ENERGY HARVESTING FROM VIBRATIONS, AIR FLOW, & TEMPERATURE CHANGE

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System on a Chip

Energy Storage

MEMS Sensor

Wireless Sensor Micro-device

Energy Harvesting

Radio
Multi-source energy harvesting

**PIEZOELECTRIC**
- Vibrations
- Air flow

**THERMEOLECTRIC**
- Temperature difference

L. Miller et al. 2009
Progress made in past 6 months:

**PIEZOELECTRIC**

**VIBRATIONS**
- $P_{rms} = 1.1 \text{ nW/beam}$, micro device on ambient source
- Developed process to modify frequency with printed mass

**AIR FLOW**
- Meso-scale prototype developed
- $P_{rms} = 1.1 \text{ mW}$, optimal conditions

**THERMOELECTRIC**

**TEMPERATURE DIFFERENCE**
- Composite materials improved
- Developed scalable fabrication process for meso-scale devices
- $P = 0.58 \mu\text{W}$ ($\Delta T = 10 \text{ K}$, 10-couple device)
Multi-source energy harvesting

PIEZOELECTRIC

VIBRATIONS

AIR FLOW
Piezoelectric operating principle

DEFORMATION (mechanical energy)  ↔  VOLTAGE (electrical energy)

PIEZOELECTRIC MATERIAL

CANTILEVER BEAM

S. Roundy, PhD Thesis UC Berkeley 2003

Figure: Wikipedia, 2010
Where we left you 6 months ago:

**PIEZOELECTRIC**

**VIBRATIONS**
- MEMS harvester fabricated
- Low resonance frequency achieved
- $P_{\text{rms}} = 1 \text{ nW}$ on shaker table
- 1 beam tested on 1 ambient source
- Printed capacitor on harvester die

**AIR FLOW**
- Project was just starting
Progress: ambient vibration harvesting

Ambient vibration source: compressor

- Tested 9 beams on 7 ambient sources – reliably produce low power
- Almost finished with model – measured accel. input ➔ predicted beam output
Successfully printed on 6 released beams with no “casualties”

$$\omega^2 = \frac{k}{m}$$

Progress: print mass $\rightarrow$ modify frequency
Progress: print mass $\rightarrow$ modify frequency

Beam power output vs frequency

Beam signals add in series!

0.1 Hz resolution
> 20 Hz shift

Shift in frequency with addition of printed mass

177.9 Hz BEFORE

192.8 Hz

172.9 Hz AFTER

0.3
0.2
0.1
0.1
0.05
0.01
0

170 175 180 185 190 195

170 175 180 185 190 195

Frequency (Hz)

RMS Power output (nW rms)

- Series, theoretical
- Series, measured
- Right, measured
- Left, measured
Progress: air flow harvester design

Top View

Back View

Cylindrical Obstacle

Fin

Stand

Time=0.8  Surface: Velocity magnitude (m/s)
Progress: air flow harvester performance

Power vs. Air Speed

RMS Power (μW)

Avg. Air Speed (m/s)

Power output > 1 mW at optimal conditions

For results shown:
Fin: 7.5 cm wide x 7 cm long
Fin material: balsa wood
Cylinder Diameter: 2.5 cm
Optimum Load R: 194 kOhm

Shedding Frequency vs. Air Speed for Various Cylinder Diameters

Shedding Freq (Hz)

Avg. Air Speed (m/s)
Multi-source energy harvesting

PIEZOELECTRIC

VIBRATIONS

THERMOELECTRIC

AIR FLOW
Multi-source energy harvesting
Thermoelectric (TE) Operating Principles

Thermoelectric (TE) Energy Harvesting

Sources of Waste Heat

<table>
<thead>
<tr>
<th>Location</th>
<th>Source</th>
<th>Temp. Gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>Boilers, Dryers, Freezers, Oven</td>
<td>10-30K</td>
</tr>
<tr>
<td>Factories</td>
<td>Exhaust pipes, Boilers, Condensers</td>
<td>10-80K</td>
</tr>
<tr>
<td>Vehicles</td>
<td>Engine, Exhaust pipes</td>
<td>60K &gt;100K</td>
</tr>
<tr>
<td>Airplanes</td>
<td>Cabin to External</td>
<td>10-50K</td>
</tr>
</tbody>
</table>
Thermoelectric Design

TE Power Output Optimization

**Optimal Range**

**Thin film elements**
- Microfabrication processes
  - 60μm max. height
- *Materials intensive*
  
  Micropelt, Inc

**Dispenser Printing**
- Optimal Feature Sizes (100-500μm)
- High throughput manufacturing

**Bulk elements**
- Diced elements from ingots
  - 1mm height min.
- *Labor intensive*
  
  Ferrotec, Inc.
Where we left you 6 months ago:

- Meso-scale prototype fabricated using dispenser printing technique

- Printable semiconductor/epoxy thermoelectric materials synthesized
Progress: innovative design of TE harvester

**Traditional Design**
- Aspect ratios from 1.5 to 2
- Commercially available
- Labor intensive assembly

**Planar Design**
- High aspect ratio pillars
- High density arrays
  - 900+ couples for D = 1cm
- Takes advantage of printing process
Progress: new design is easily scalable

1. Print Electrodes
2. Print N-type Semiconductor
3. Print P-type Semiconductor
4. Heat/Cure

- 3-layer printing process
- Element lengths are controllable
- Printing process is scalable to larger production processes (i.e. screen printing, flexography)
Progress: performance of TE prototype

**Thermoelectric Materials**

- n-Type $zT$
  - $zT$ vs. Temperature (°C)
  - Bi$_2$Te$_3$, PbTe, CoSb$_3$, SiGe

- p-Type $zT$
  - $zT$ vs. Temperature (°C)
  - Sb$_2$Te$_3$, TAGS, Yb$_{14}$MnSb$_{11}$, PbTe, CeFe$_4$Sb$_{12}$, SiGe

**Flexible TE Devices**

- 10 Couple Device
- $\Delta T = 10$ Kelvin
- Losses from contact resistance

- Measured power output
  - 2.2 $\mu$W
  - 0.58 $\mu$W

**Snyder et al (2008)**

Flexible Polyimide Substrate

Printed TEMaterials

Leg Dim.: 5 mm Length, 500 $\mu$m width, 200 $\mu$m thick
Progress summary

**PIEZOELECTRIC**

**VIBRATIONS**
- $P_{\text{rms}} = 1.1 \text{ nW}/\text{beam}$, micro device on ambient source
- Modified frequency by 20 Hz with printed mass
- Beam signals add when in series

**AIR FLOW**
- Meso-scale prototype designed, built, & characterized in duct
- $P_{\text{rms}} = 1.1 \text{ mW}$, optimal conditions

**THERMOELECTRIC**

**TEMPERATURE DIFFERENCE**
- Synthesized efficient, printable composite TE materials ($ZT \sim 0.4$)
- Developed scalable fabrication process for meso-scale devices
- $P = 0.58 \mu W$ ($\Delta T = 10 \text{ K}$, 10-couple device)
Thank you! Any questions?

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