A Batteryless Thermoelectric Energy-Harvesting Interface Circuit with 35mV Startup Voltage

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Self-Powered Applications

- Energy efficiency of IC’s is crucial
- Micro-power sensor systems

Batteryless solutions desirable
Energy Processing Circuits

- Amount of electrical power obtained – better metric for energy harvesters

End-to-end efficiency is critical
Outline

• Thermoelectric Energy Harvesters
• Startup Technique
• Architecture and Energy Transfer Circuits
• Measurement Results
• Conclusion
Thermoelectric Energy Harvesters

- Convert heat energy to electrical energy
- Consists of p- and n-type Bismuth Telluride
- One p-n leg generates ~ 0.2mV/K

Seebeck Effect
Equivalent Circuit of Thermal Harvester

\[ V_T = S \Delta T \]

- Electrically in series, Thermally in parallel
- For a 10cm\(^2\) harvester, \( S = 23\text{mV/K} \), \( R_T = 5\Omega \)
- Extremely low voltage output

*Lim, Nasa Tech Briefs, 2008*
Mechanically Assisted Startup

- Small vibrations present in human motion
- Vibration driven switch kick-starts energy transfer
Mechanically Assisted Startup

\[
\begin{align*}
V_{DD} &= \left(\sqrt{\frac{L}{C_{DD}}}\right) V_T \\
i_L &= \frac{V_T}{R_T}
\end{align*}
\]

- \( L = 20 \mu \text{H}, \ C_{DD} = 470 \text{pF} \) and \( R_T = 5 \Omega \)

35mV input needed to get 1V at \( V_{DD} \)
Startup Block

Mechanical Startup
Architecture

- Digitally assisted control
- Storage block acts as energy buffer
- Buck converter outputs a 1.8V regulated supply
Storage Block – Boost Converter

- Activated when $V_{DD} > 1.8V$
- M3 is actively turned ON
- Storage voltage is unregulated
Zero Current Switching

- Pulse-width of PG is adjusted closed-loop to achieve zero current switching
DC-DC Buck Converter

- DC-DC is activated only after $V_{STO} > 2.4V$
- Pulse Frequency Modulation mode of control
• Pulse-width of NIN is adjusted closed-loop to achieve zero current switching
Disabling Start Block

- **$V_{DD}$** shorted with $V_L$ once $V_L > 1.8V$
- Start block is disabled
Maximum Power Transfer

\[ P_{\text{max}} = \frac{V_{TH}^2}{R_T} \]

\[ P_{\text{STO}} \approx \frac{V_{TH}^2}{8L_{\text{STO}}f_s} \]

- Free running boost converter switching at \( f_s \)
Maximum power transfer obtained by just choosing $f_s$ appropriately

\[
\frac{V_{TH}^2}{R_T} = \frac{V_{TH}^2}{8L_{STO}f_s}
\]

\[
f_s \approx \frac{R_T}{8L_{STO}}
\]
Test-Chip

- 0.35µm digital CMOS process
- Active area = 1.7mm²
Measured Startup Waveform

- \( V_T = 50\text{mV}; \quad R_T = 5\Omega \)
• Voltage source with $5\Omega$ resistance
• Startup – 35mV; Operational down to 25mV
Power Obtained at Storage Capacitor

- Obtained power stays constant from 2.4V – 5V
- Verifies operation of ZCS block

\[ V_T = 100 \text{mV} \]
\[ R_T = 5 \Omega \]
## Comparison with state-of-the-art

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lhermet ISSCC 2007</th>
<th>Doms ISSCC 2009</th>
<th>Carlson VLSI 2009</th>
<th>EnOcean</th>
<th>This work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>0.35μm</td>
<td>0.35μm</td>
<td>0.13μm</td>
<td>n/a</td>
<td>0.35μm</td>
</tr>
<tr>
<td>Min. input voltage</td>
<td>1V</td>
<td>0.6V</td>
<td>20mV</td>
<td>20mV</td>
<td>25mV (35mV to startup)</td>
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<tr>
<td>External voltage?</td>
<td>None</td>
<td>2V battery</td>
<td>Minimum of 650mV</td>
<td>None</td>
<td>None</td>
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<tr>
<td>Output Voltage</td>
<td>1.75V-4.3V</td>
<td>2V</td>
<td>1V regulated</td>
<td>4V-4.5V</td>
<td>1.8V regulated</td>
</tr>
<tr>
<td>Peak efficiency</td>
<td>50% (just boost converter)</td>
<td>70% (just boost converter)</td>
<td>52% (end-to-end)</td>
<td>20% (end-to-end)</td>
<td>58% (end-to-end)</td>
</tr>
<tr>
<td>Maximum Power Tracking?</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Conclusions

• Batteryless thermoelectric energy harvesting interface circuit with 35mV startup voltage

• Provides end-to-end efficiency of 58% with maximum power point tracking

• Optimized interface circuits are a key enabler of self powered systems

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