Chip Scale TEG and its Use for a Wireless Machine Health Monitoring System

Baoxing Chen and Jane Cornett
Analog Devices, Inc.

3/30/2017
Internet of Things
Rapidly growing number of wireless sensors require reliable and maintenance-free power sources

- Smart Buildings
- Infrastructure Monitoring
- Wearable Sensors
- Livestock Monitoring
- Asset Tracking
- Plane/Vehicle Area Network
- Crop Production
Chip-Scale Thermoelectric Harvester Improves Upon Discrete Solution

- Enable “Deploy & Forget” WSN
- Replace or extend battery life
- Compact, economic & reliable
- Easy to use & integrated

**Downsides of traditional discrete devices:**
- Large and expensive
- Low thermal resistance
- Low output voltage
- Unreliable

**Chip-scale thermoelectric harvester:**
- Proprietary MEMS structure
- Small size, high power density
- Low cost, high efficiency
- High output voltage for better power management efficiency
- Elimination of startup components
- Reduced cost and size of heat spreader
- Integration with other functions

**Vertical Pyramid**

**Pyramid**
Thermoelectric Basics

**Seebeck Effect**

\[ V = S \ T \]

**Thermoelectric Power Generation**

\[ \eta_{\text{max}} = \frac{\Delta T}{T_{\text{hot}}} \frac{\sqrt{1 + ZT}}{\sqrt{1 + ZT} + \frac{T_{\text{cold}}}{T_{\text{hot}}}} - 1 \]

\[ ZT = \frac{(S_p - S_n)^2 T}{(\sqrt{\rho_n \kappa_p} + \sqrt{\rho_p \kappa_n})^2} \]

\[ K = K_e + K_{\text{phonon}} \]

\[ \frac{\kappa_e}{\sigma T} = L_0 = \frac{\pi^2}{3} \left( \frac{k_B}{e} \right)^2 \]

**Maximize ZT:**
- Phonon Glass;
- Electron Crystal

**Thermoelectric Cooling**

\[ I \]

**Best room temp prop:** Bi\(_2\)Te\(_3\)

\[ T_c \]

[Image showing thermoelectric devices and formulas]

---

**Carrying Concentration**

- Semiconductors
- Metals

**ZT vs. Temperature (K)**

Current Bulk Thermoelectric Materials

- Bi\(_2\)Te\(_3\)
- PbTe
- Sn\(_2\)Ge\(_3\)
- CoSb\(_3\)
- CoSb\(_3\)
- CoSb\(_3\)
- CoSb\(_3\)
- CoSb\(_3\)
- Yb\(_7\)Co\(_9\)Sb\(_{12}\)
- ZnSb
Thermal Impedance Matching For Maximum Power Output

\[
\Delta T(\text{device}) = \frac{R_{tp} \parallel R_{pp}}{R_{cold} + R_{hot} + R_{tp} \parallel R_{pp}} \Delta T
\]

- External thermal impedance depends on size of heat spreader
- Devices with large thermal impedance reduce heat spreader size & cost

\[
P = \frac{(S\Delta T \frac{R_{th}}{R_{th} + R_{ex}})^2}{RES} = \frac{(S\Delta T \frac{R_{th}}{R_{th} + R_{ex}})^2}{\frac{\rho}{\kappa} R_{th}}
\]

Load Matching
 Thermal Impedance Matching

Max Power
Modeling of Bi$_2$Te$_3$ Vertical Structures

- Quick 1D thermal models used to determine optimal device configurations and predict device performance
  - Includes Joule & Peltier heating
- In-depth 3D COMSOL modeling to fine-tune device performance, explore adjustments to structures and elucidate problem areas
Power Optimization of Vertical Devices

(a) Device schematic showing the interconnect, heat sink/external thermal resistance, and n-type/p-type layers.

(b) Graph showing the matched load voltage and matched power as a function of thermoelectric leg length.

(c) Graph showing the matched power output at different fill fractions and thermoelectric leg lengths.

(d) Graph comparing the matched power output for different fill factors and thermoelectric leg lengths with various fill materials.
Projected Performance of Bi$_2$Te$_3$-based Devices

Performance compared with competitor:

- *ADT Projected Performance for 3mmx3mm:*
  - Both vertical and pyramid devices have higher voltage and output power over entire range of temperature gradients

- **Vertical structure**
  - Larger output voltage but **thicker** films (10µm)

- **Pyramid structure:**
  - Better output power with **thinner** films (5µm)
Device Performance Characterization
Methods

- **Basic characterization premise:** Measure device performance under known temperature gradient
  - Accurate measurement of $\Delta T$ difficult and critical for device characterization

- **Methods used:** Device sandwiched between heated and cooled metal blocks

**IR Imaging**
High resolution to elucidate problem areas

**Calibration Measurement**
Temperatures measured by thermocouples embedded in blocks
Device Performance Characterization

Sample results

Example set of data collected for a single device

*Devices tested at a range of $\Delta T$*

- Larger $\Delta T$ → More power
- Maximum power achieved for matched load conditions
Device Performance Characterization
Sample results

Example set of data collected for a single device

Power at matched load $\propto \Delta T^2$
Machine Health Monitoring
Wireless sensor node powered by TEG

ADI sensor node package prototype:
- Target application: *Machine health monitoring*
- Designed to match thermal impedance of device for *optimal device performance*
- Investigation of new technology for minimal losses at package interfaces
- Sensor node powered entirely by *ADI TEG technology*
Wireless Machine Health Monitoring System

- Records machine vibration history including vibration level to predict problems before serious damage
- Allows for active maintenance to reduce machine down-time and maintenance cost
- Ultra-low power, high resolution 3-axis accelerometers allows for vibration frequency analysis to detect possible fault type and location
### Power Budget for Machine Health Monitor

#### Sleep (3.7µA)

<table>
<thead>
<tr>
<th>Component</th>
<th>Sleep</th>
<th>Measurement (4.82 mA)</th>
<th>Data transfer (5.93 mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADXL355</td>
<td>0</td>
<td>200µA</td>
<td>0</td>
</tr>
<tr>
<td>ADXL372</td>
<td>0</td>
<td>21µA</td>
<td>0</td>
</tr>
<tr>
<td>ADT7302</td>
<td>0</td>
<td>1.6mA</td>
<td>0</td>
</tr>
<tr>
<td>ADXL362</td>
<td>270nA</td>
<td>270nA</td>
<td>270nA</td>
</tr>
<tr>
<td>ADP5092</td>
<td>360nA</td>
<td>360nA</td>
<td>360nA</td>
</tr>
<tr>
<td>ADuCM3029</td>
<td>2µA (hibernate)</td>
<td>2.5mA</td>
<td>2.5mA</td>
</tr>
<tr>
<td>BLE</td>
<td>1µA (extended sleep)</td>
<td>1.8µA</td>
<td>3.4mA</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>3.63µA</td>
<td>4.3mA</td>
<td>5.9mA</td>
</tr>
</tbody>
</table>
Summary and Conclusions

- Chip scale TEG for powering a wireless machine health monitoring system is demonstrated

- Acknowledgement: the speakers would like to acknowledge contribution from ADI TEG team and university collaborators, especially Albert O’Grady for system development and Jaiwen Bai for package development