Optimization of chip-scale thermoelectric energy harvesters for room temperature energy harvesting applications

EnerHarv 2018

J Cornett, H Berney, M Morrissey, S Haidar, M Dunham, S Geary, W Lane, B Chen

Outline

- Introduction to thermoelectricity
  - Thermoelectric effects
  - Refrigeration and power generation applications
  - Thermoelectric energy harvesting
- Design and modeling of TEGs
- ADI's chip-scale TEG
  - Device architecture
  - Process flow overview
- TEG-powered condition-based monitoring

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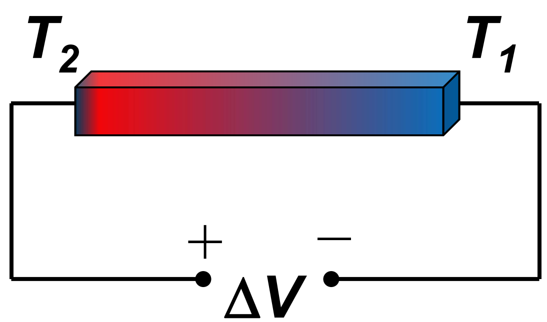
Thermoelectric Phenomena

Seebeck Effect



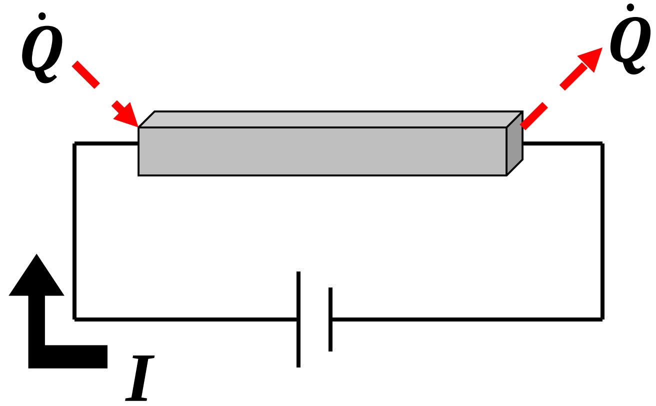
$$S = -\frac{\Delta V}{T_2 - T_1}$$

Seebeck coefficient

p-type: $S > 0$

n-type: $S < 0$

Peltier Effect



$$\pi = \frac{\dot{Q}}{I}$$

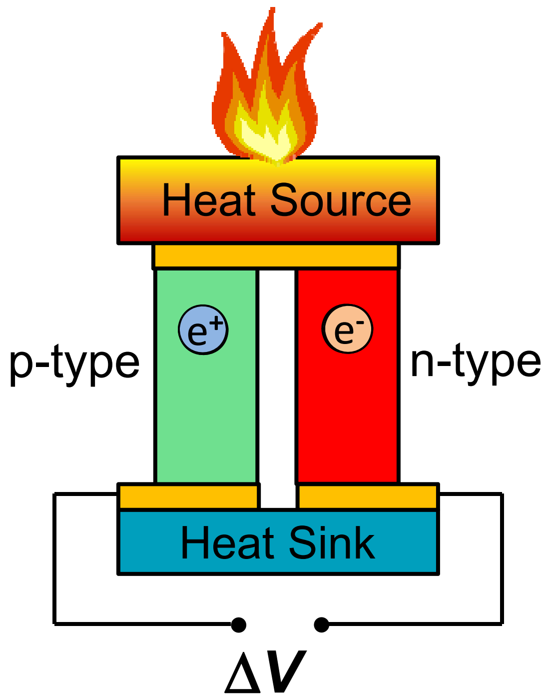
Peltier coefficient

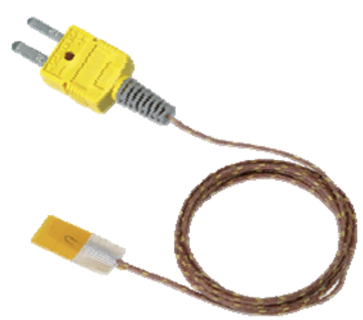
p-type: $\pi > 0$

n-type: $\pi < 0$

Thermoelectric Phenomena

Power Generation





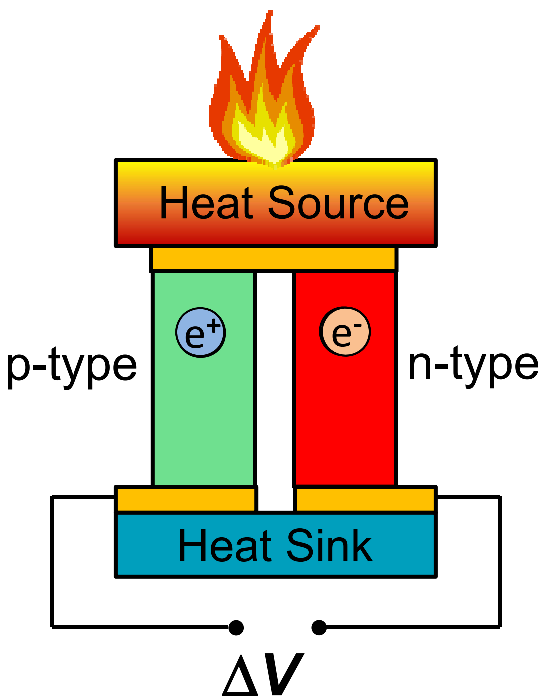
$$S_{pn} = S_p - S_n$$

$$\Delta V_{pn} = \Delta V_p - \Delta V_n$$

$$= S_{pn} \cdot \Delta T$$

Thermoelectric Phenomena

Power Generation



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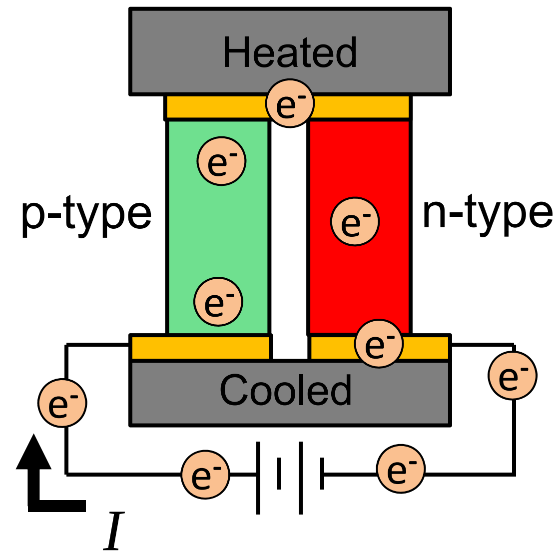
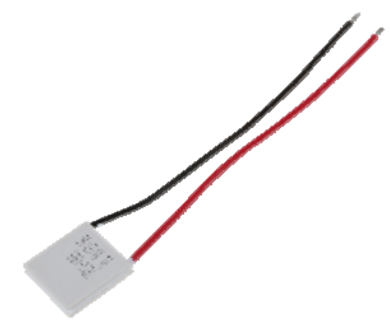
Refrigeration





$$\pi_{pn} = \pi_p - \pi_n$$

$$\dot{Q}_{pn} = \dot{Q}_p - \dot{Q}_n$$

$$= \pi_{pn} \cdot I$$

AHEAD OF WHAT'S POSSIBLE™

Thermoelectric Figure of Merit

Maximize

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

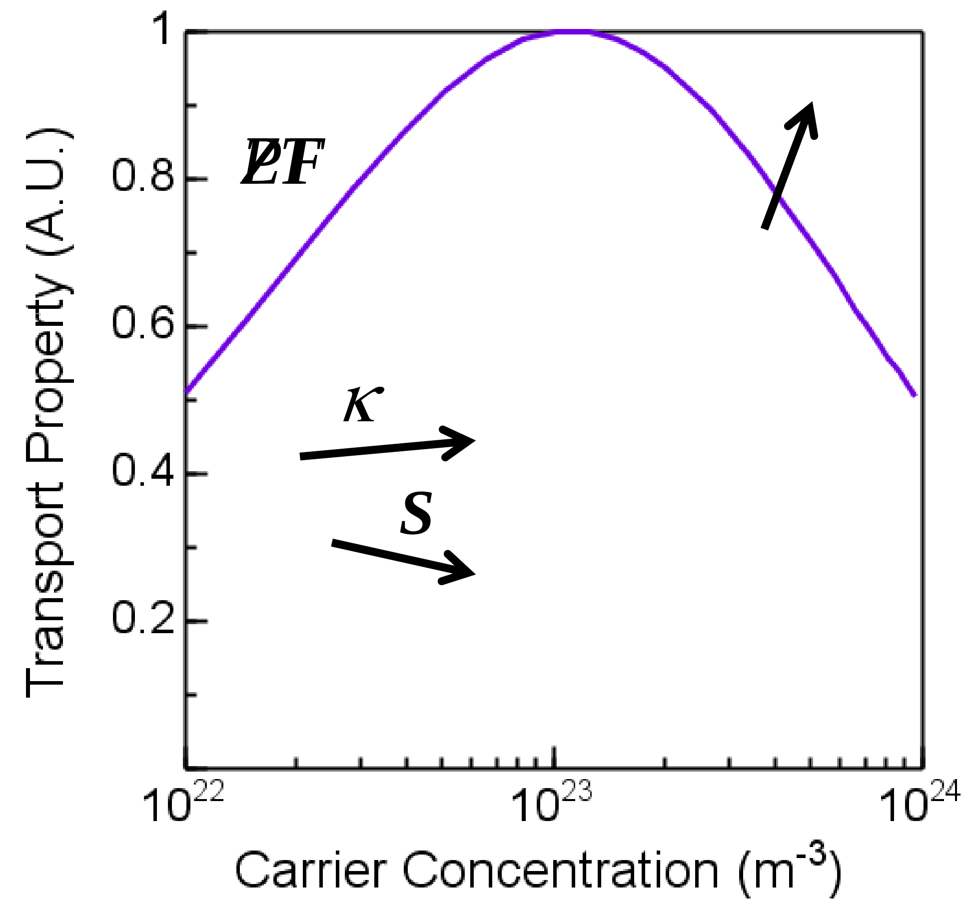
Minimize

- σ : Electrical conductivity
- S : Seebeck coefficient
- σS^2: Power factor
- κ : Thermal conductivity

In general:

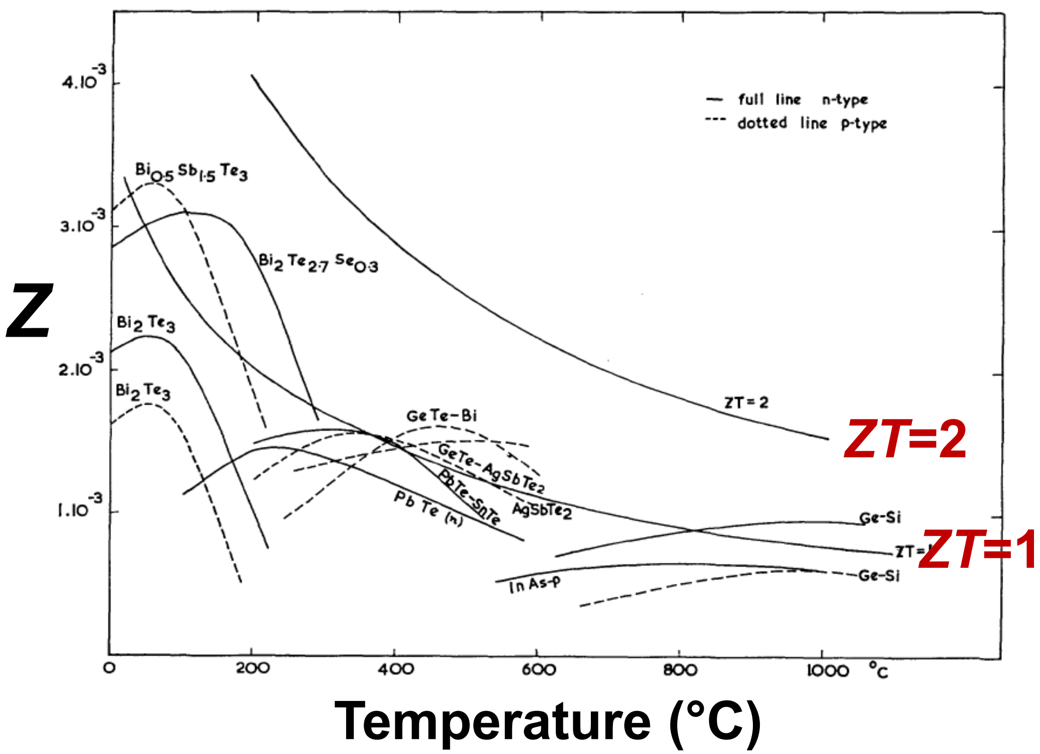
- σ increases, S decreases
- σ increases, κ increases

$$\kappa_e \propto \sigma$$

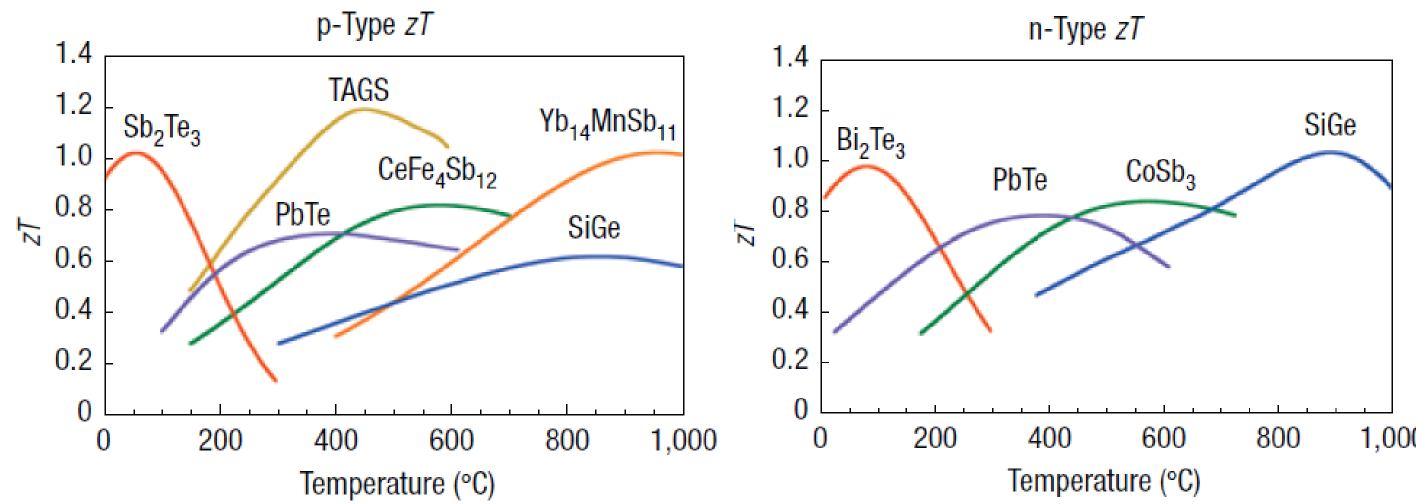


State-of-the-Art ZT Values

ZT in 1970



ZT in 2008



Best room temperature thermoelectric materials: Bi_2Te_3- and Sb_2Te_3-related

Wright, D.A. *Metallurgical Reviews* **15,** 147 (1970)

Snyder, G. et al. *Nature Mater.* **7,** 105-114 (2008)

Refrigeration Applications

CPU


Laser diodes


Picnic baskets

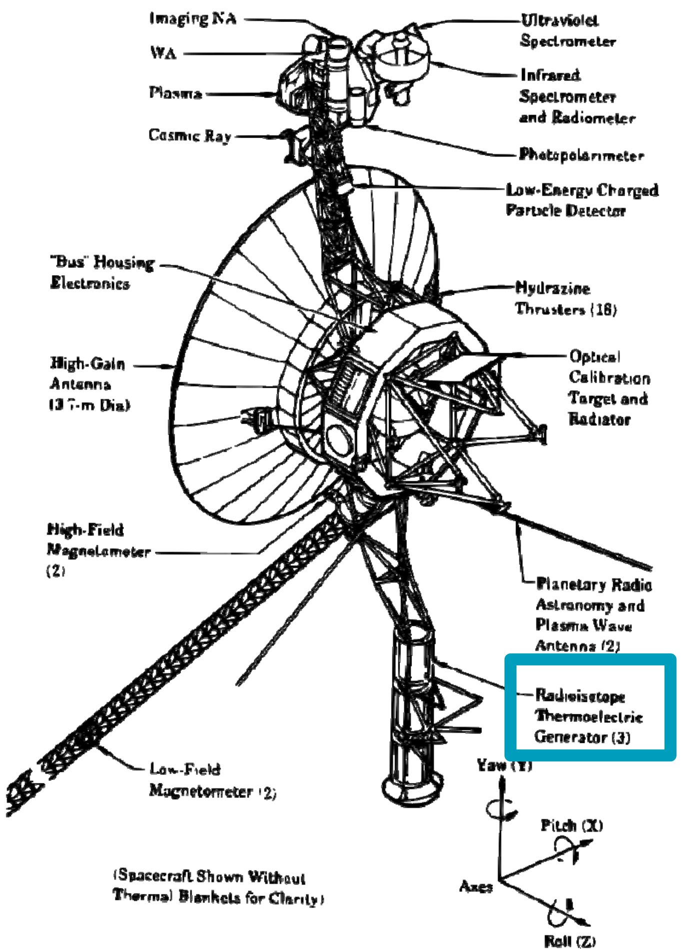

Car seats

Wine coolers

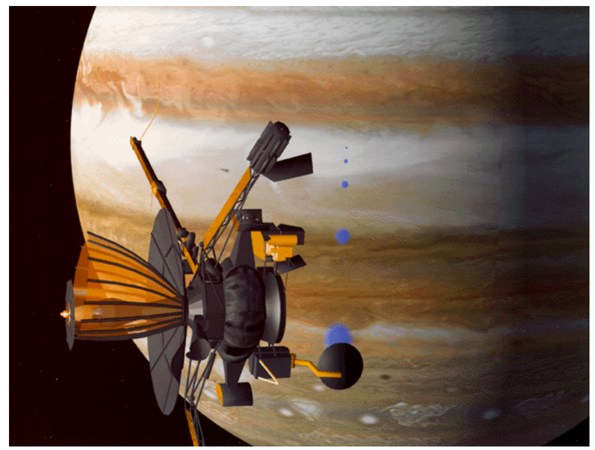
Power Generation Applications

In Space

Voyager (1977-?)



Galileo (1989-?)



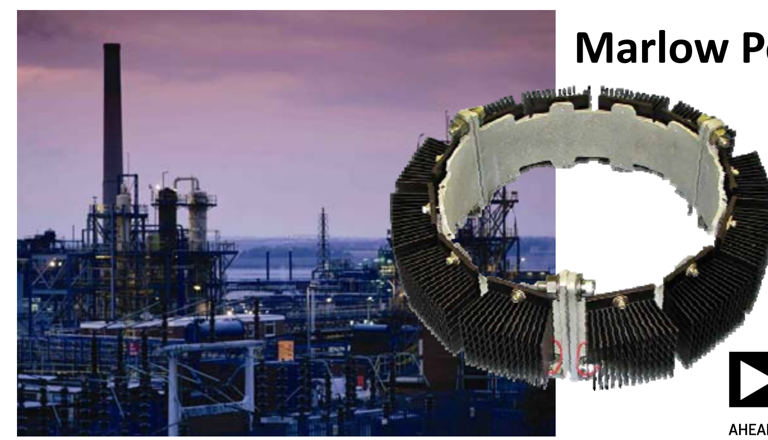
Mars Rover Curiosity (2011-?)

On Earth

Ford Lincoln MKT

Chevy Suburban

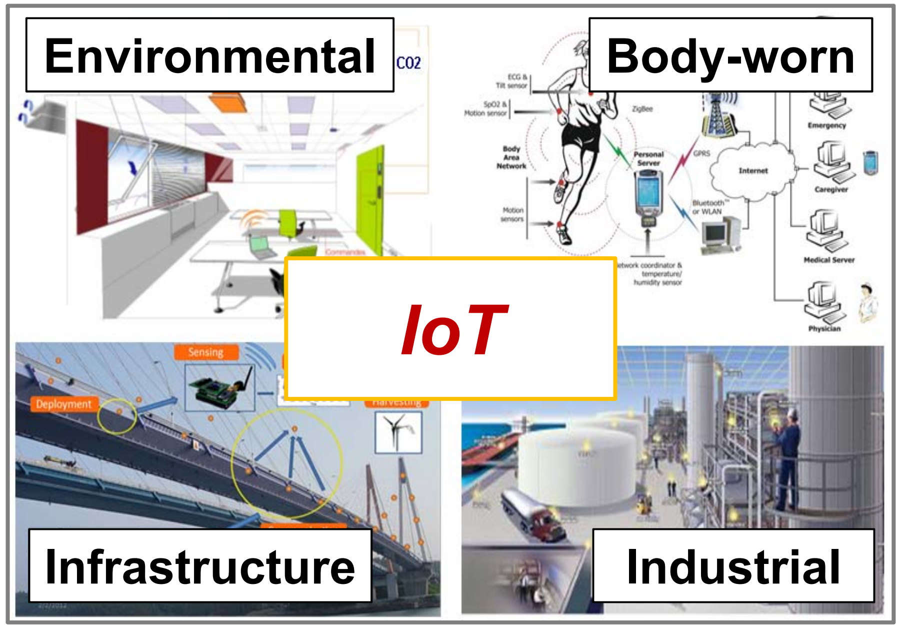
BMW X6



Marlow PowerStrap

Power Generation Applications: The Internet of Things

- ***Problem:*** **Continuously growing market of small wireless devices and sensors require power**



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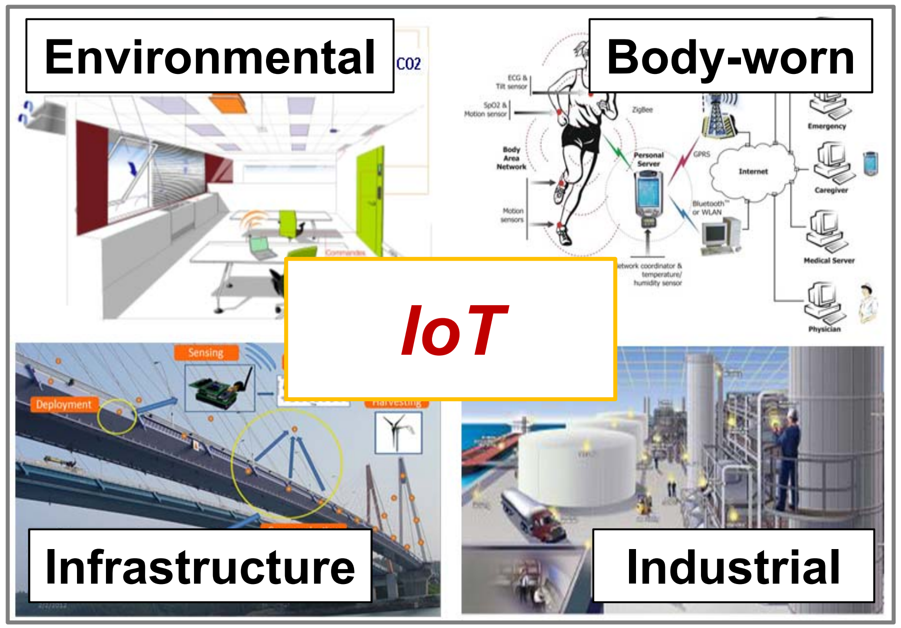
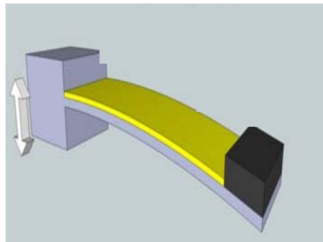


- ***Solution:*** **Energy harvesting**

Generating small amounts of power from external, otherwise wasted sources

Solar

Wind



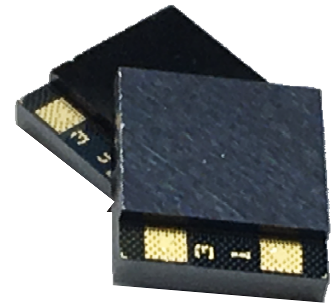
Vibration

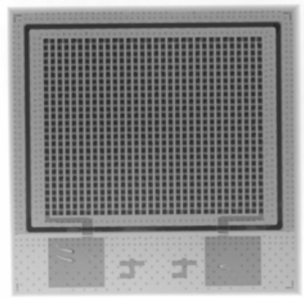
Heat

Thermoelectric energy harvesting!

Chip-Scale Thermoelectric Energy Harvesting

vs





Bulk TEG

- Large device area
- Expensive
- Bulk processing: Low number of TE legs
- Low device thermal resistance
- Low output voltage

Chip-scale TEG

- Small device area (***10mm²***)
- Low-cost
- Microfabrication: Hundreds to thousands of TE legs
- High device thermal resistance: ***Optimize ΔT captured***
- High output voltage: ***Maximize efficiency*** of power management

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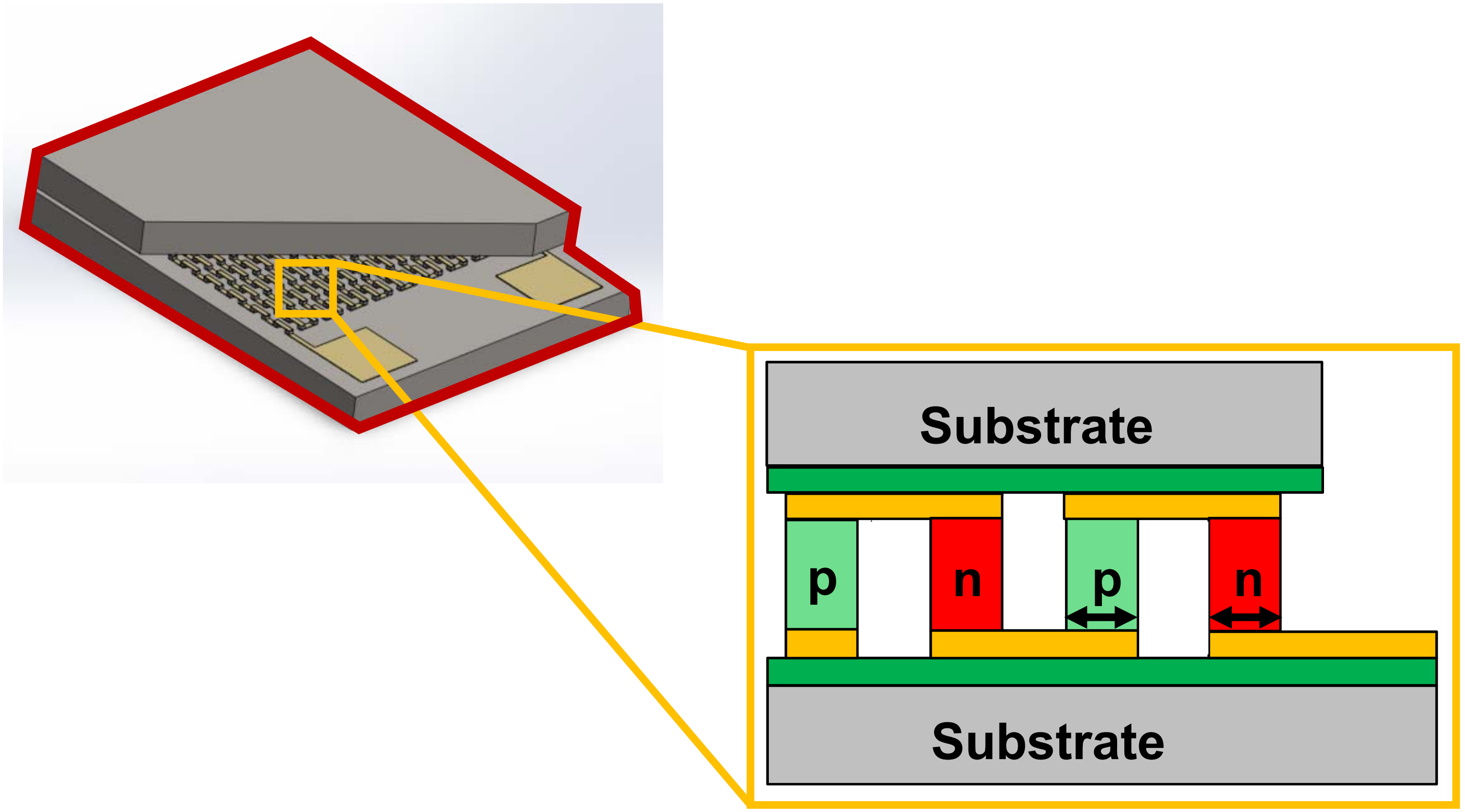
Design of Chip-Scale TEGs

Design parameters:

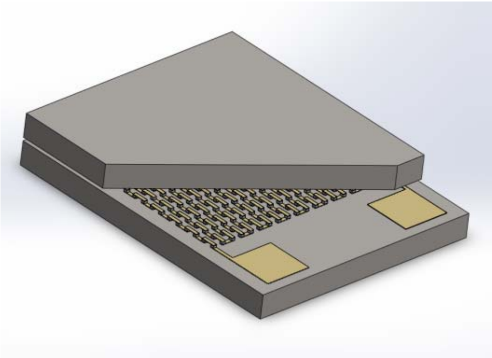
- Total device area
- Substrate material and thickness
- TE materials
- Interconnect materials
- TE element height
- TE element area
- Number of TE elements (fill factor)
- Filler material

Device characteristics:

- Electrical resistance
- Thermal resistance
- Output voltage (device Seebeck)



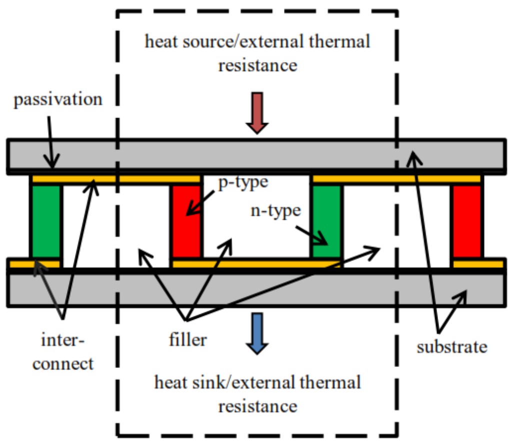
Modeling of Chip-Scale TEGs



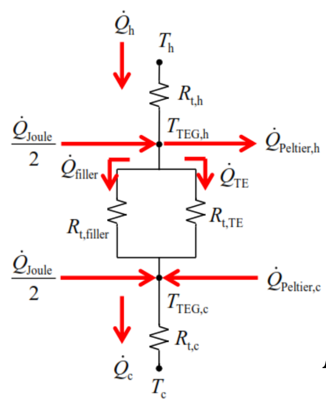
Complete TEG

Modeling of Chip-Scale TEGs

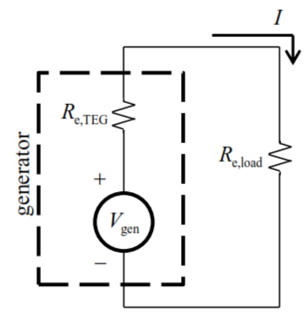
Complete TEG



Simplify thermal and electrical systems:
Single Thermocouple



1D thermal resistor network



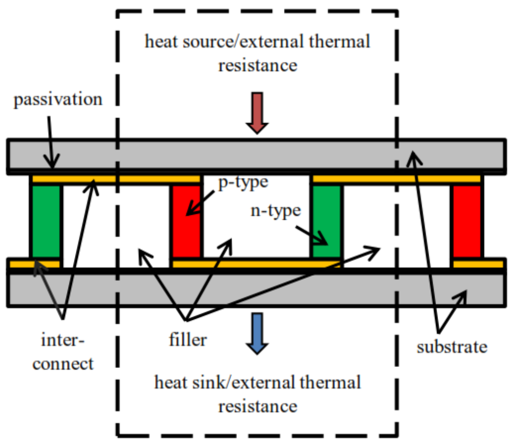
$$P_{load} = \frac{V_{load}^2}{R_{load}} \propto (\Delta T_{TEG})^2$$

Simplified electrical circuit

Dunham, *et al*., 2015, Energy

Modeling of Chip-Scale TEGs

Complete TEG



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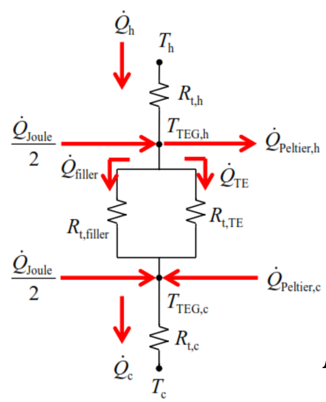

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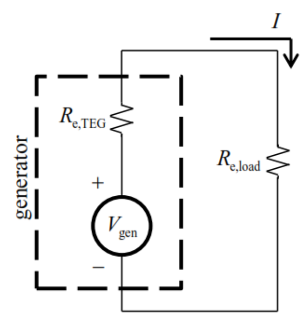

$$P_{load} = \frac{V_{load}^2}{R_{load}} \propto (\Delta T_{TEG})^2$$

Simplified electrical circuit

Performance Matrix

Change # of TCs

[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
20	4.99	1668	5	2040	804	1.39	0.58	2400
20	4.99	1668	10	2040	367	0.96	0.38	2500
20	4.99	1668	12	2040	288	0.85	0.34	2500
20	4.99	1668	15	2040	209	0.72	0.29	2500
20	4.99	1668	20	2040	135	0.58	0.23	2500
20	4.99	1668	30	2040	70	0.43	0.16	2600
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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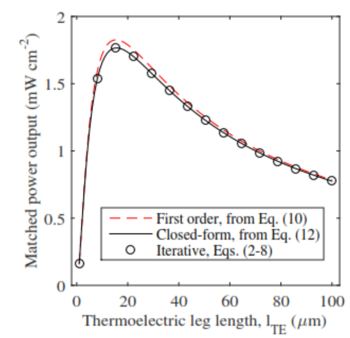
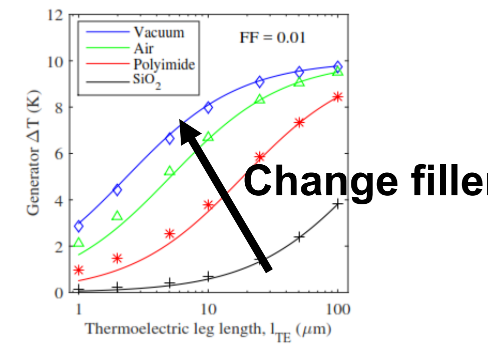


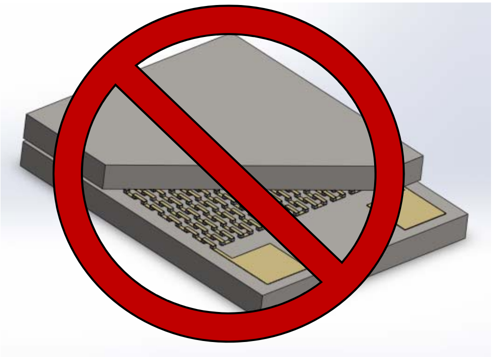


Change leg length

Excellent 1st approximation for expected device performance

Dunham, *et al.*, 2015, Energy

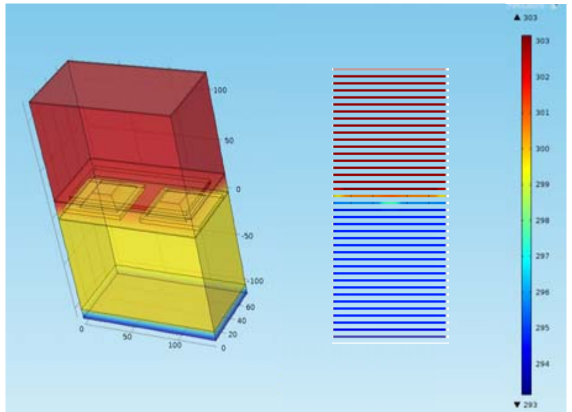
Modeling of Chip-Scale TEGs
Using 3D finite elemental analysis software

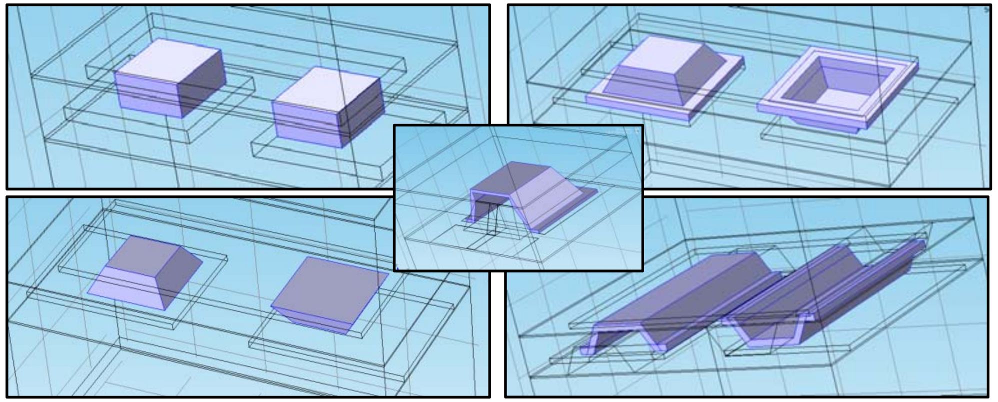


Complete TEG

3D FEA Modeling (COMSOL)

- ***Fine-tune device performance***
- ***Explore 3D adjustments to geometry***
- ***Elucidate problem areas***

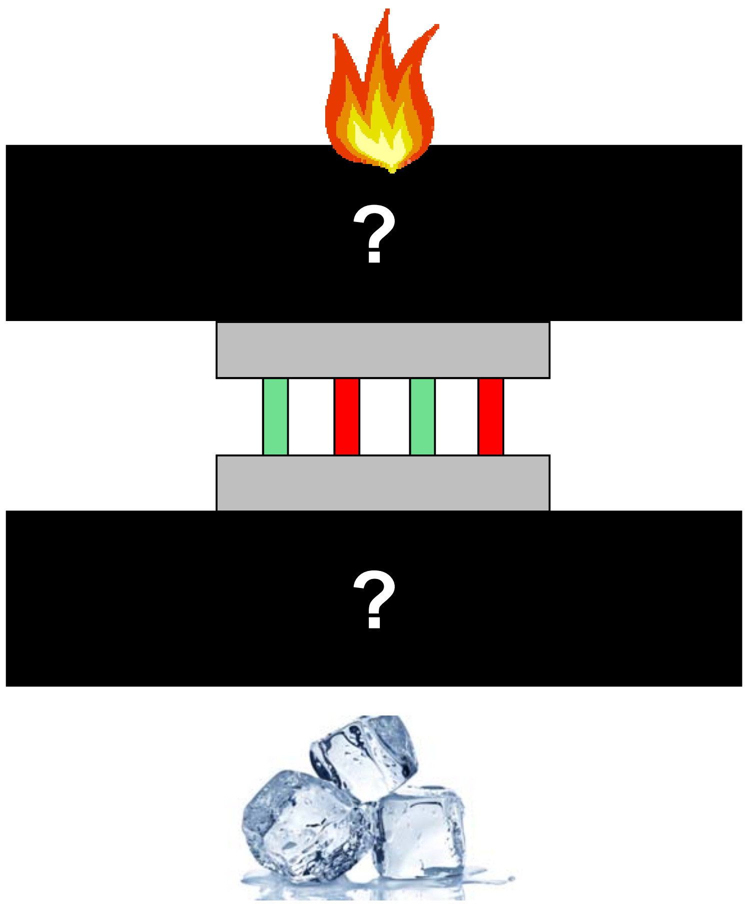




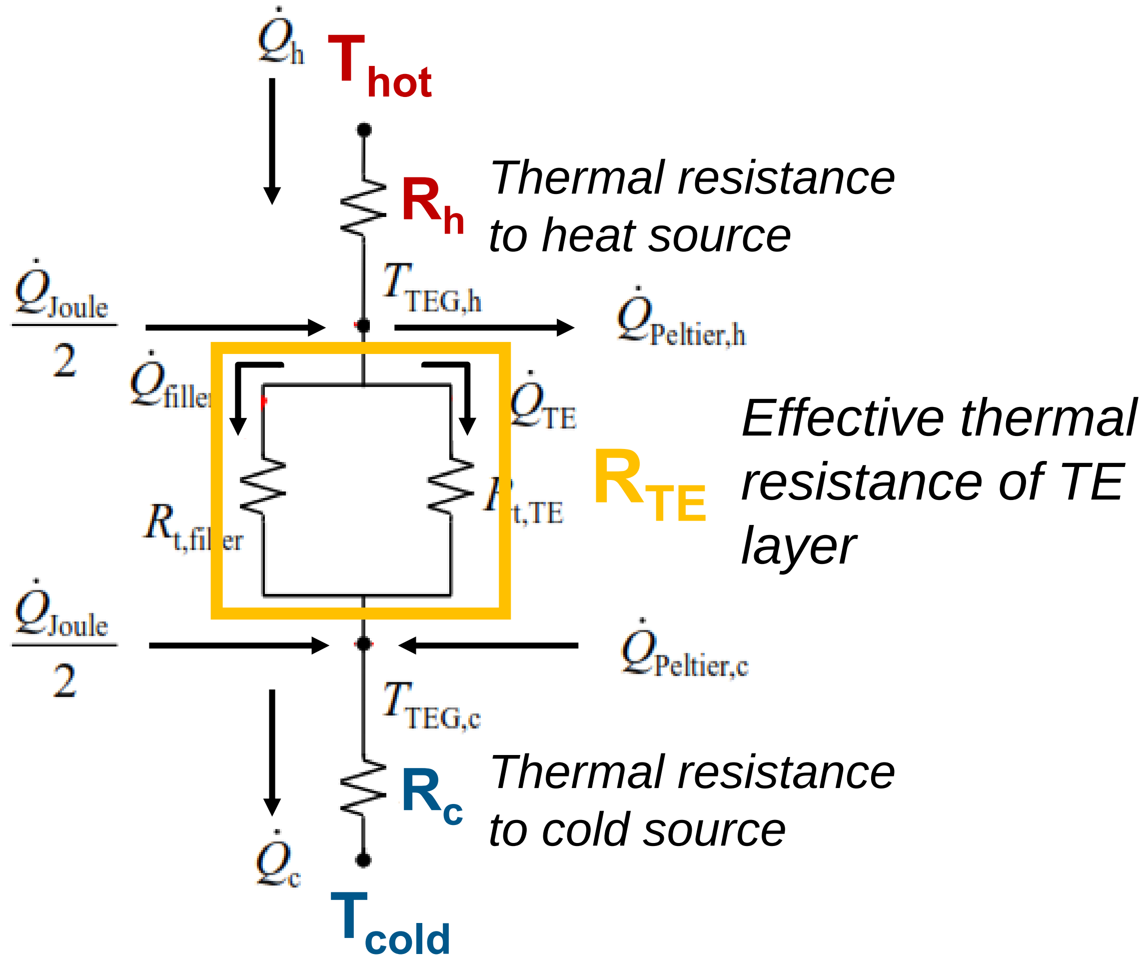
Simplify thermal and electrical systems: Single Thermocouple

Important Design Constraint
Thermal resistance of TEG

Heat source



Heat sink



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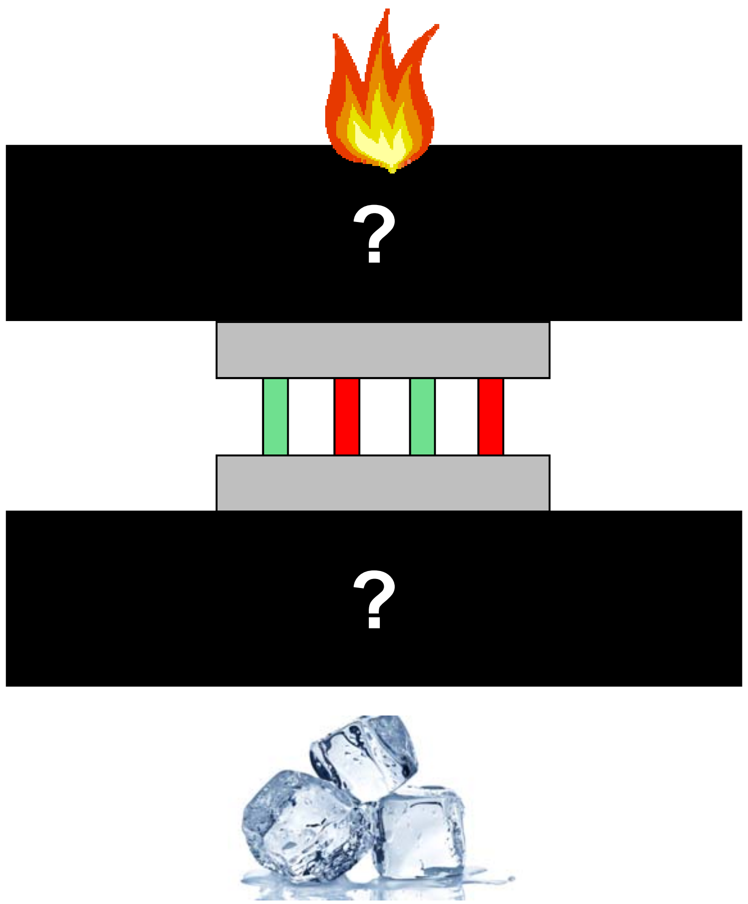

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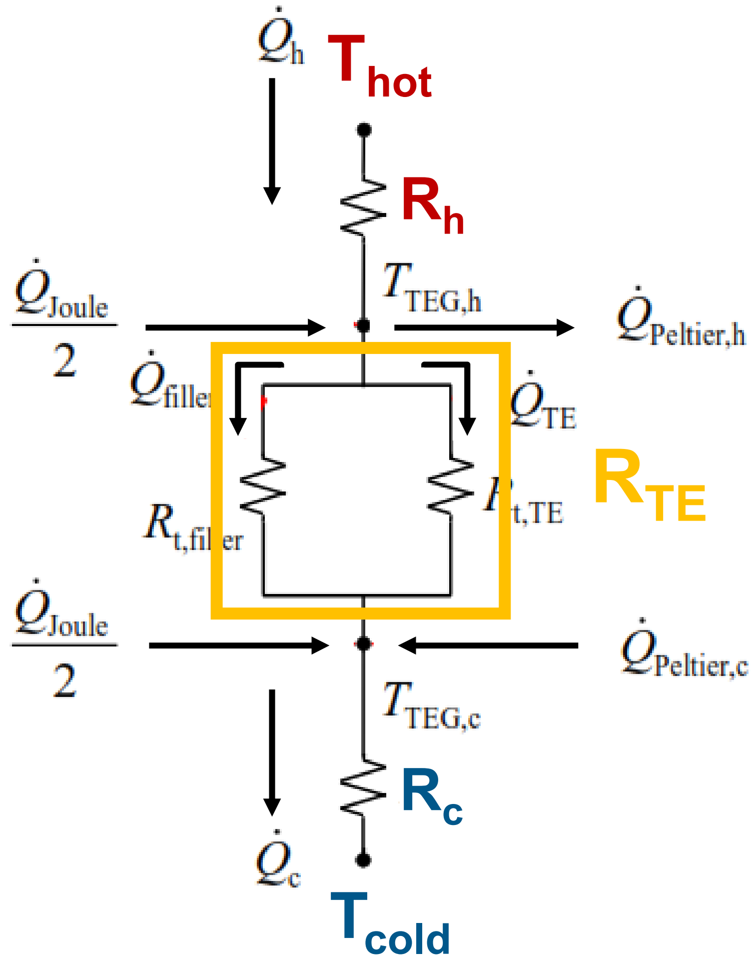


Condition for Maximum Power Output

$$R_{TE} = R_h + R_c$$

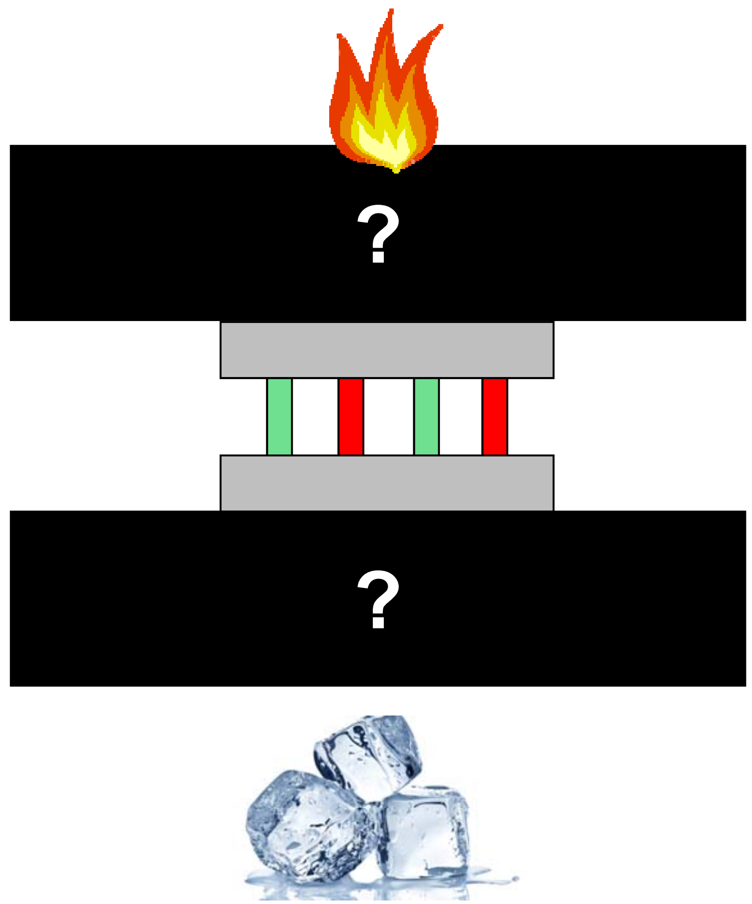
Thermal impedance matching

$$\Delta T_{TE} = \frac{T_h - T_c}{2}$$

Half of total *ΔT* falls across TE

Important Design Constraint
Thermal resistance of TEG

Heat source



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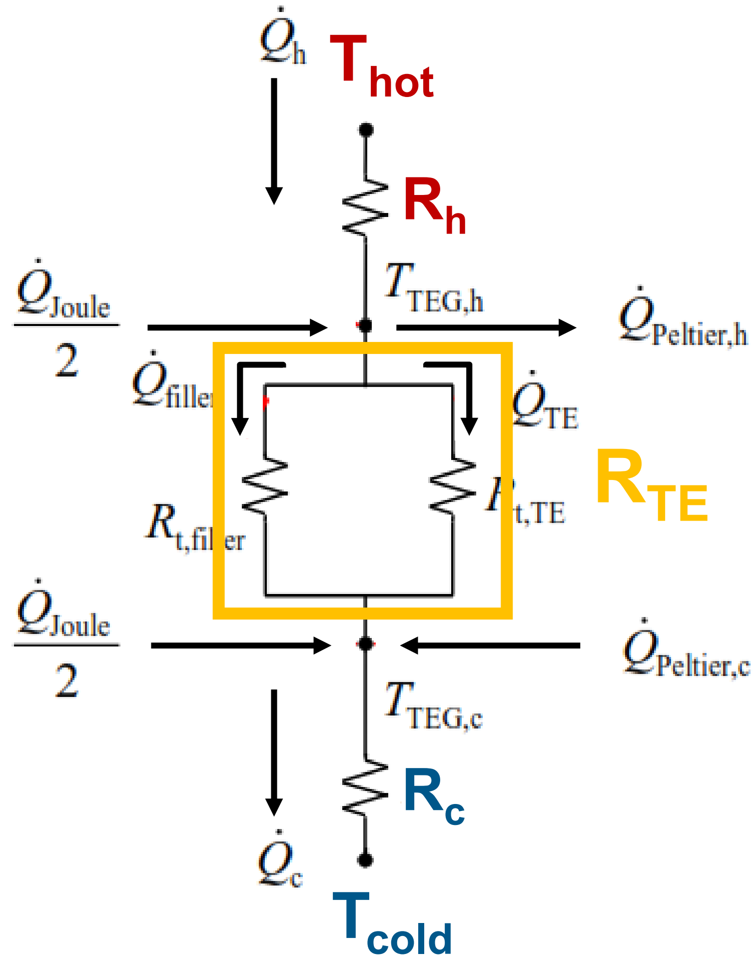

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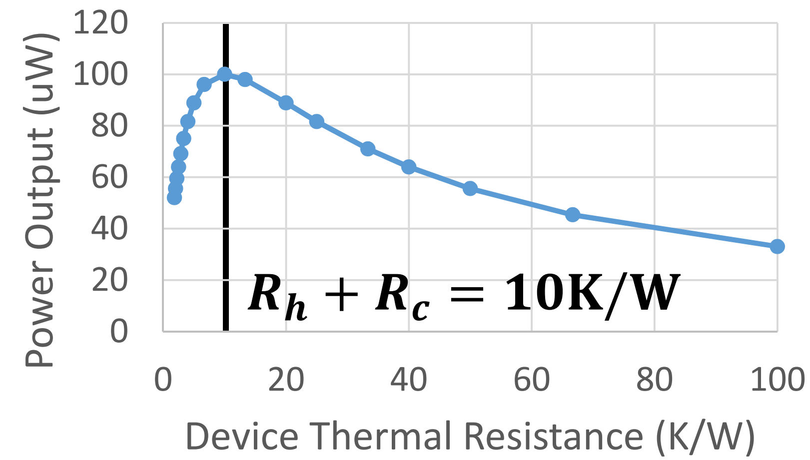
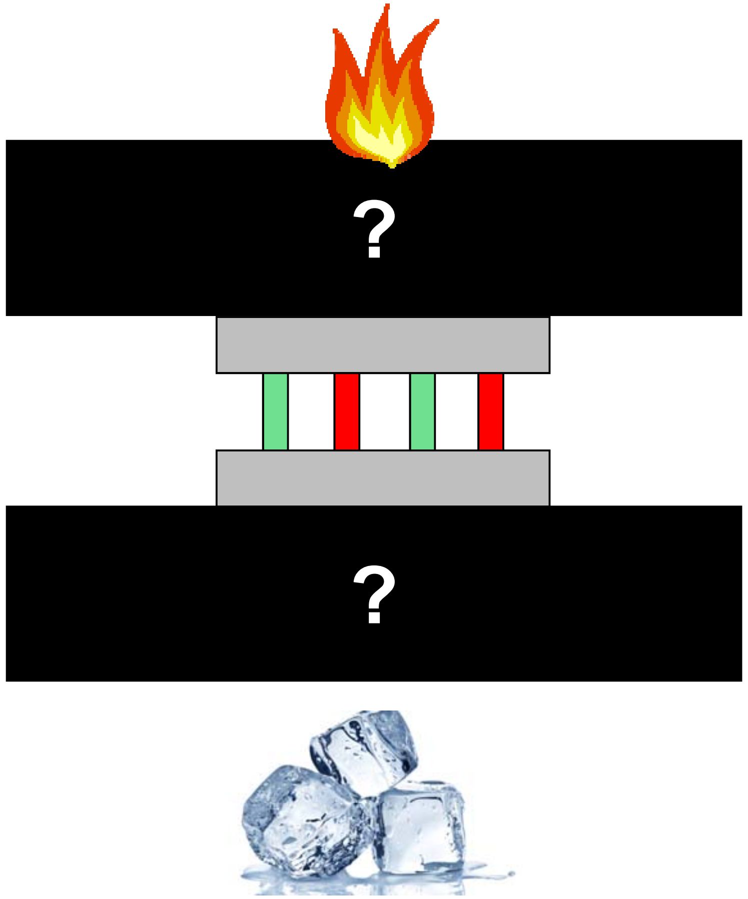


***** Max power will shift to lower device resistances with inclusion of Peltier, Joule effects *****

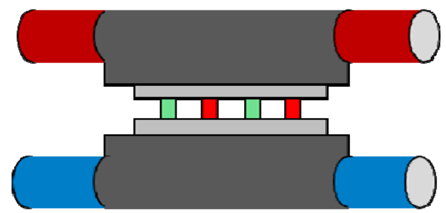
Representative Values for R_h, R_c

Heat source



Heat sink

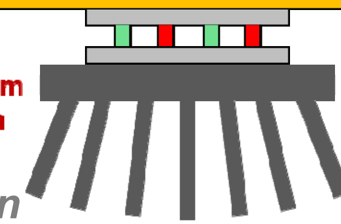
Hot Water Pipe
$T_h \sim 35°C$
Metal surface



Cold Water Pipe
$T_c \sim 20°C$
Metal surface

Metal-to-metal contact with thermal adhesive or grease:
~1 K/W

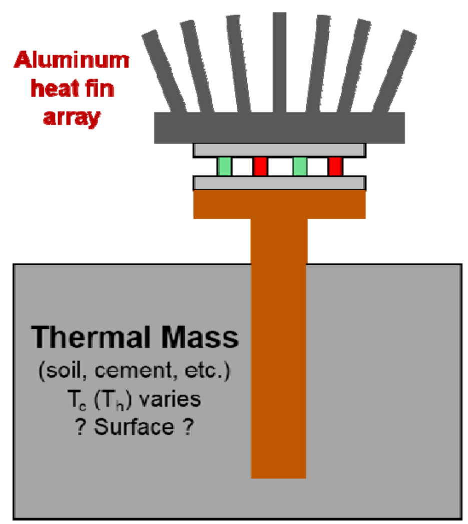
Industrial Equipment
$T_h \sim 35\text{-}50°C$
Metal surface



Aluminum heat fin array, ~20cm² with natural convection:
~10 K/W

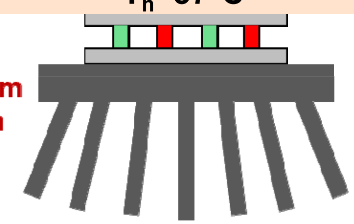
"Cold Source"
Ambient air
$T_c \sim 25°C$

Ambient Air
T_h (T_c) varies



Skin contact w/ 4cm diameter watch face:
~50 K/W

Skin
T_h~37°C



"Cold Source"
Ambient air
$T_c \sim 25°C$

Contact via heat pipe to thermal mass:
?? K/W
(depends highly on materials and time-dependent temperatures)

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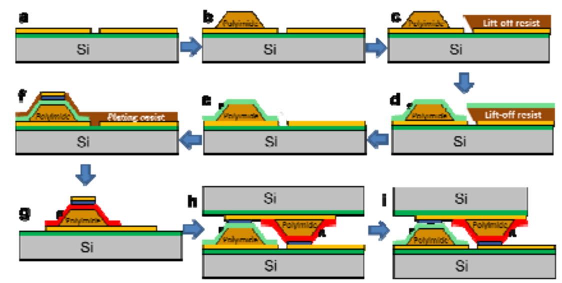
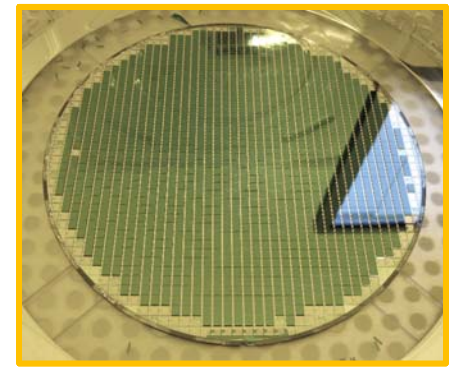
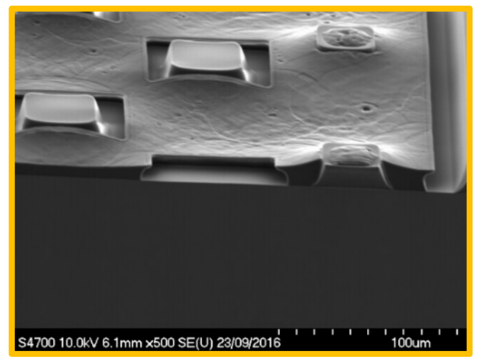
ADI Chip-Scale Thermoelectric Generator (TEG)

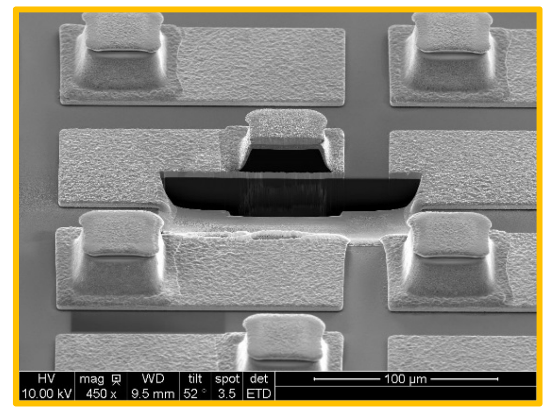
- **Leveraging ADI manufacturing and processing know-how to build high-performance, low-cost devices**
  - **Target: 400μW from ΔT=10°C**

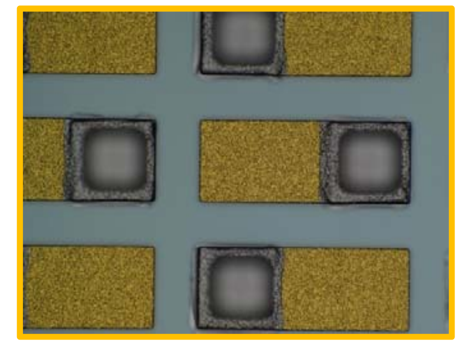
In-house 8” wafer processing











ADI Chip-Scale Thermoelectric Generator (TEG)

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  - Target: **400µW from ΔT=10°C**

  - Chip-scale device area: ***~10mm²***

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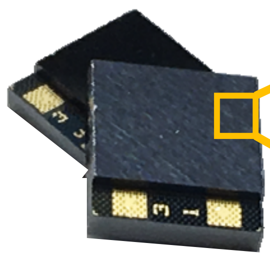
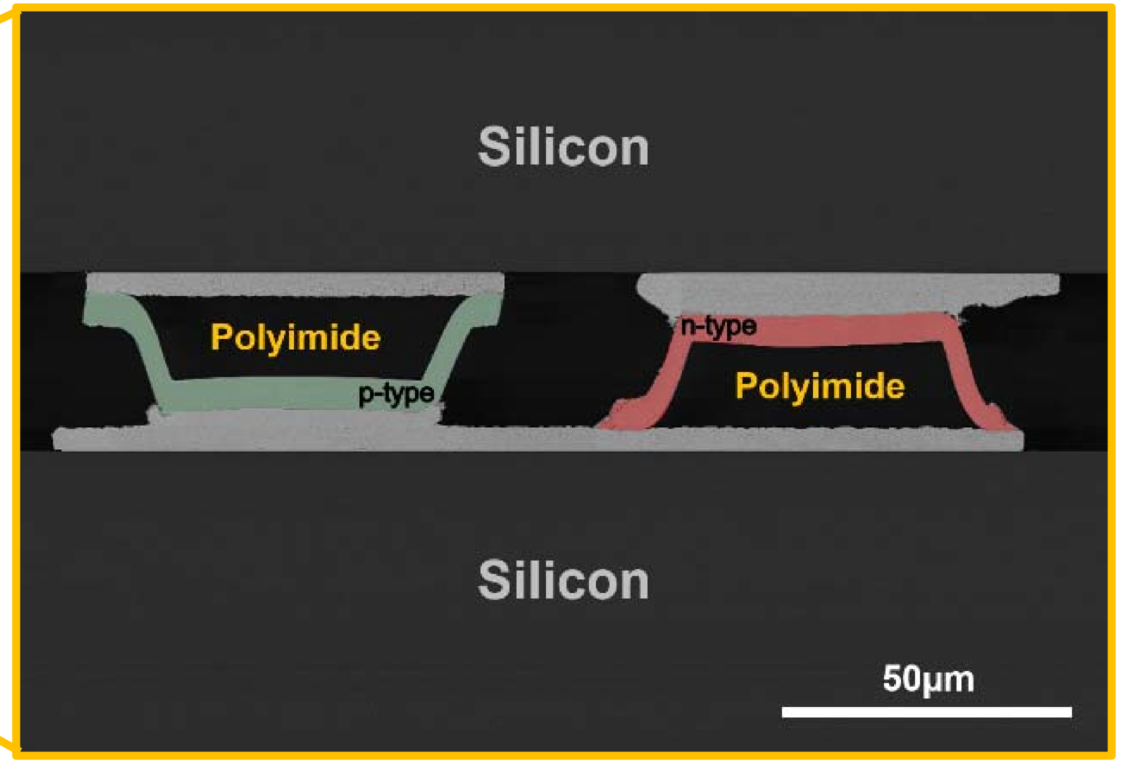
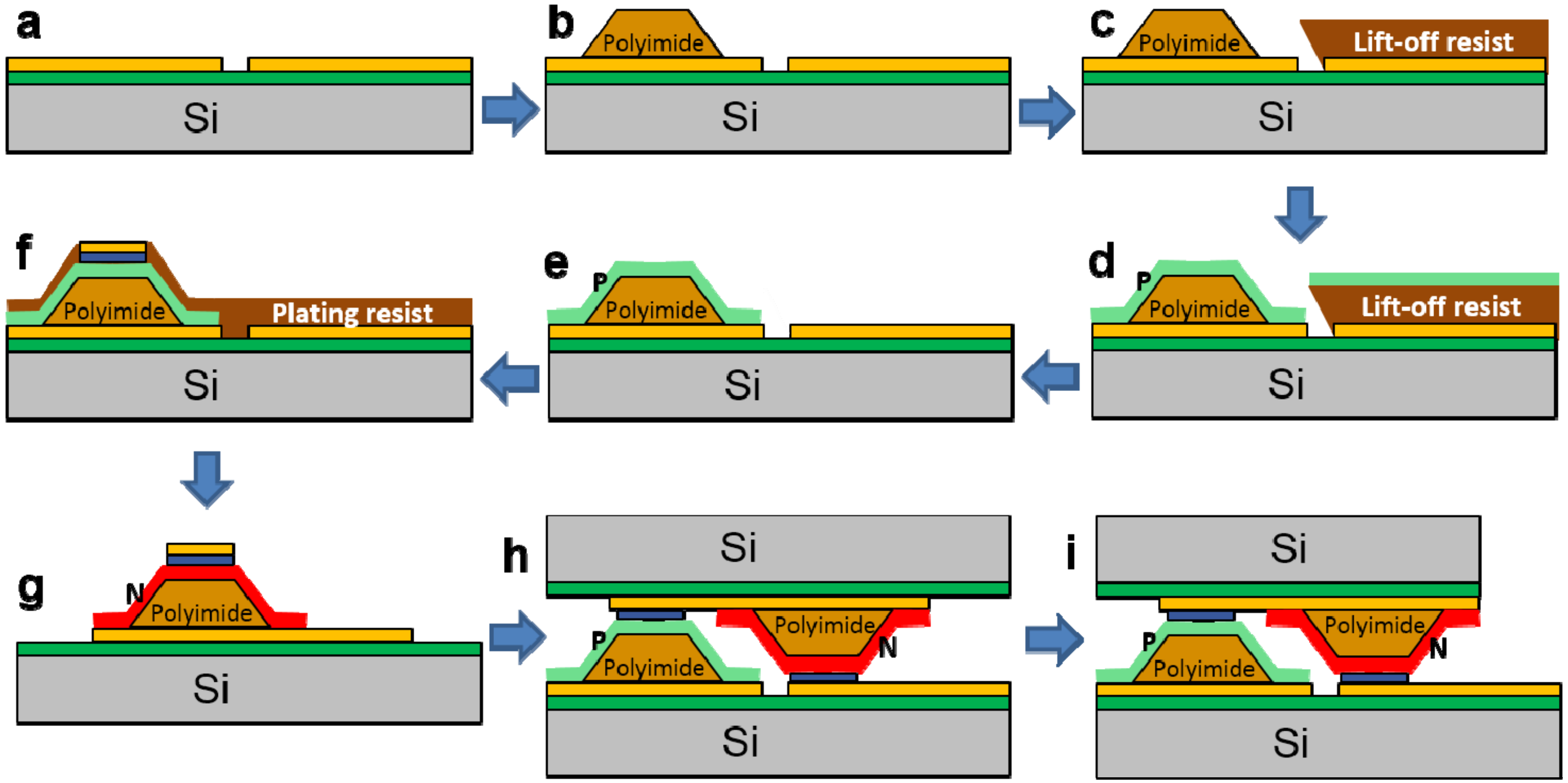




- Chip-scale device area: ***~10mm²***
- Active materials: ***Based on Bi_2Te_3***
- Make use of ADI-patented device architecture: ***TE materials deposited along polyimide slope***
- Long leg length, large thermal resistance without time-consuming, expensive depositions

Optimized to power wireless sensor nodes and other small devices from thermal energy sources close to room temperature

Process Flow for ADI Chip-Scale TEG



a. **Plating of interconnect**

b. **Polyimide deposition**

c. **Lift-off resist litho**

d. **Bi_2Te_3 (Sb_2Te_3) deposition**

e. **Lift-off**

f. **Plating resist litho**

g. **Plating of bond materials**

h. **Wafer-level bond**

i. **Singulation and dicing**

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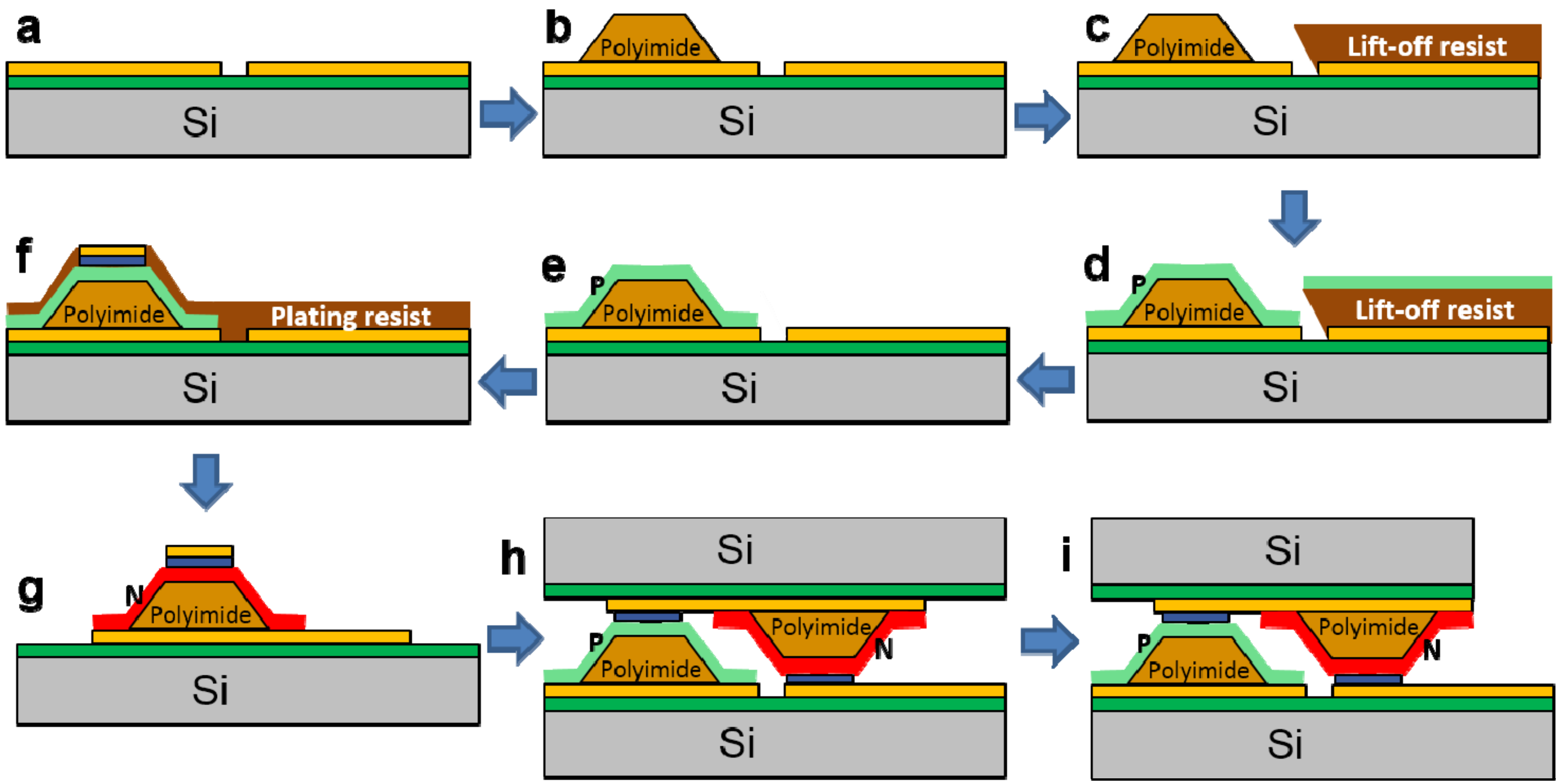

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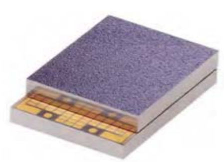
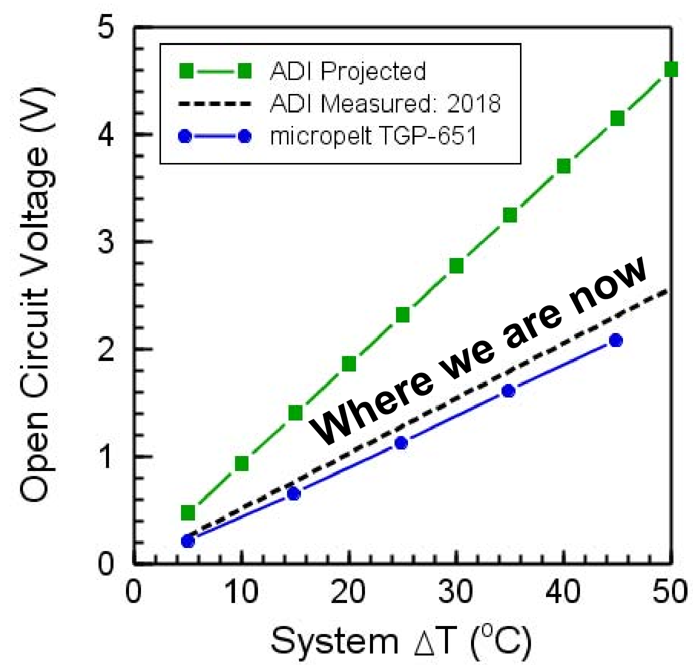
Projected Performance of ADI Chip-Scale TEG

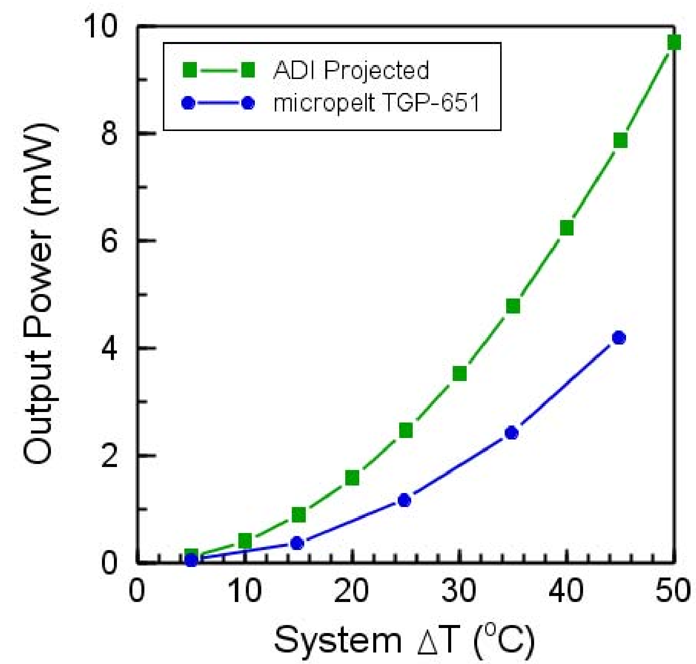
ADI TEG
Projected performance

Performance compared with:

micropelt TGP-651
- Bi_2Te_3-based
- 3mm x 3mm





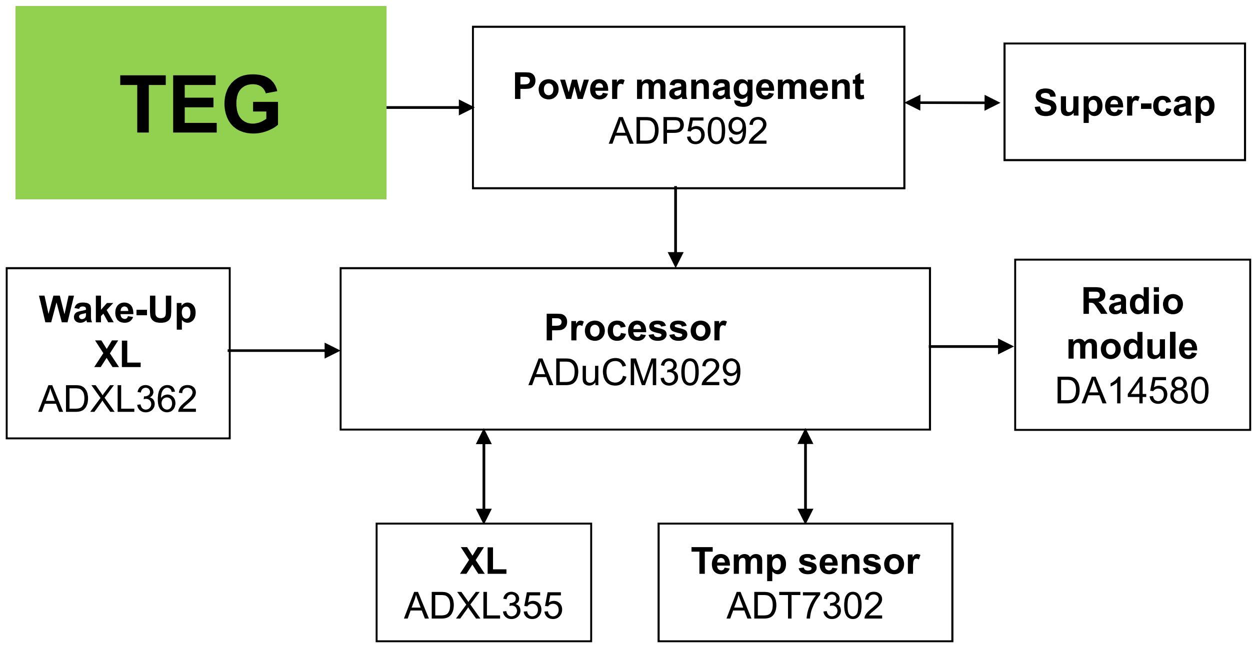


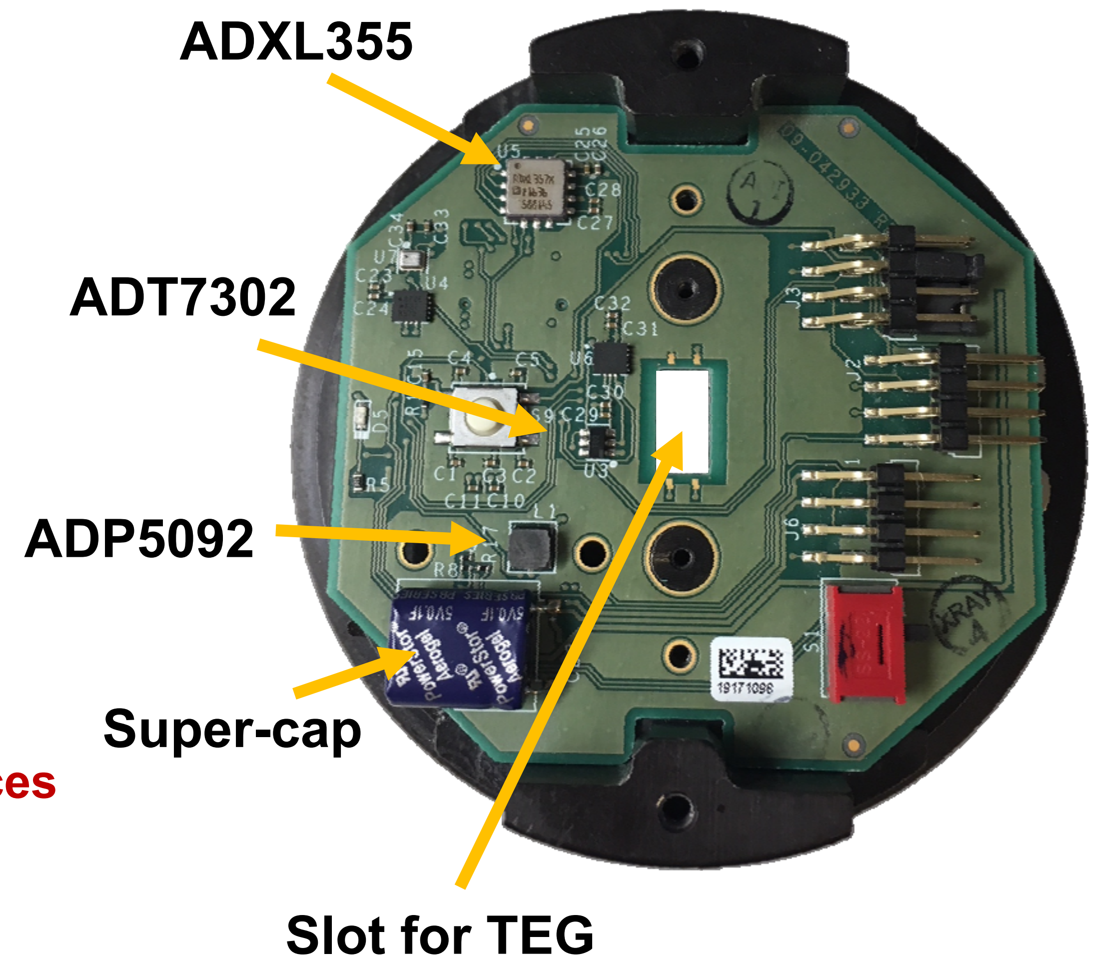
- **ADI TEGs predicted to have better performance (higher voltage and higher output power) than competitor**
  - Measured output voltage already surpasses Micropelt
  - ***Resistance and power output improvements ongoing***
- **Schedule for sampling:**
  - **1st gen. prototypes: *Completed May 2017***
  - **Customer sampling: *Summer 2018***

Outline

- Introduction to thermoelectricity
  - Thermoelectric effects
  - Refrigeration and power generation applications
  - Thermoelectric energy harvesting
- Design and modeling of TEGs
- ADI's chip-scale TEG
  - Device architecture
  - Process flow overview
- TEG-powered condition-based monitoring

TEG-Powered CbM Sensor Node

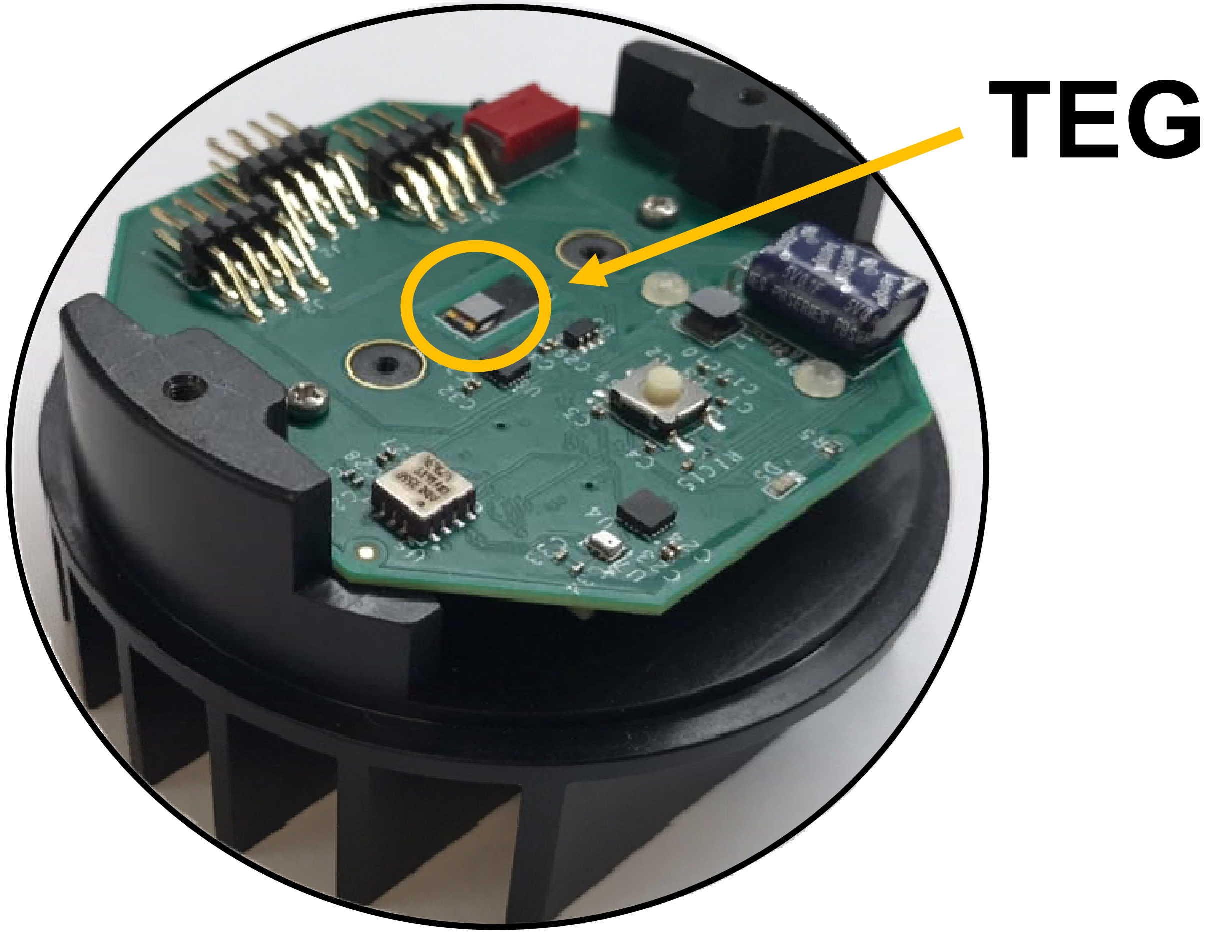


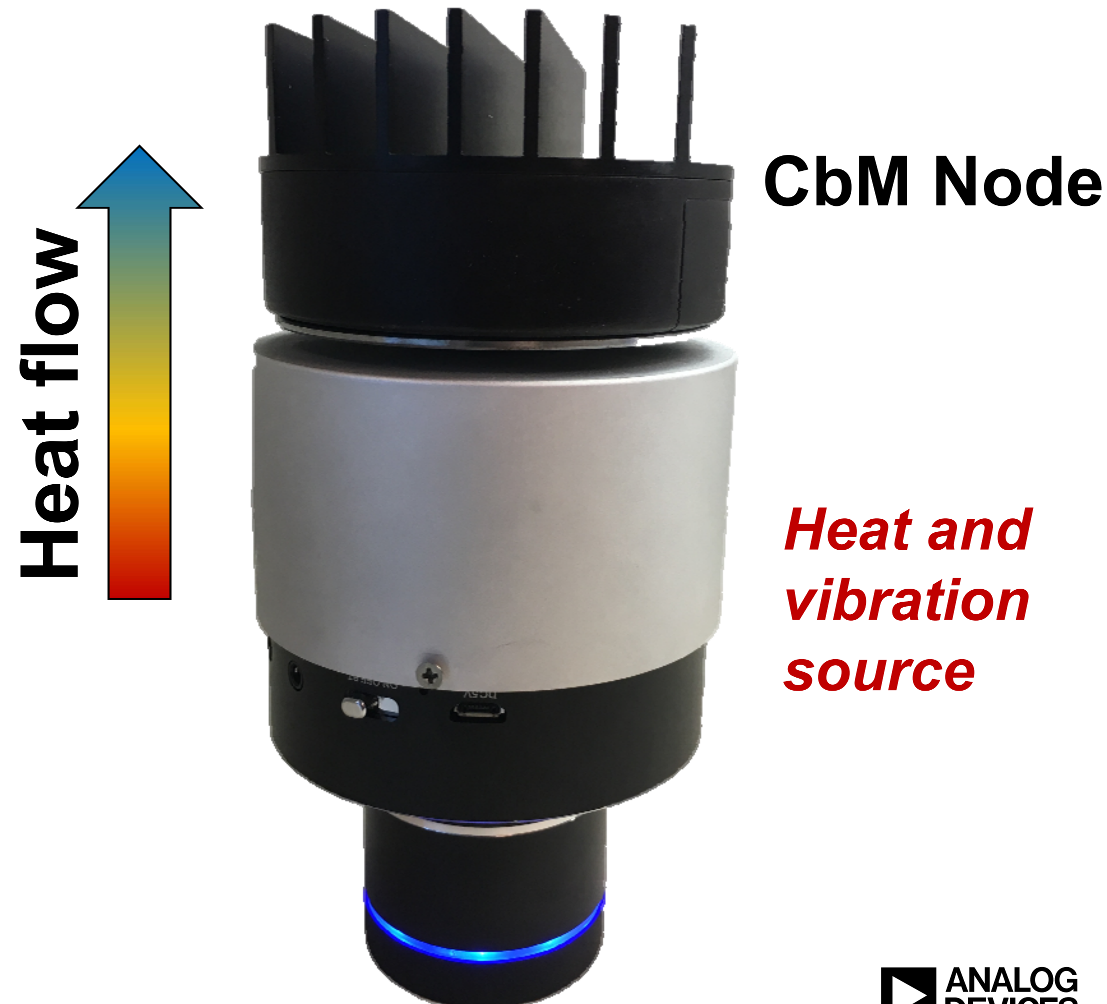


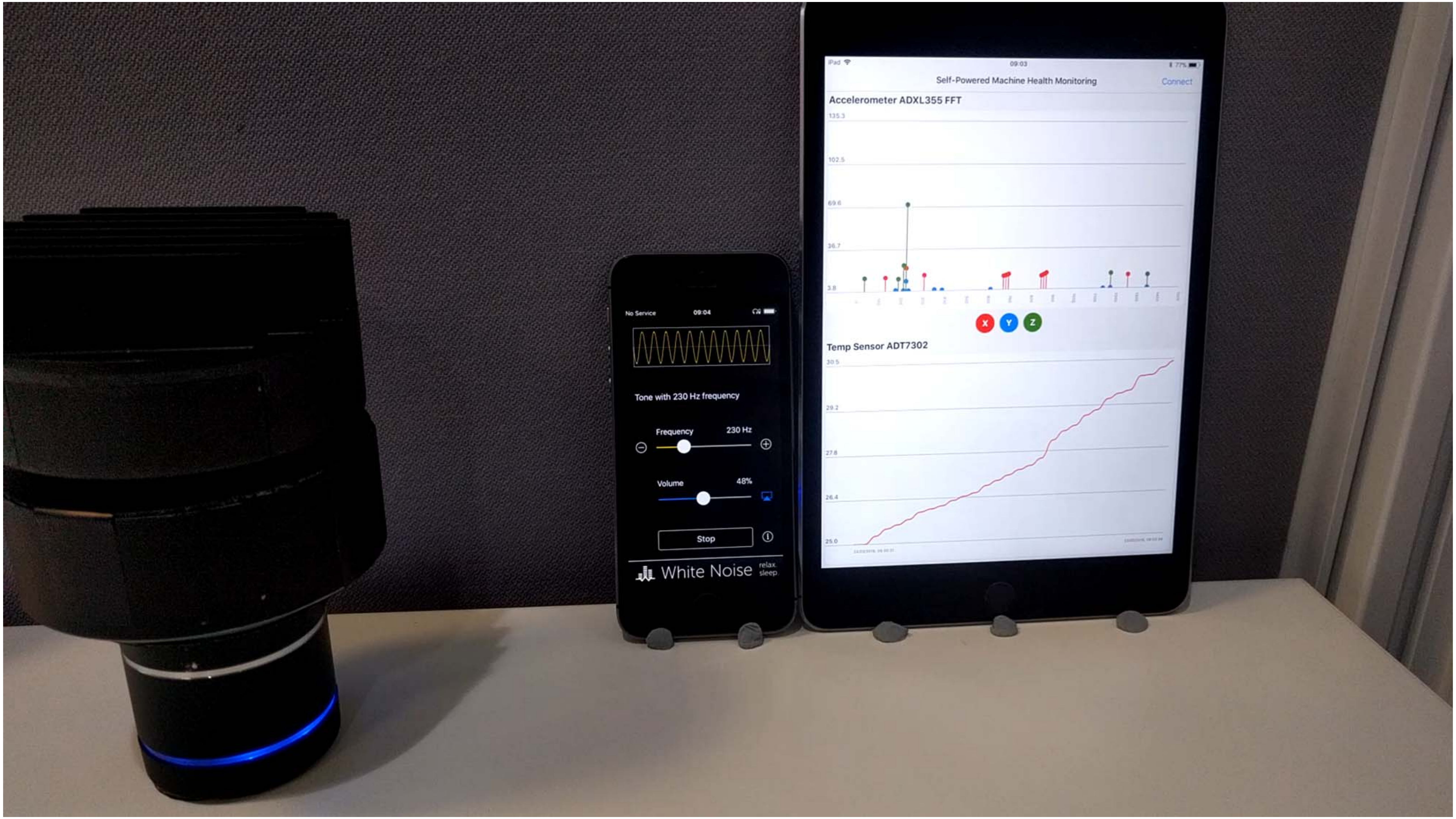
- ANALOG DEVICES ***components***
  - **ADuCM3029 microcontroller: SPI, I²C, UART interfaces**
  - **Ultra-low power ADP5092 power management**
  - **Low power vibration (ADXL263, ADXL355) and temperature (ADT7032) sensors**

ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

TEG-Powered CbM Sensor Node






09:03
Self-Powered Machine Health Monitoring
Connect
Accelerometer ADXL355 FFT
135.3
102.5
69.6
36.7
3.8
X
Y
Z
Temp Sensor ADT7302
30.5
29.2
27.8
26.4
25.0
No Service
09:04
Tone with 230 Hz frequency
Frequency
230 Hz
Volume
48%
Stop
White Noise
relax.
sleep.

TEG-Powered CbM Sensor Node
Average Power Consumption

Update rate	**DA14580** *BLE*	**ADuCM3029** *uC*	**ADXL355** *XL*	**ADXL362** *Wake-up*	**ADT7302** *Temp*	**Total**
30 sec	172	16.1	5.56	4.89	0.24	**199**
30 min	5.82	0.433	0.093	5.39	0.004	**11.7**

Average power in µW

- **Data updates every 30 sec:** Power consumption dominated by transmission → ΔT ~ ***10°C***
- **Data updates every 30 min:** Wake-up XL power consumption comparable to BLE → ΔT ~ ***2°C***

ANALOG DEVICES
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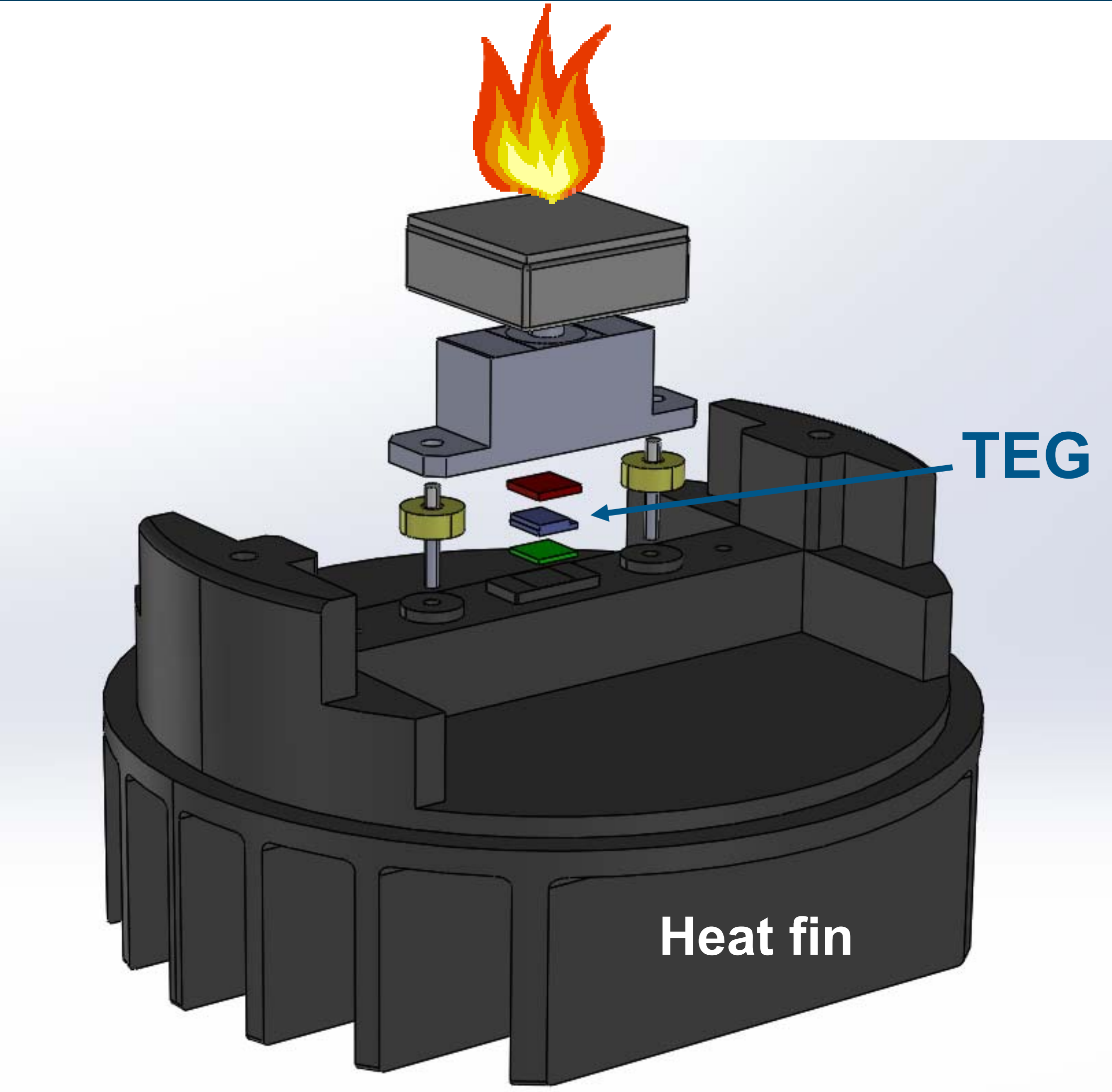
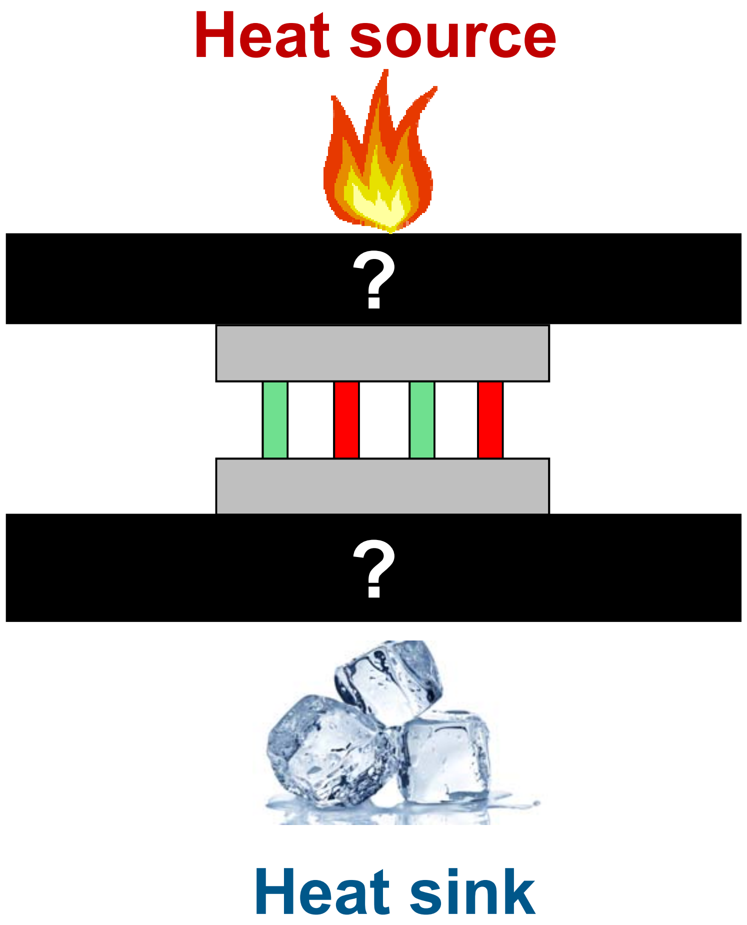
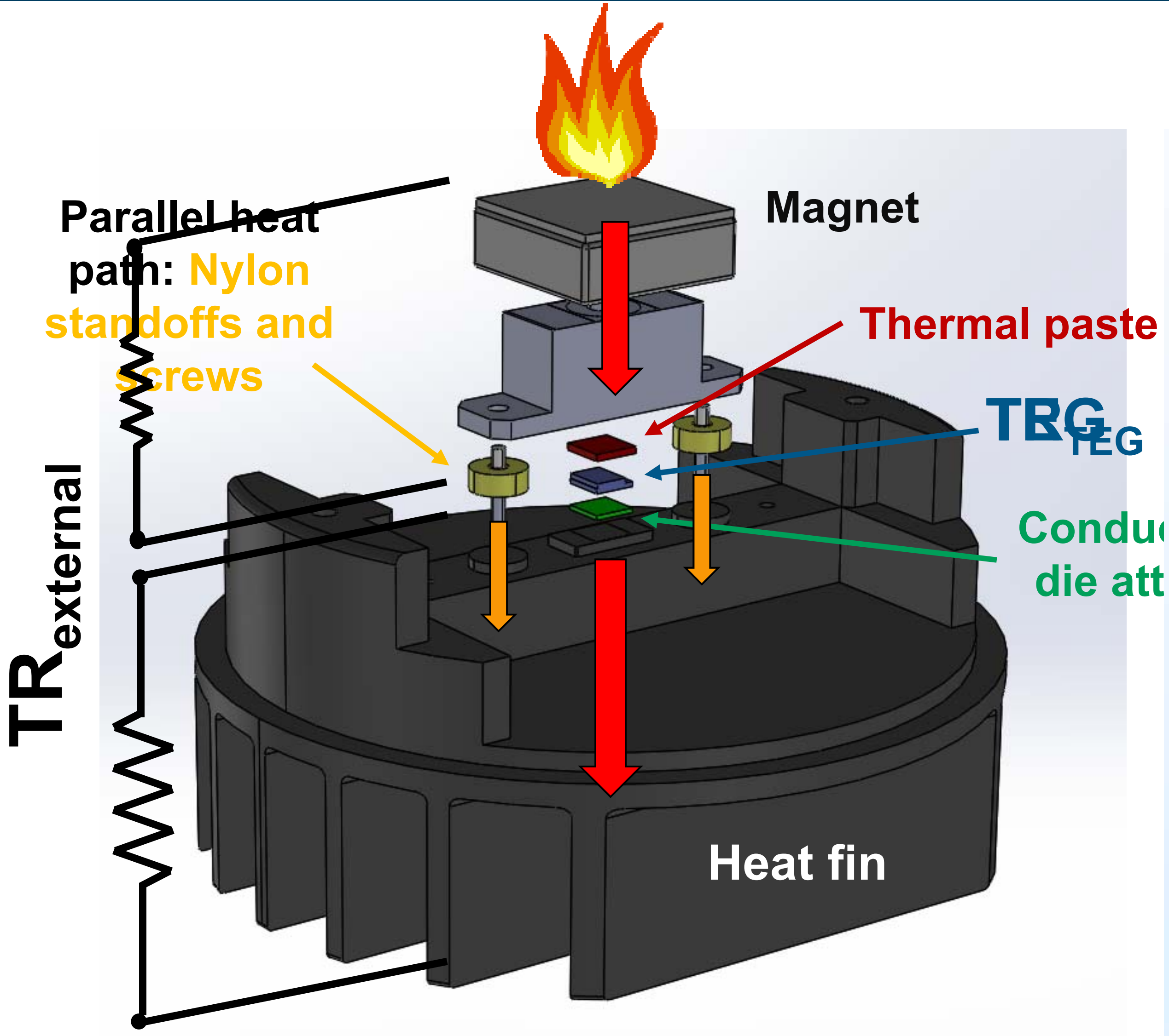
Thermal Breakdown



PCB and plastic housing not shown

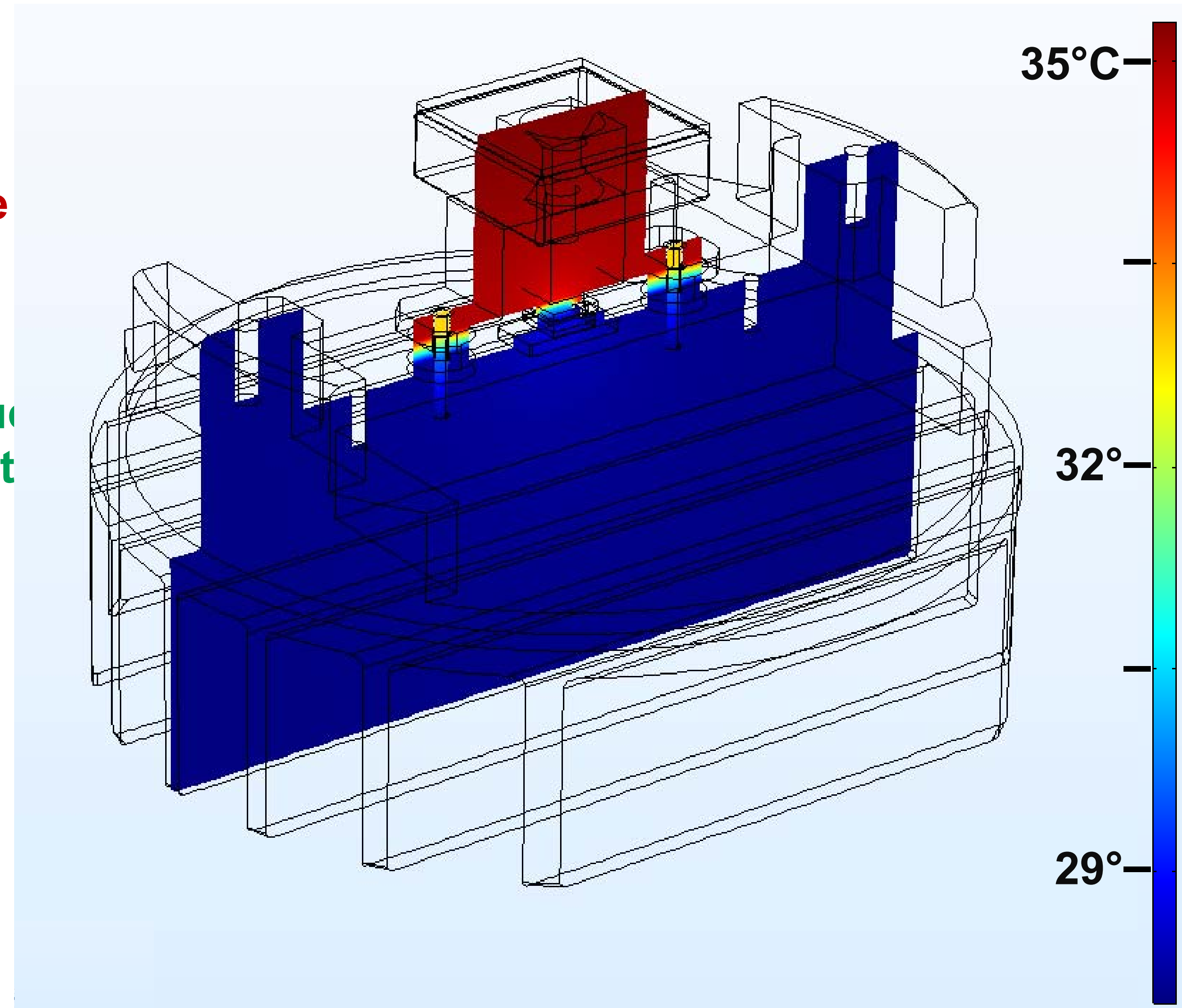


Thermal Breakdown



PCB and plastic housing not shown

Modeled Temperature Profile



Summary

- ***Introduction to thermoelectricity***
  - ***Make use of fundamental materials property***
  - ***Can be used to heat/cool (input current) or to generate power (input ΔT)***
  - ***Device efficiency related to TE material* ZT**
- ***Thermoelectric energy harvesting:* Chip-scale technology offers significant advantages over typical bulk solutions**
- ***TEG design and modeling***
  - ***A lot can be learned from simple 1D models***
  - ***Key device design requirement:* Thermal impedance matching**
- ***ADI chip-scale TEG***
  - ***Based on patented device architecture: TE material deposited along polyimide slope***
  - ***Large thermal resistance: Optimized for harvesting small amounts of energy from sources close to room temperature***
- ***Condition-based monitoring sensor node: Smart sensing powered by TEG***
  - ***ANALOG DEVICES technology covers entire signal chain***

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- Tzeno Galchev

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