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

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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 µW/cm³ 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)

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

- \( P \): power
- \( S \): strain
- \( d_{31} \): piezo coefficient
- \( c_p \): elastic modulus
- \( t_p \): thickness
- \( R \): resistance
- \( \varepsilon \): permittivity

Power \( \sim \) Strain^2
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

Pyrochlore PZT
Pt (111)
Si (002)
PZT (211)
PZT (110)
PZT (111)
PZT Morphology

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

- Film porosity
- Crystallized underlayers
- Ti/Pt
- PZT
- Adhesion problems

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

**Piezoelectric coefficient vs. Voltage**

- ~25 pm/V

**Out-of-plane Piezoelectric Hysteresis, Sample ID: LMM6D(01)**
- 600-nm PZT / Pt / Ti / SiO₂ / Si
- ~45 pm/V
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

Array and isolated rectangular cantilevers

Array of trapezoidal cantilevers

Simplified deflection test setup: movie

Microscope Objective

Adjust Focus

V_{AC} Source

800 \mu m

525 \mu m
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} = ($16/part) (1E6 parts made)^{-0.20}$
  - $Y = $1/part after 1 million are made

Expect Power Output: 1 - 10 µW/cm³

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

Voltage vs time

Shaker

Input Vibration
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