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

Baoxing Chen and Jane Cornett
Analog Devices, Inc.

3/30/2017

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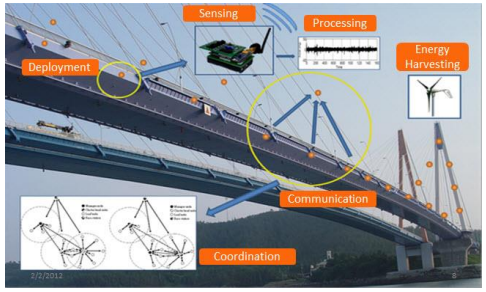
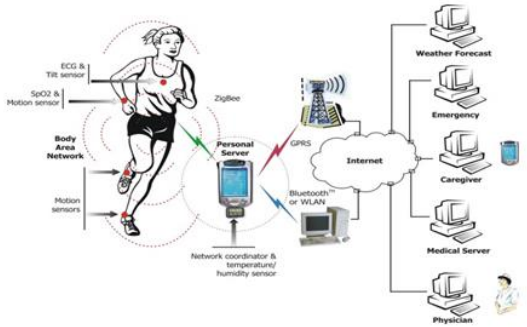
Internet of Things

Rapidly growing number of wireless sensors require reliable and maintenance-free power sources

Smart Buildings

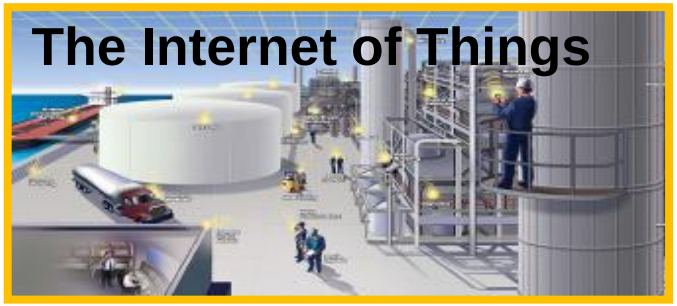


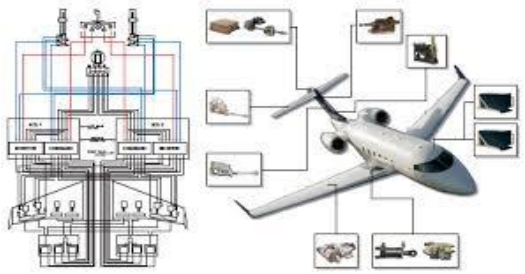
Infrastructure Monitoring



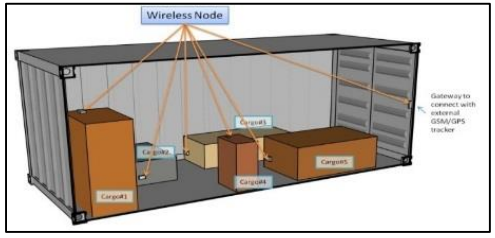
Wearable Sensors

Livestock Monitoring

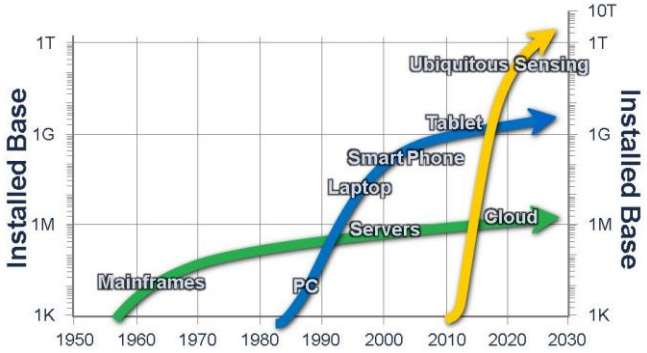




Plane/Vehicle Area Network



Asset Tracking



Crop Production

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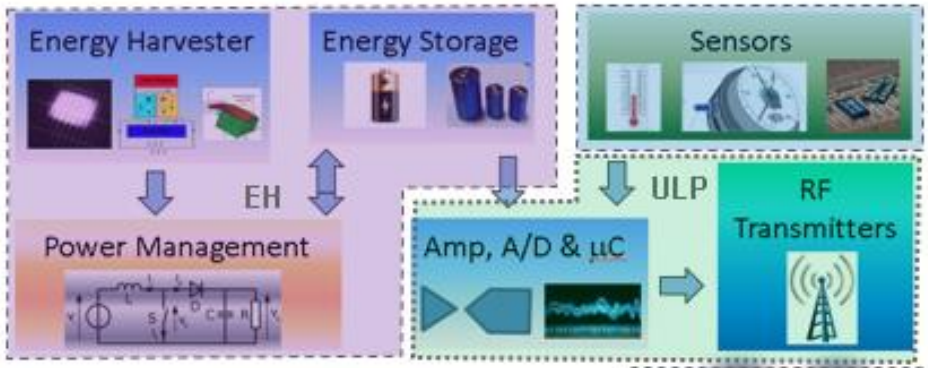
Chip-Scale Thermoelectric Harvester Improves Upon Discrete Solution



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

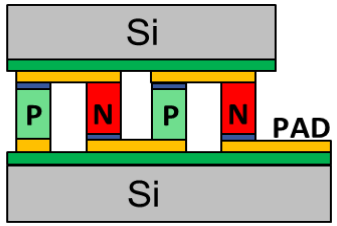
Chip-scale thermoelectric harvester:

- 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

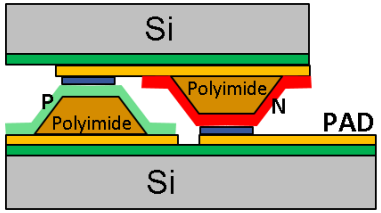
Downsides of traditional discrete devices:

- Large and expensive
- Low thermal resistance
- Low output voltage
- Unreliable

Vertical



Pyramid



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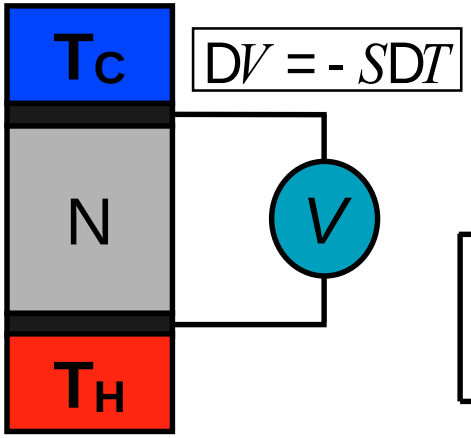
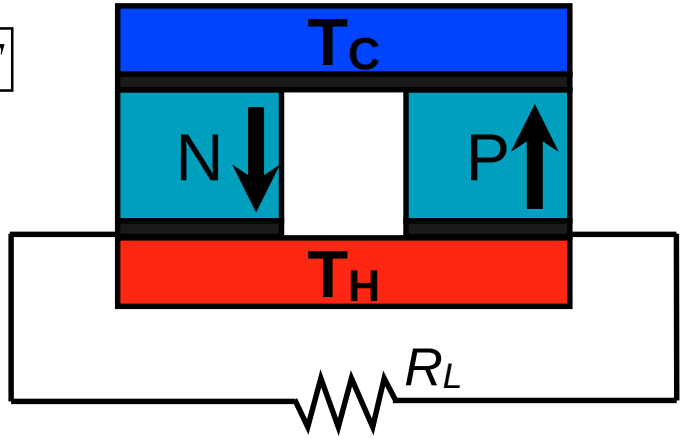
Thermoelectric Basics

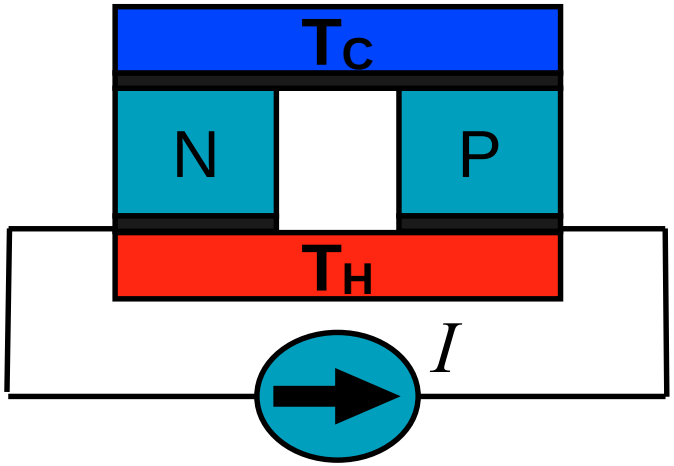


$$\Delta V = -S\Delta T$$

Seebeck Effect



Thermoelectric Power Generation



Thermoelectric Cooling

$$\eta_{max} = \frac{\Delta T}{T_{hot}} \frac{\sqrt{1+Z\overline{T}}-1}{\sqrt{1+Z\overline{T}}+\frac{T_{cold}}{T_{hot}}}$$

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

$$\frac{S^2\sigma}{\kappa}T$$

$$\kappa = \kappa_e + \kappa_{phonon} \qquad \frac{\kappa_e}{\sigma T} = L_0 = \frac{\pi^2}{3}\left(\frac{k_B}{e}\right)^2$$

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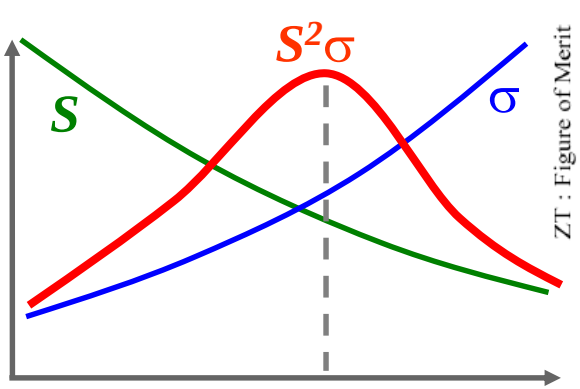
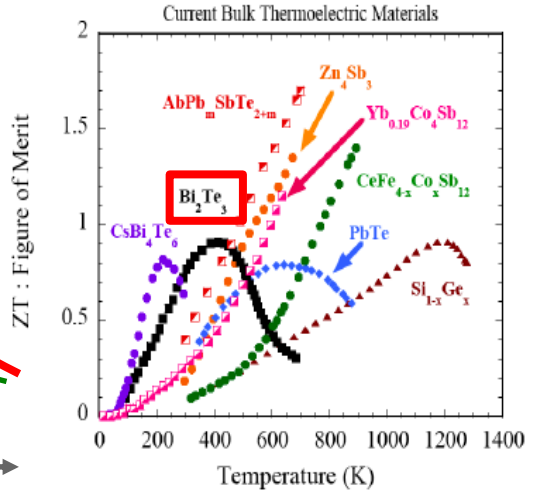
Maximize ZT: Phonon Glass; Electron Crystal





Best room temp prop: Bi_2Te_3

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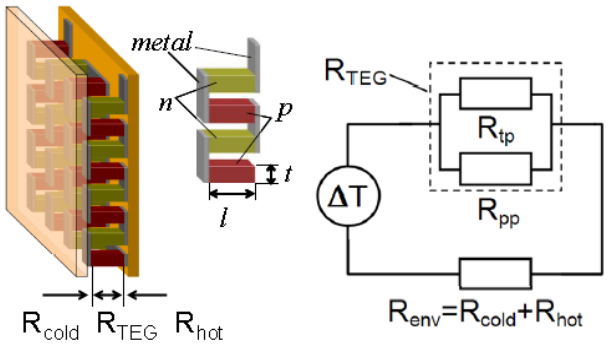
Thermal Impedance Matching For Maximum Power Output



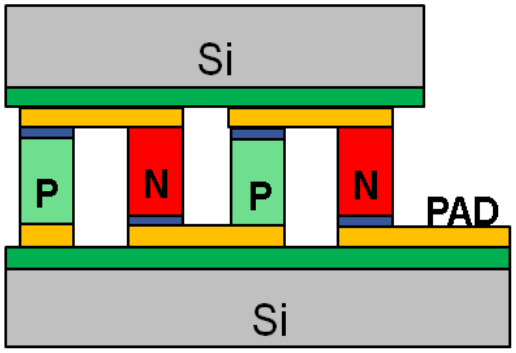
$$\Delta T(device) = \frac{R_{tp} \parallel R_{pp}}{R_{cold} + R_{hot} + R_{tp} \parallel R_{pp}} \Delta T$$

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

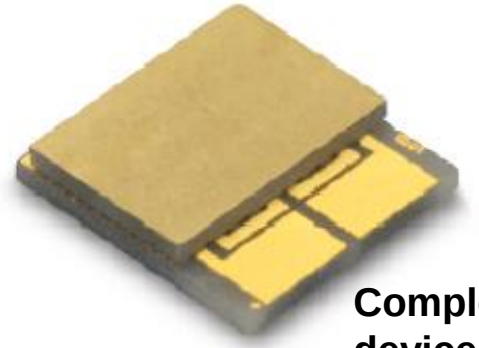
$$P = \frac{(V_{src} \frac{R_L}{R_{src} + R_L})^2}{R_L}$$

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

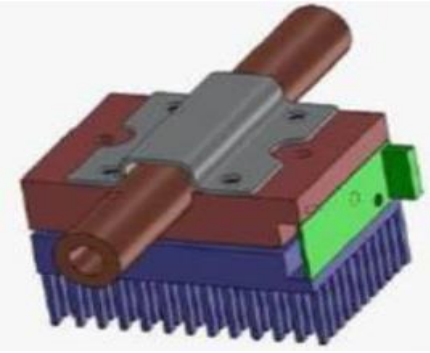
Load Matching
Thermal Impedance Matching → **Max Power**



Internal architecture



Complete device



System implementation

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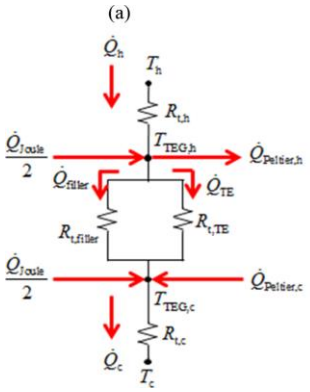
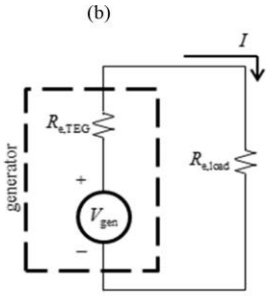
Modeling of Bi_2Te_3 Vertical Structures

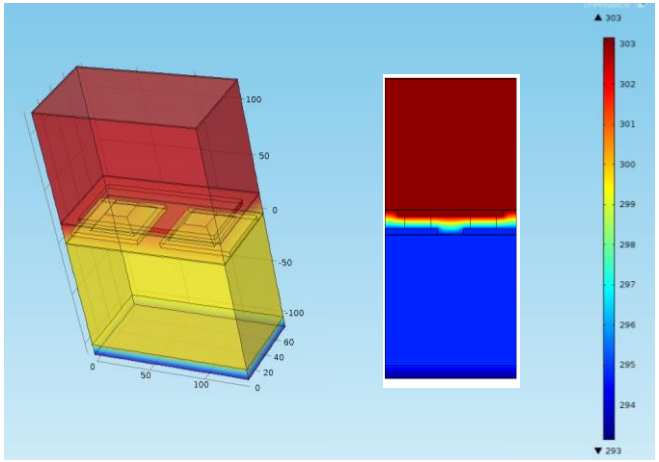
- Quick 1D thermal models used to determine optimal device configurations and predict device performance
  - Includes Joule & Peltier heating
- In-depth 3D COMSOL modeling to fine-tune device performance, explore adjustments to structures and elucidate problem areas

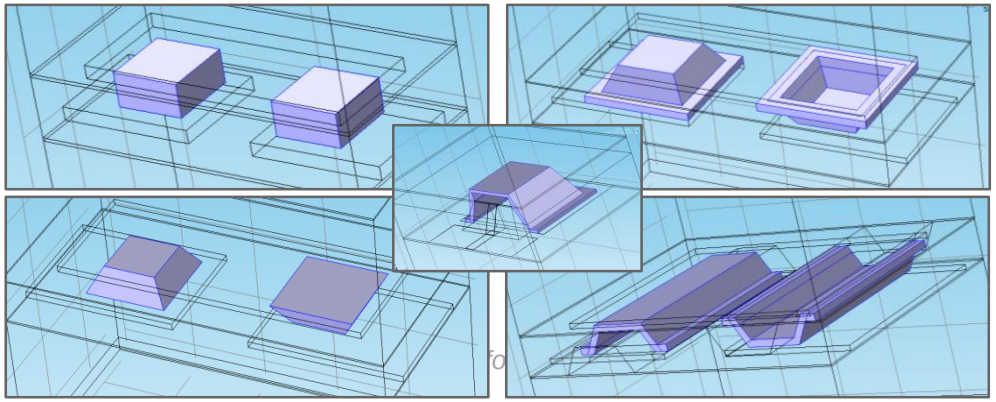




Thermal Resistor Network

3D Model of Single Thermocouple





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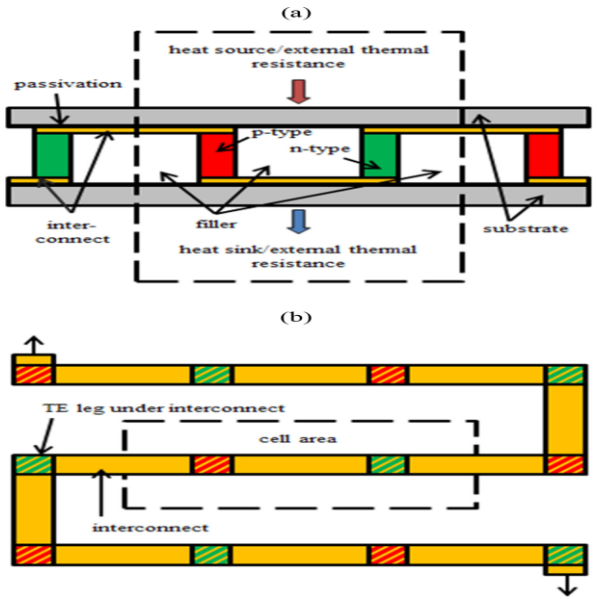
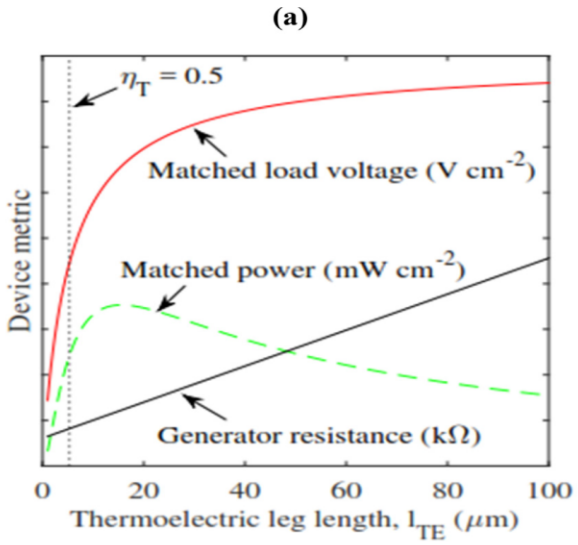
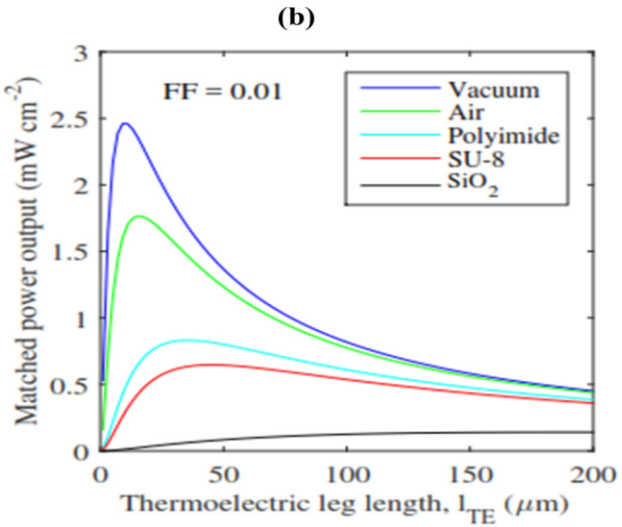
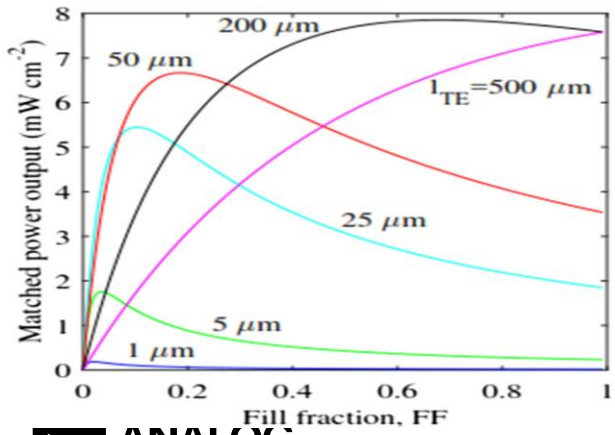
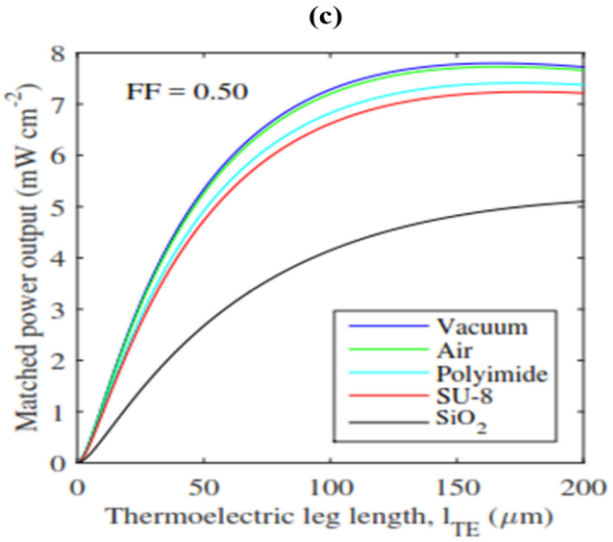
Power Optimization of Vertical Devices

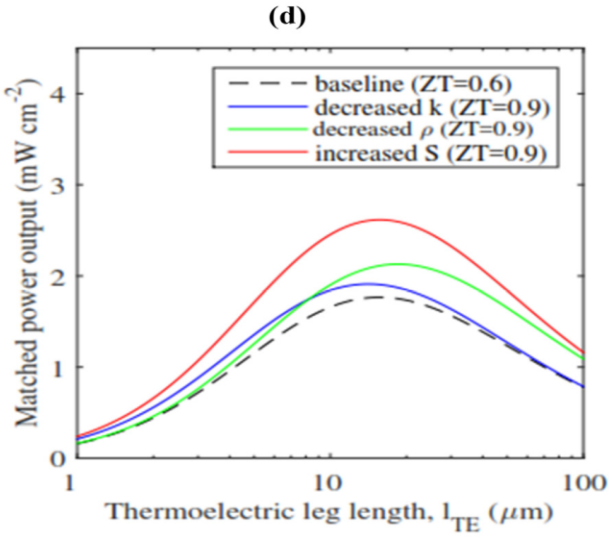












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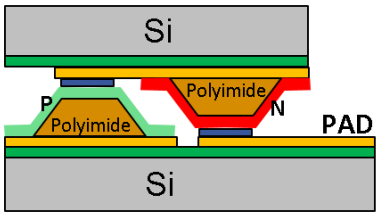
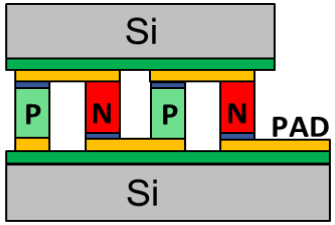
Energy 93 (2015) p2006-2017

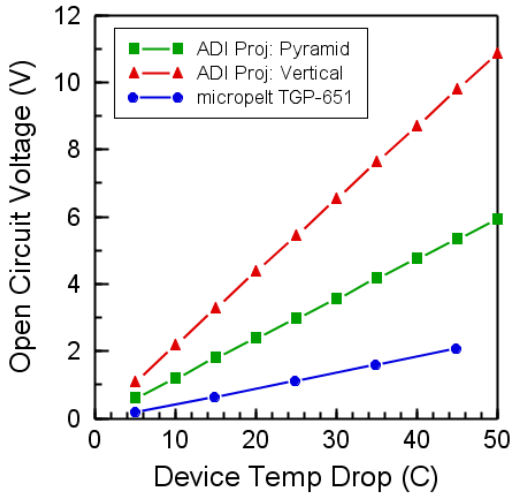
Projected Performance of Bi_2Te_3-based Devices

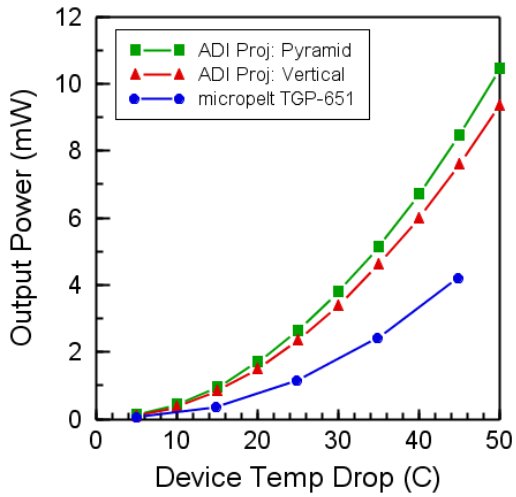
Pyramid



Vertical



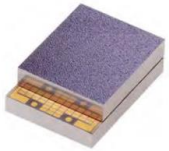




Performance compared with competitor:

micropelt TGP-651

- Bi_2Te_3-based
- 3mm x 3mm



- **ADI 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)

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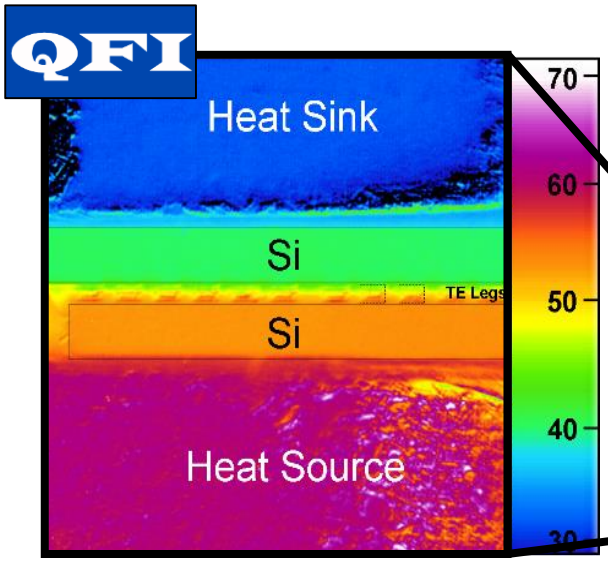
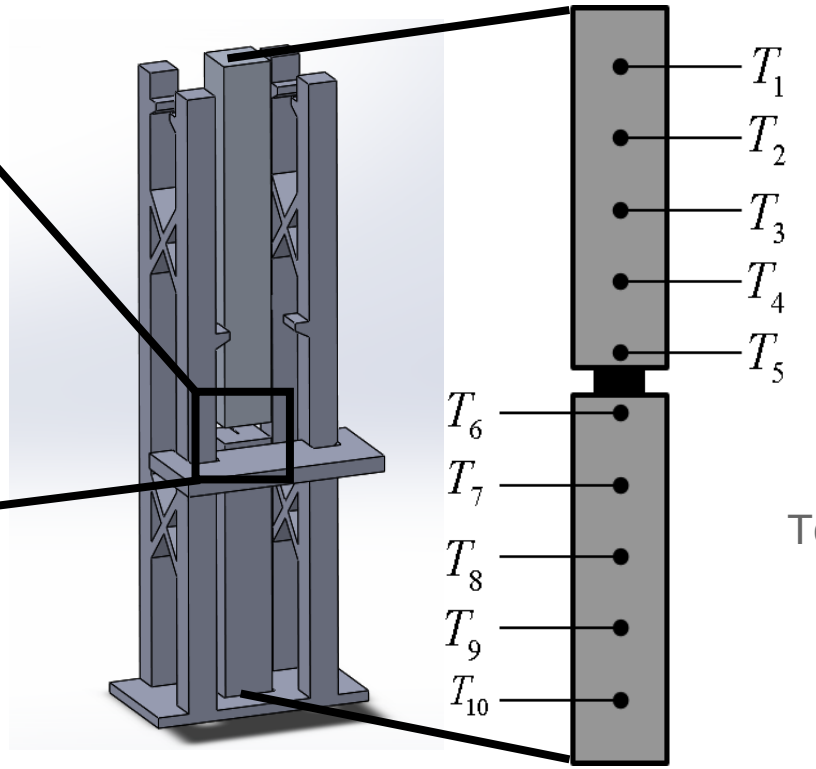
Device Performance Characterization
Methods

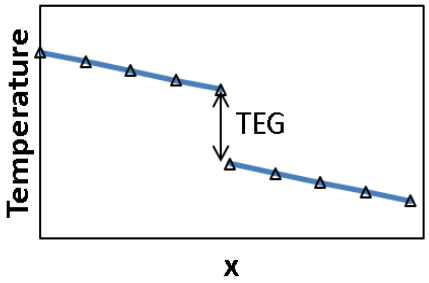
- **Basic characterization premise: Measure device performance under known temperature gradient**
  - Accurate measurement of ΔT **difficult** and **critical** for device characterization
- **Methods used: Device sandwiched between heated and cooled metal blocks**



IR Imaging

High resolution to elucidate problem areas

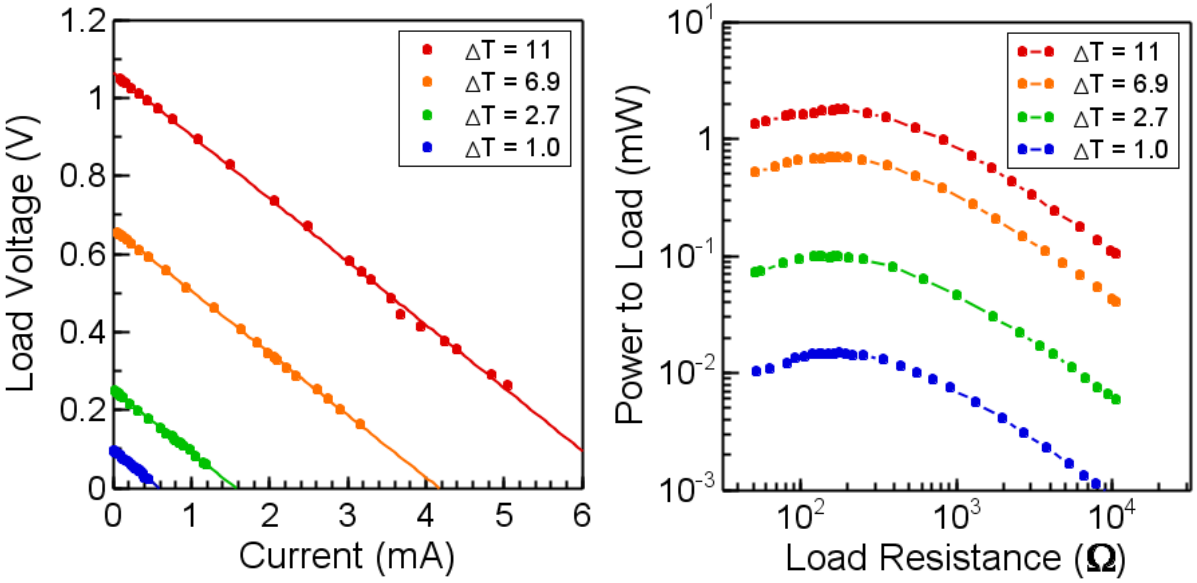




Calibration Measurement

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 ΔT

- Larger ΔT ➡ More power
- Maximum power achieved for matched load conditions

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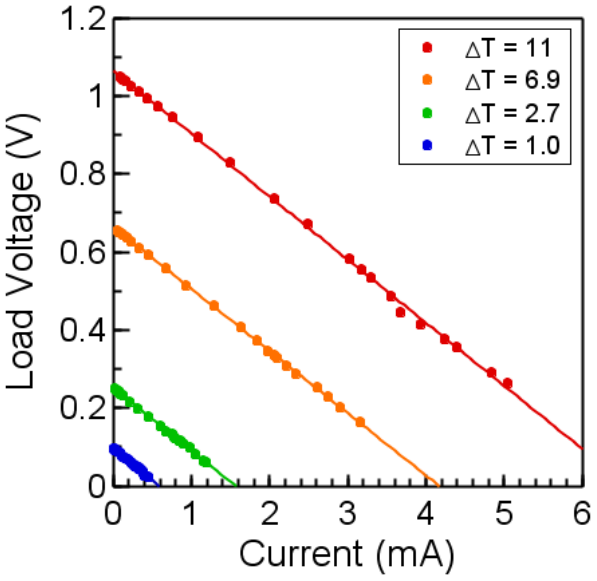
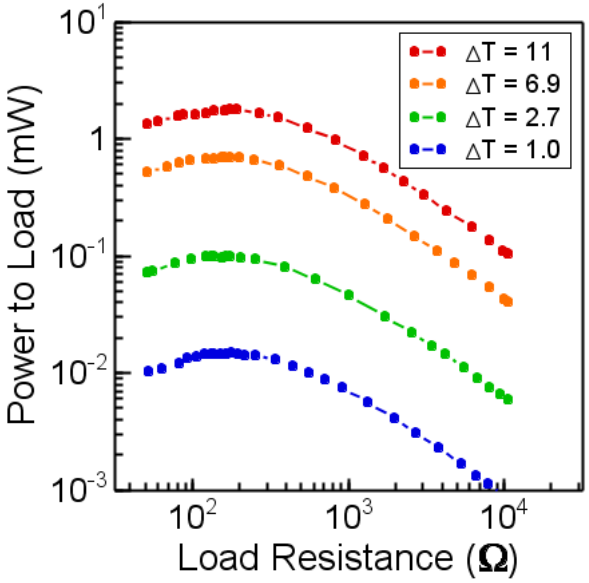
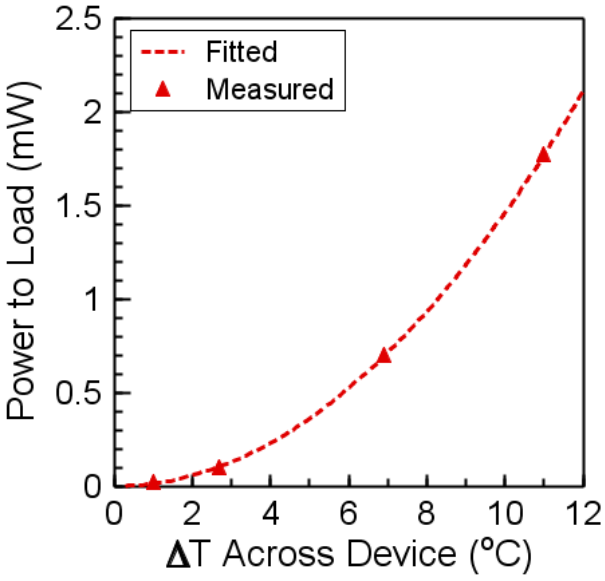
Device Performance Characterization
Sample results



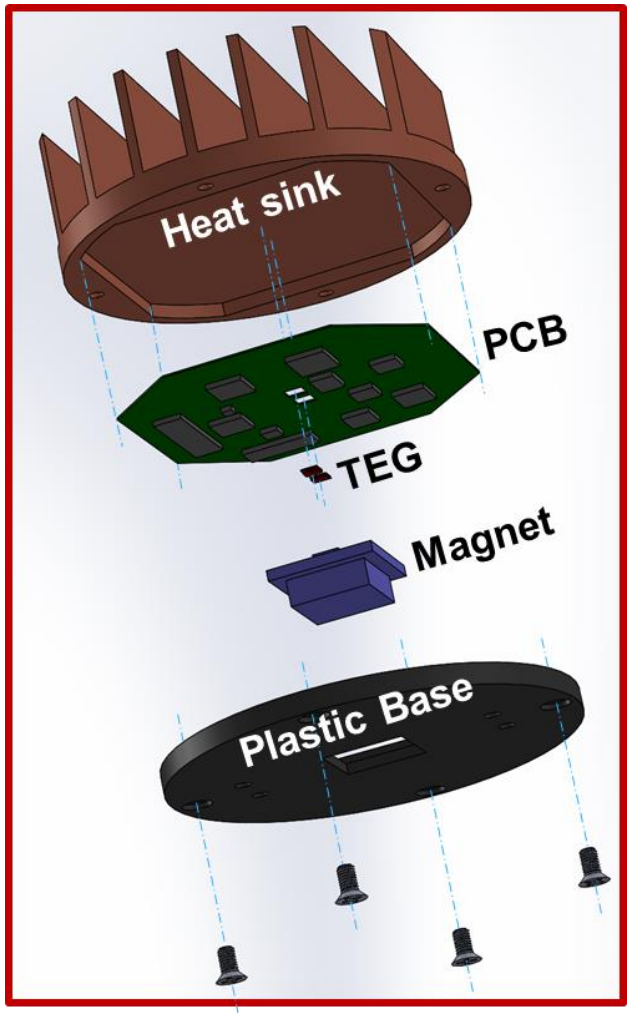




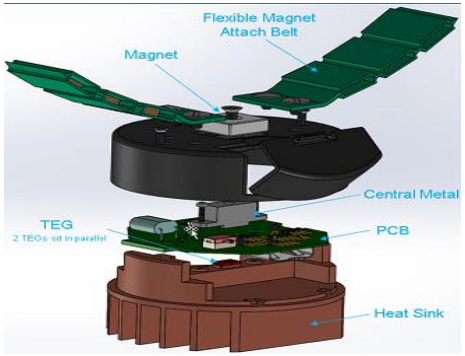
Example set of data collected for a single device

Power at matched load
$\propto \Delta T^2$

Machine Health Monitoring
Wireless sensor node powered by TEG



BTLE Interface



- **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***

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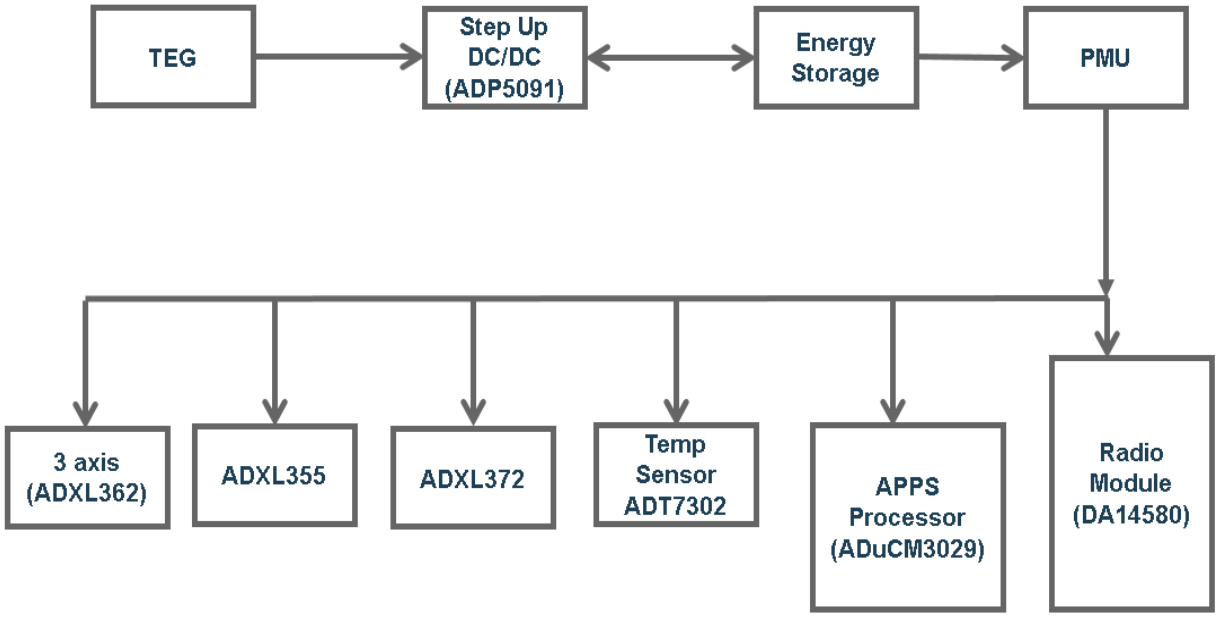
Wireless Machine Health Monitoring System

TEG-Powered Sensor Node



- 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

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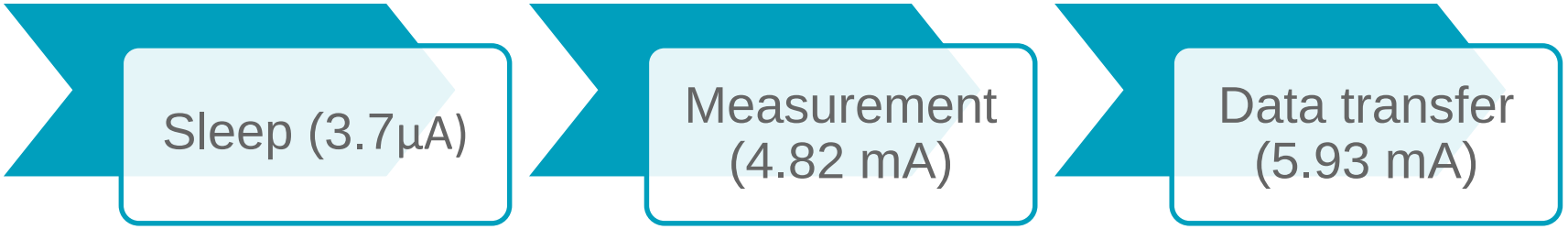
Power Budget for Machine Health Monitor



ADXL355	0	200µA	0
ADXL372	0	21µA	0
ADT7302	0	1.6mA	0
ADXL362	270nA	270nA	270nA
ADP5092	360nA	360nA	360nA
ADuCM3029	2µA (hibernate)	2.5mA	2.5mA
BLE	1µA (extended sleep)	1.8µA	3.4mA
Total	3.63µA	4.3mA	5.9mA

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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