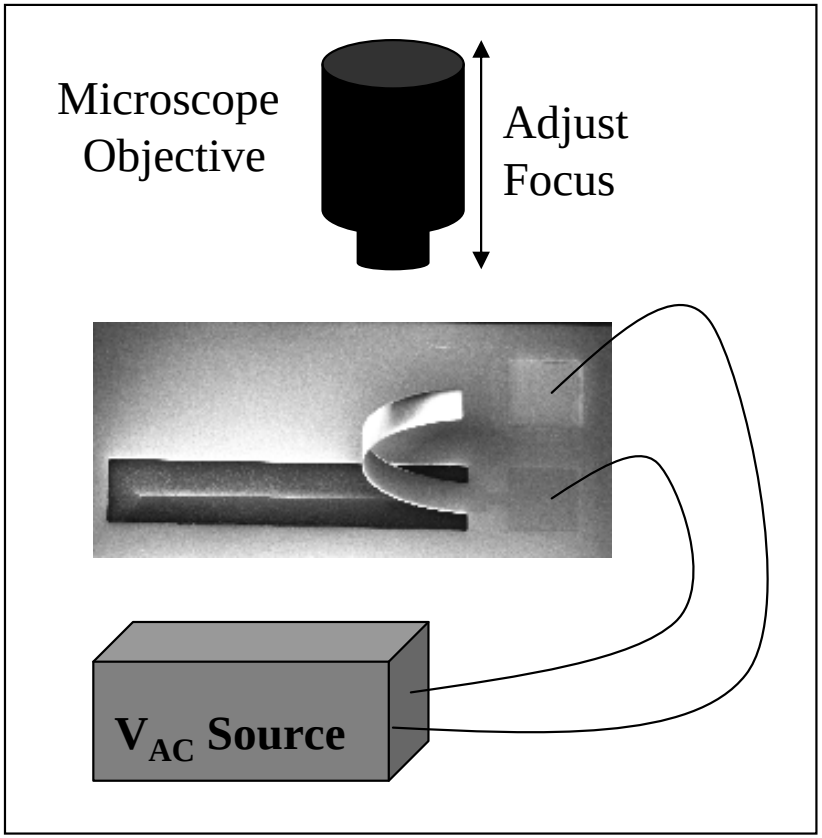


First generation:
- Low remnant polarization P_r



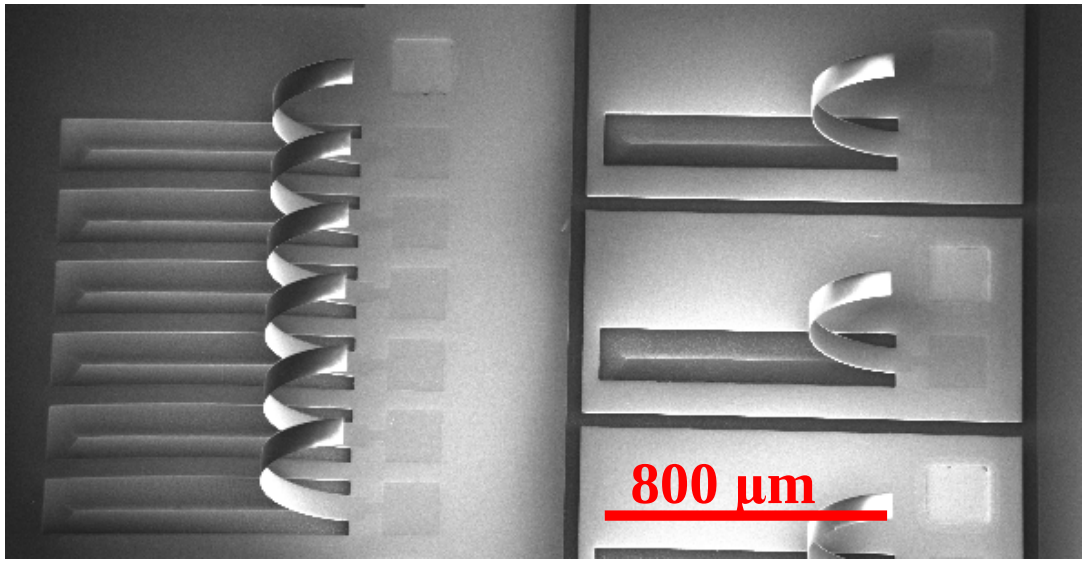
Third generation:
- Higher P_r
- Reproducible polarization

First Generation Prototype

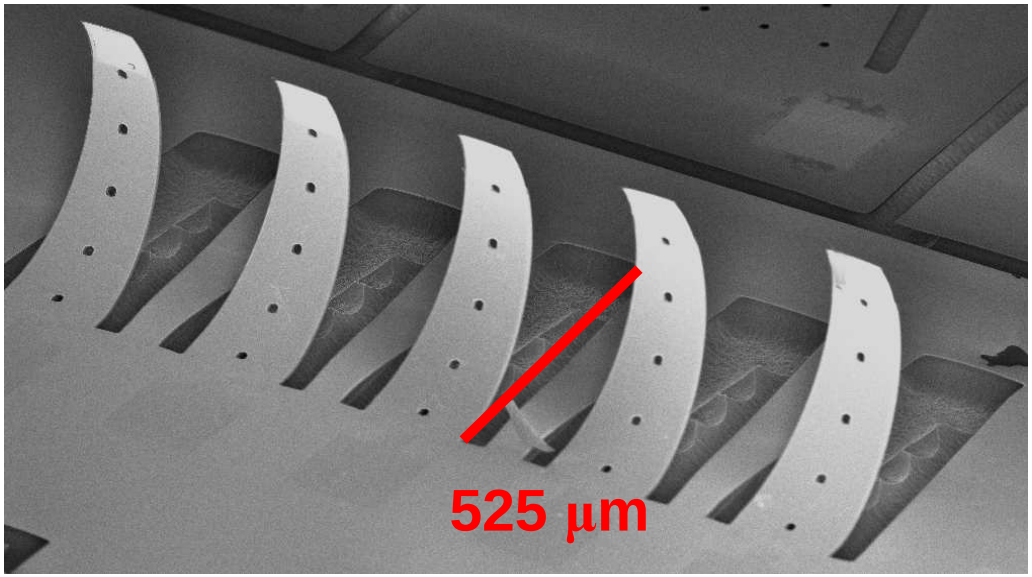


Simplified deflection test setup: movie

Array and isolated rectangular cantilevers



Array of trapezoidal cantilevers



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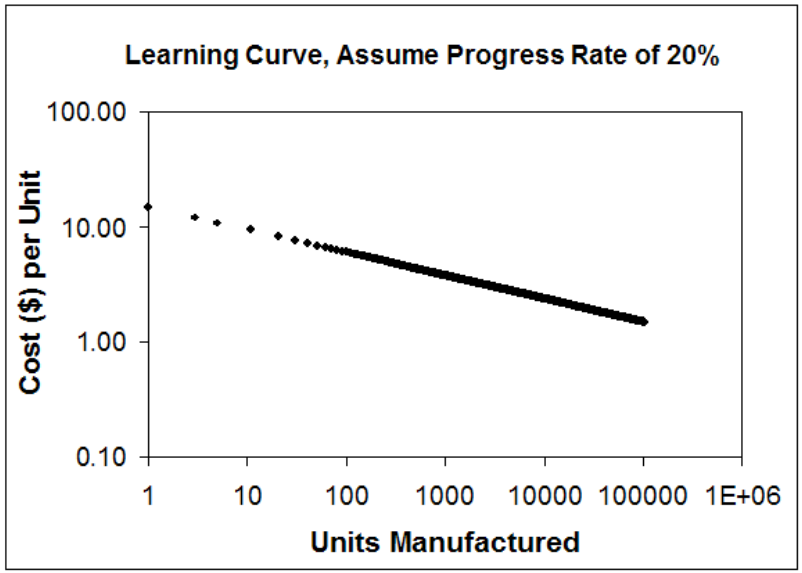
Current & Expected Cost Estimate

- Current cost/wafer
  - Mat'ls $174 + Outsourcing $100 + Microlab fees $2385 + Labor $350 = $3009/wafer
  - 80 chips/wafer = $37/chip for 4"
  - 180 chips/wafer = $16/chip for 6"



- Future cost estimate: learning curve eqn
  - $Y = a X^{-b}$ = ($16/part) (1E6 parts made)^(-.20)
    Y = $1/part after 1 million are made

Yelle, L.E. (1979) "The Learning Curve: Historical Review and Comprehensive Survey", Decision Sciences Vol. 10, pp. 302 – 328.
http://www.ifm.eng.cam.ac.uk/csp/summaries/learningcurve.html and http://www.nrel.gov/docs/fy06osti/39904.pdf

Expect Power Output: 1 - 10 μW/cm^3

Test as sensor (harvester) this month:

- Vibration input
- Air flow input

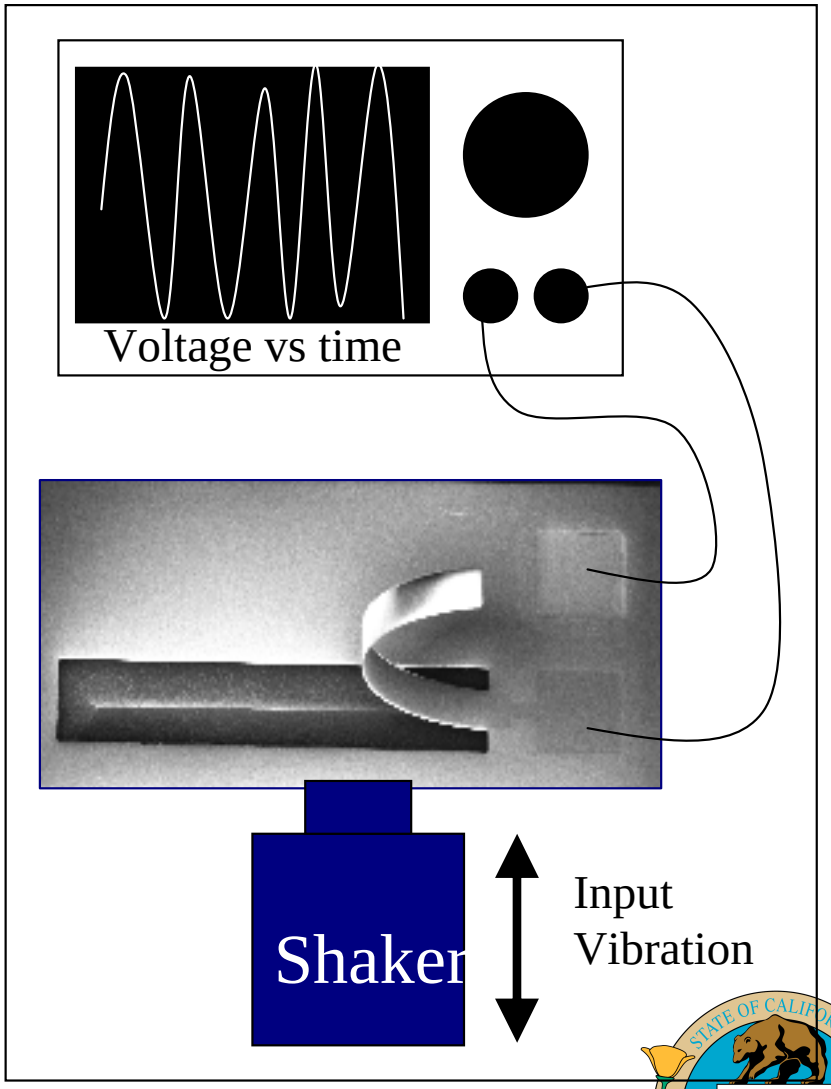
Integrate components:

- Energy generation
- Energy storage
- Sensor
- Radio

Fabricate 2nd generation device:

- Improve power output

Simplified voltage output test setup



Key Take-Aways

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What is Sol-gel PZT?

Lead Acetate Trihydrate: $Pb(CH_3CO_2)_23H_2O$

Zirconium n-Propoxide: $Zr(C_3H_7O)_4$

Titanium iso-Propoxide: $Ti[(CH_3)_2CHO]_4$

Plus Solvents, Dilutants, Catalysts