Thermoelectric Generation from SNAP III to Body Heat Harvesters: Inventing Materials to Unleash Technology

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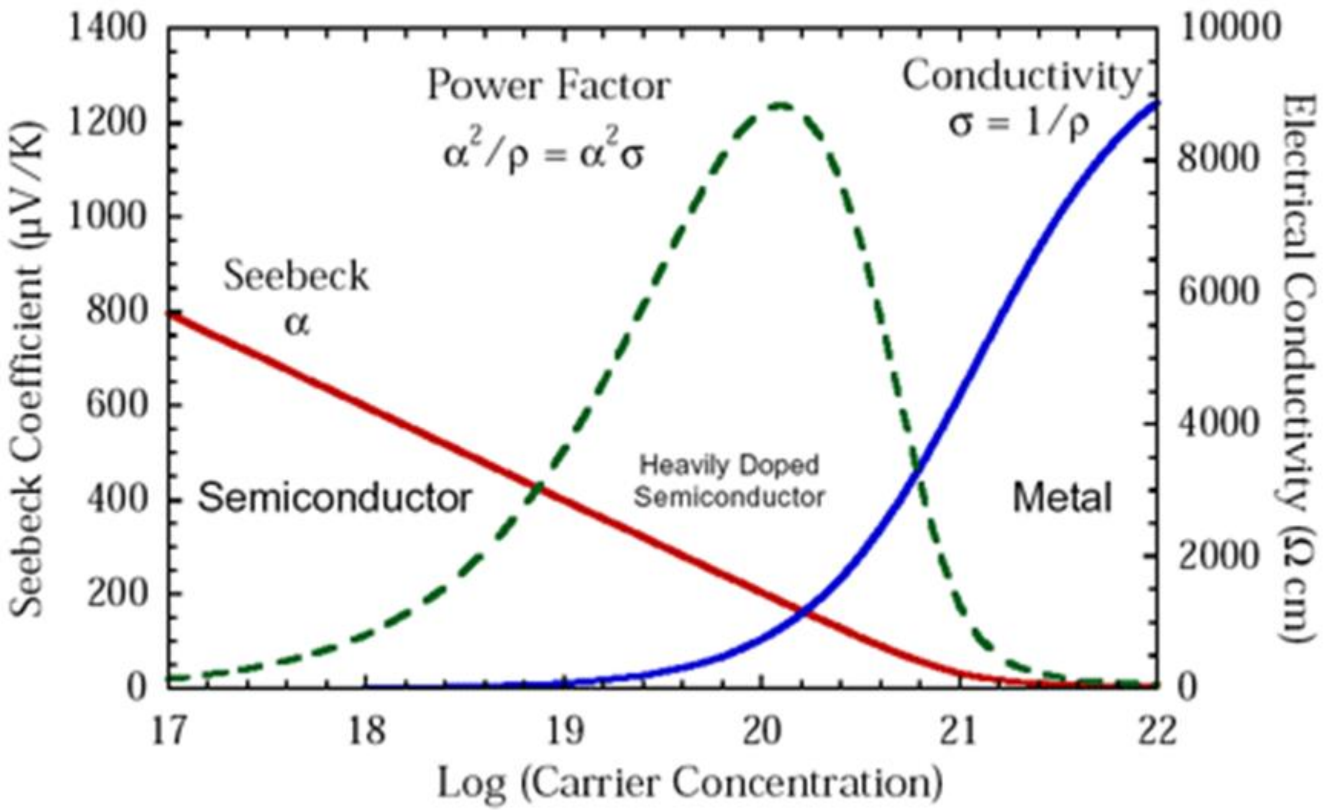
Thermoelectric Phenomena

Thermoelectric
Figure of Merit

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

α – Seebeck coefficient
σ – electrical conductivity
κ – thermal conductivity
T – absolute temperature



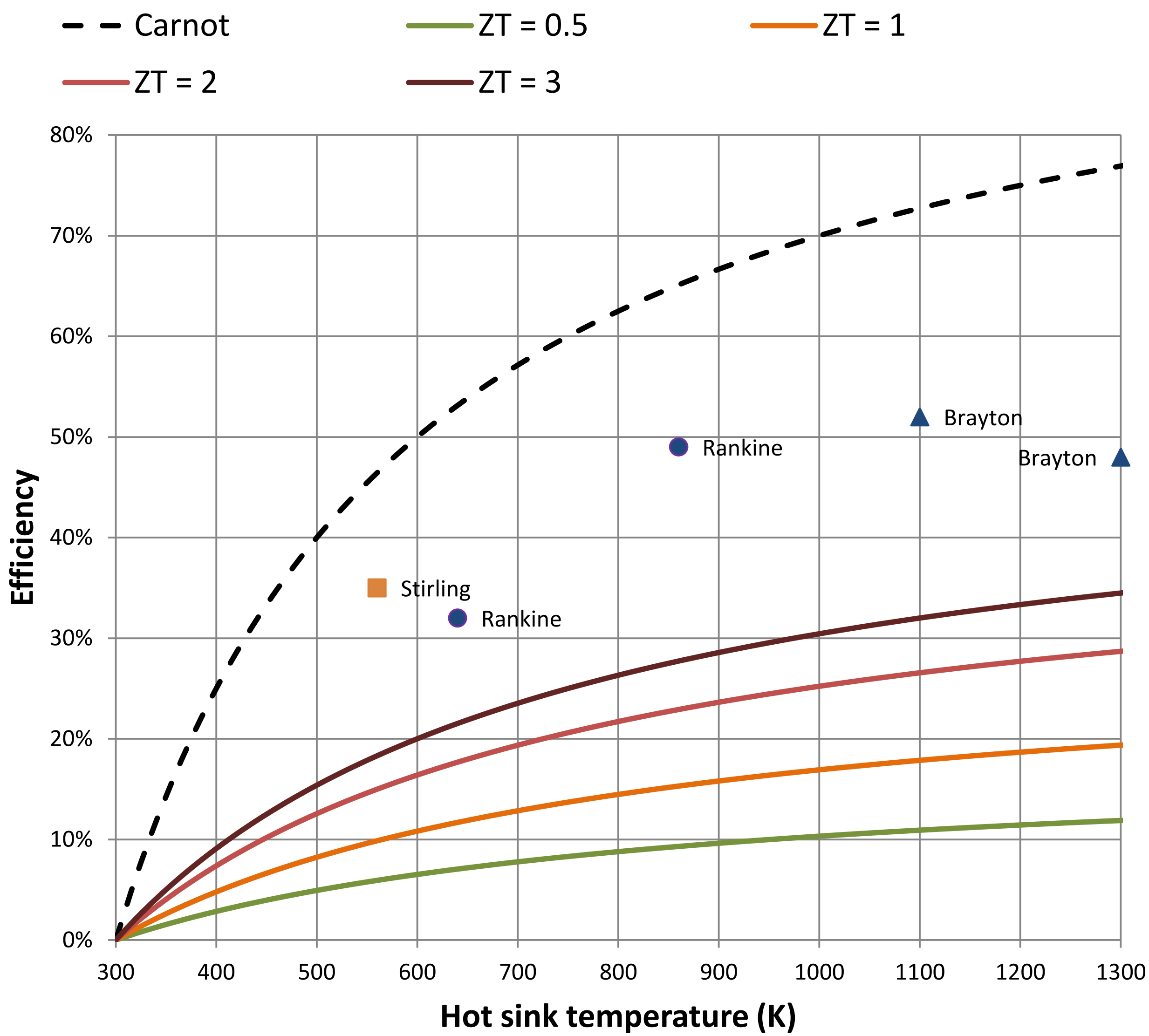
Thermoelectric Generators

Pros

- No moving parts
- High reliability
- Can be miniaturized

Cons

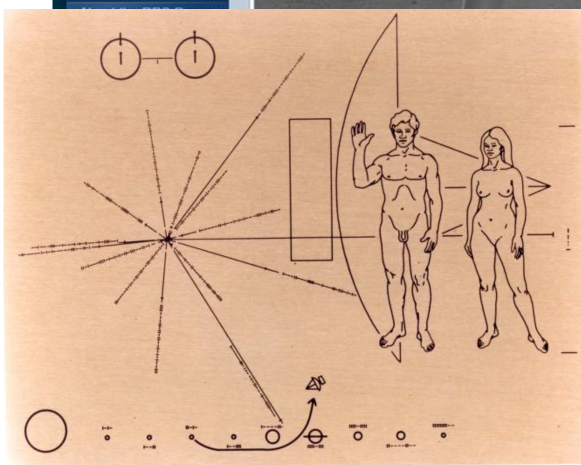
- Very low efficiency
- Relatively high costs

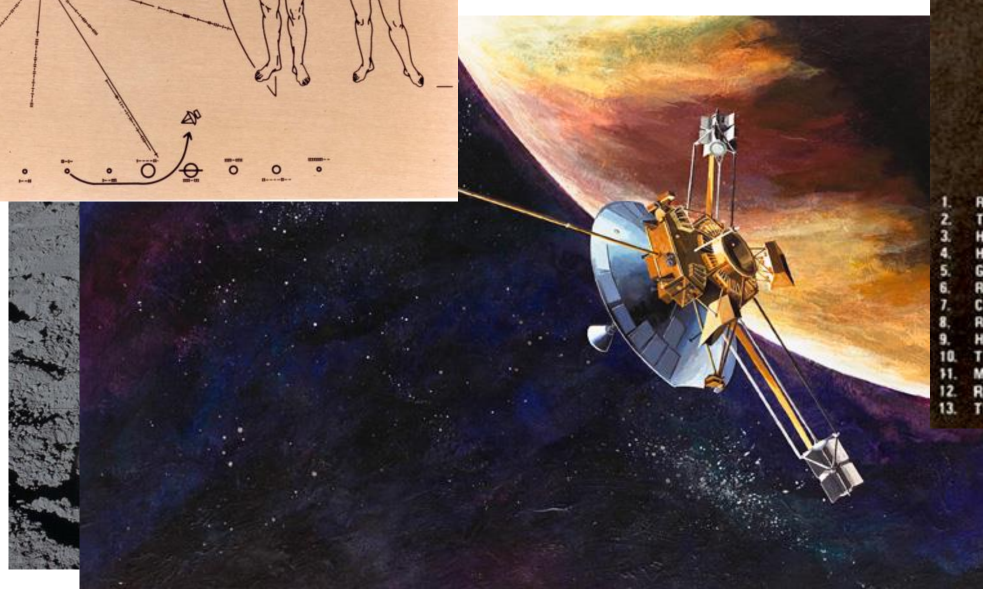


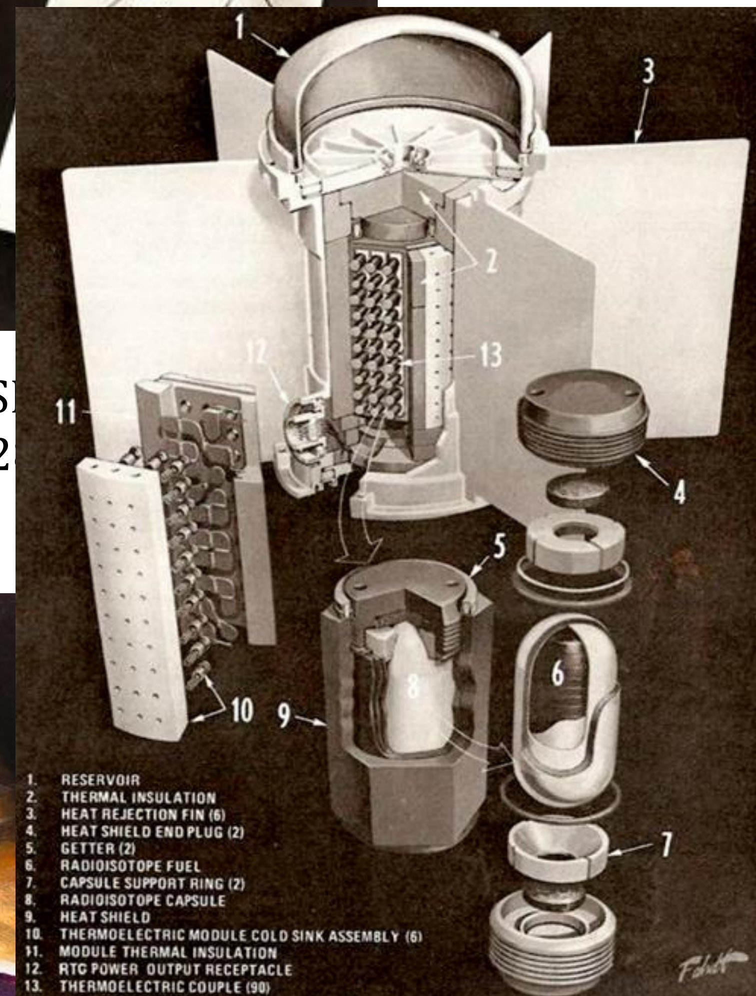
TEGs before 2000

Pioneer 2 - Launched 1972

RTEG still working in 2002 upon leaving solar system







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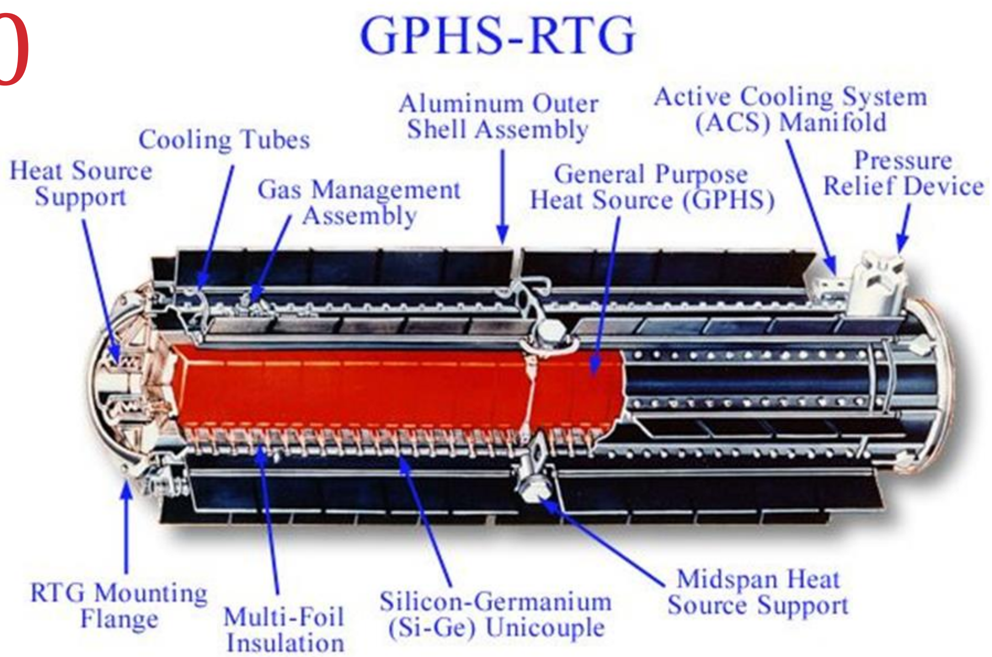
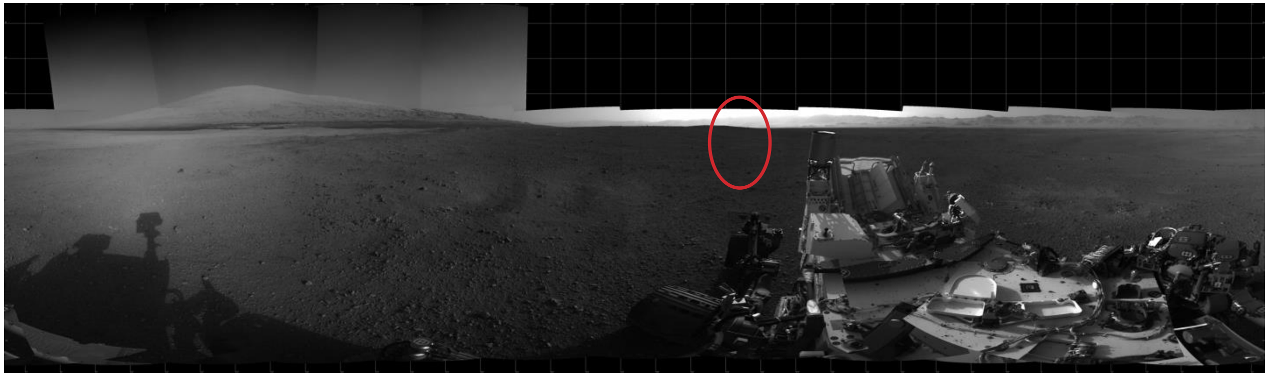
TEGs before 2000

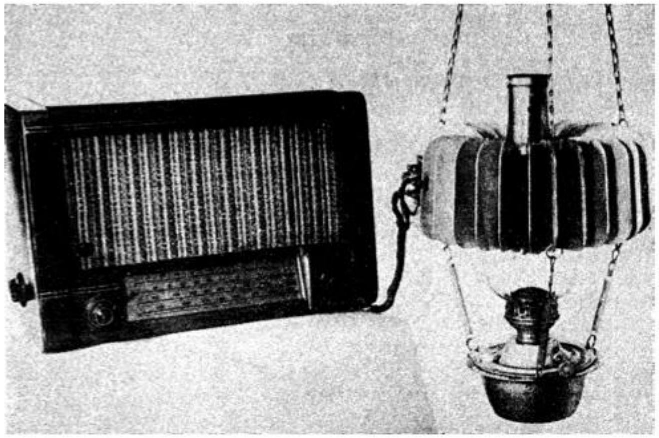


GPHS-RTG on Mars (Curiosity)
292 W_e



Still the key technology for outer space exploration

Thermoelectricity on Earth before 2000

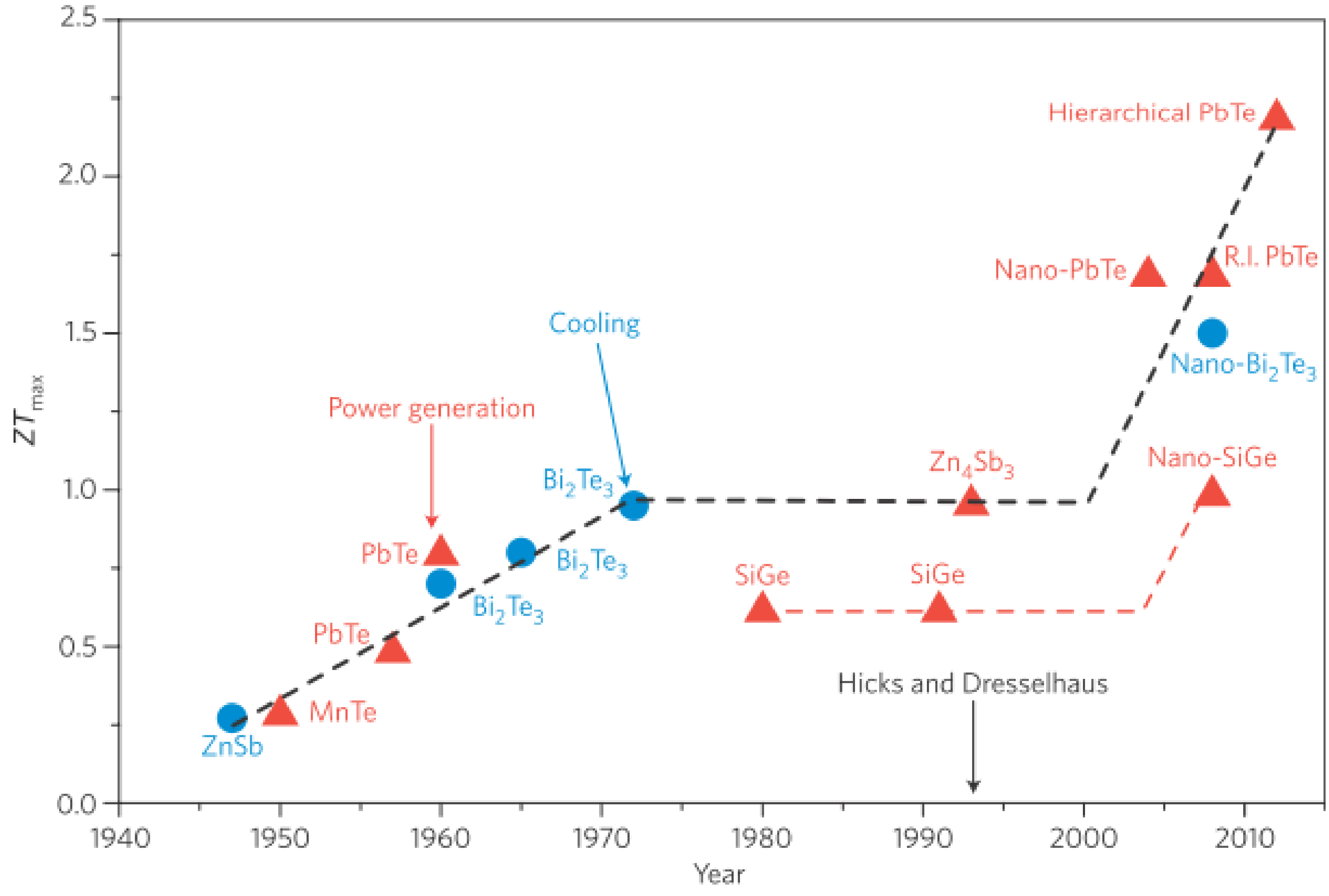


Oil burning lamp using the first commercial TEG (ZnSb- constantan) (USSR - 1948)

RTG for pacemakers (USA - 1974)

Body heat harvester (Japan - 1998)

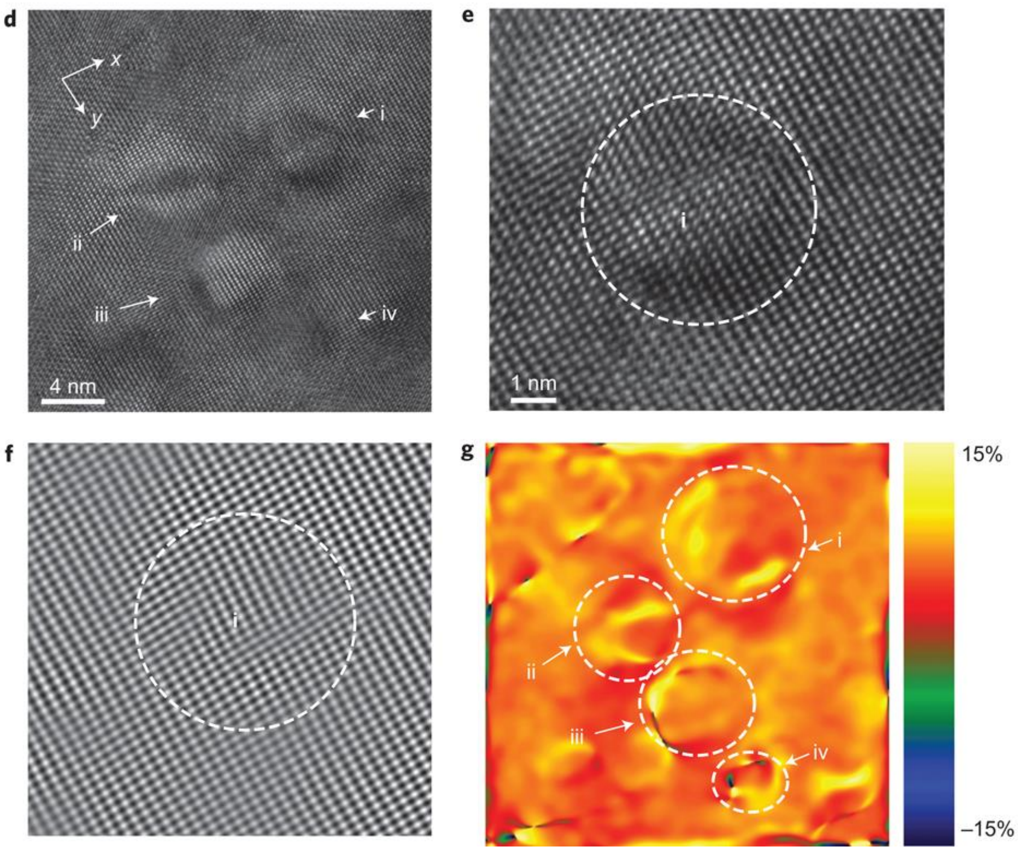
Thermoelectricity and Nanotechnology



The nanotechnological strategies

Decreasing the thermal conductivity by introducing λ-selective scattering centers:

- nanowires
- nanolayers
- nanoprecipitates
- endotaxy



The nanotechnological strategies

Increasing the power factor by

- energy filtering
- modulation doping
- band engineering

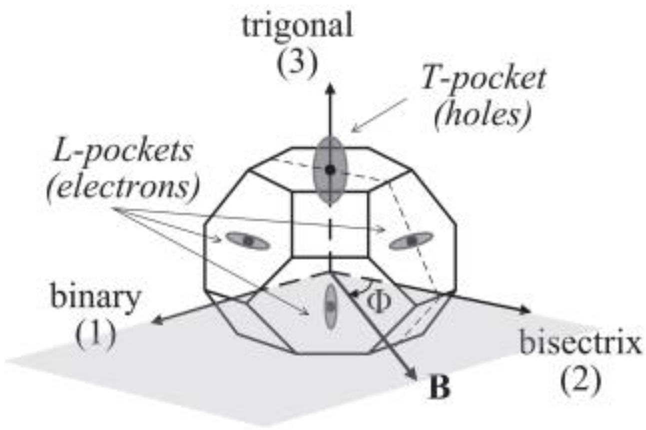
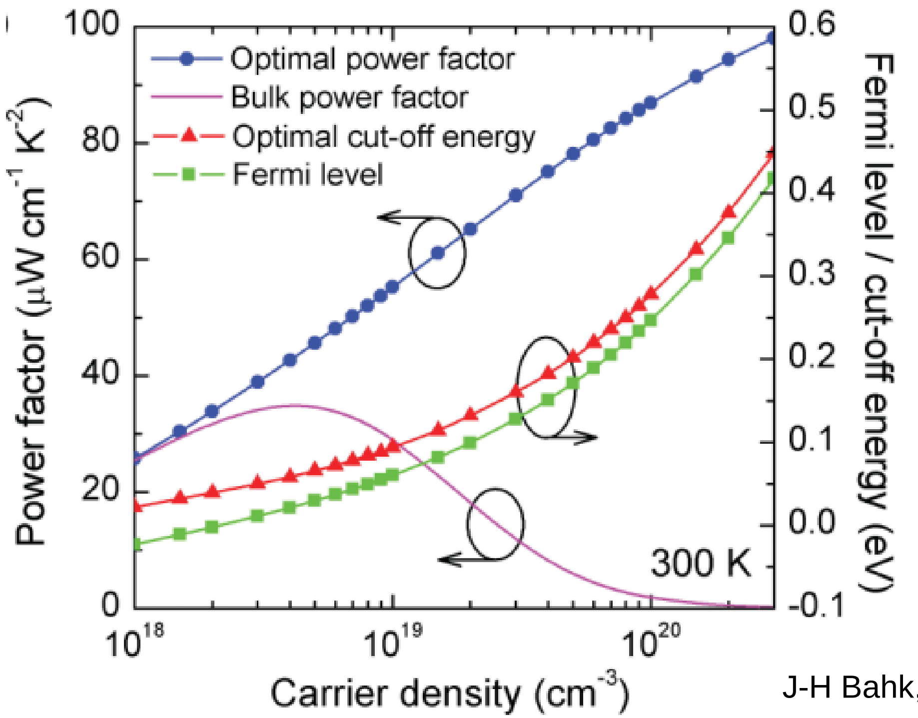


Figure 1. Electron and Hole Fermi surfaces of bismuth at the Brillouin zone and the orientation of the externally applied magnetic field B.

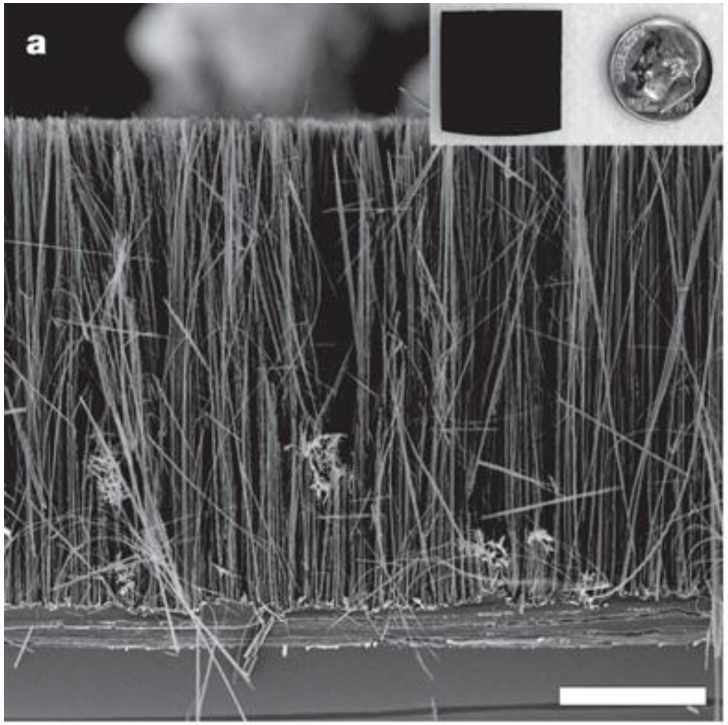
A. Popescu, LM Woods, Adv. Funct. Mater. 2012, 22, 3945

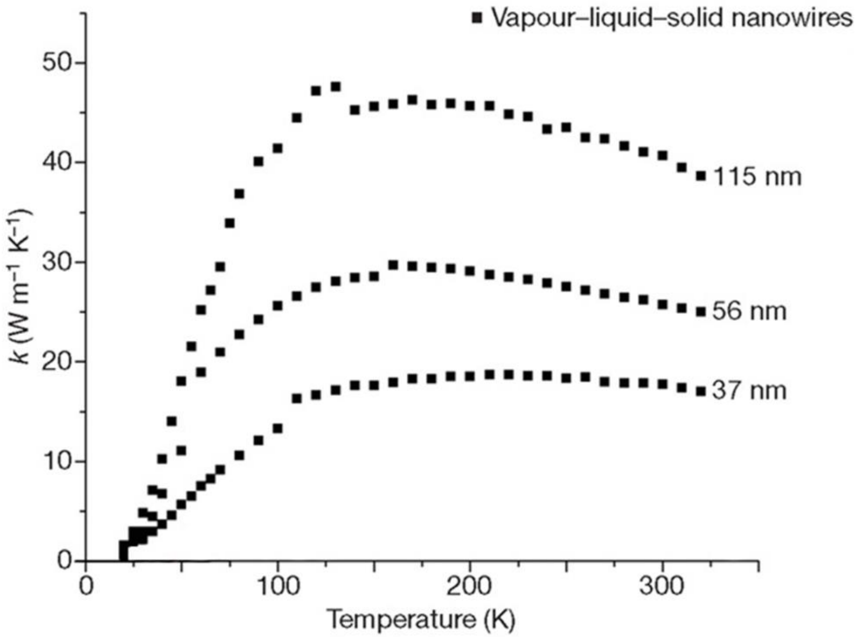


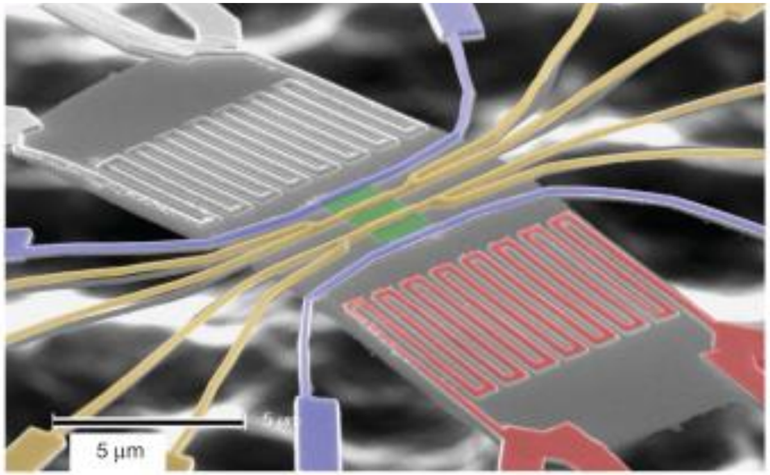
J-H Bahk, Z. Bian,A, Shakouri, PRB 87, 075204 (2013)

Nanotech Silicon

Silicon in itself is a poor TE material but *ZT* could be raised by nanostructuring, lowering κ.





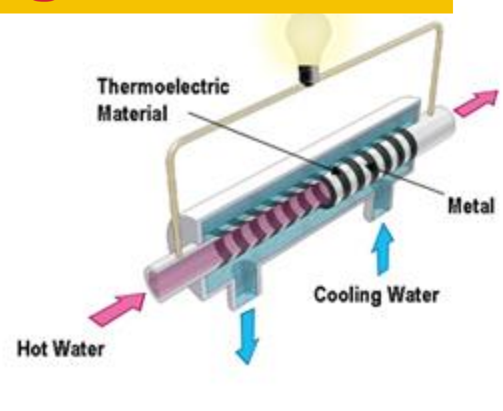


A.I. Boukai et al., Nature 451(7175), 168–171 (2008)
A.I. Hochbaum et al., Nature 451(7175), 163–167 (2008)

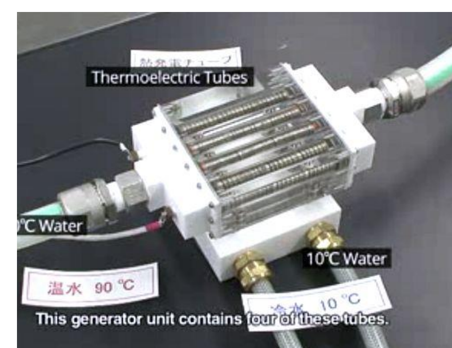
New opened horizons, New ways of thinking

‘Thermoelectric mod
reach 7% conversion
of US$2/Watt in 201

Nonetheless, microharvesting is still the largest niche



A schematic view of
Panasonic's thermoelectric conversion tube



Economics

- Installation costs
- Euro/watt
- Abundance

Technology

- Thermal matching
- Contact resistance
- Heat dissipation
- Power density
- Treasuring pro's

Science

- Temperature range
- Thermal power acceptance
- Metallurgical issues

Cost factors

Threshold of acceptance strongly depends upon application:

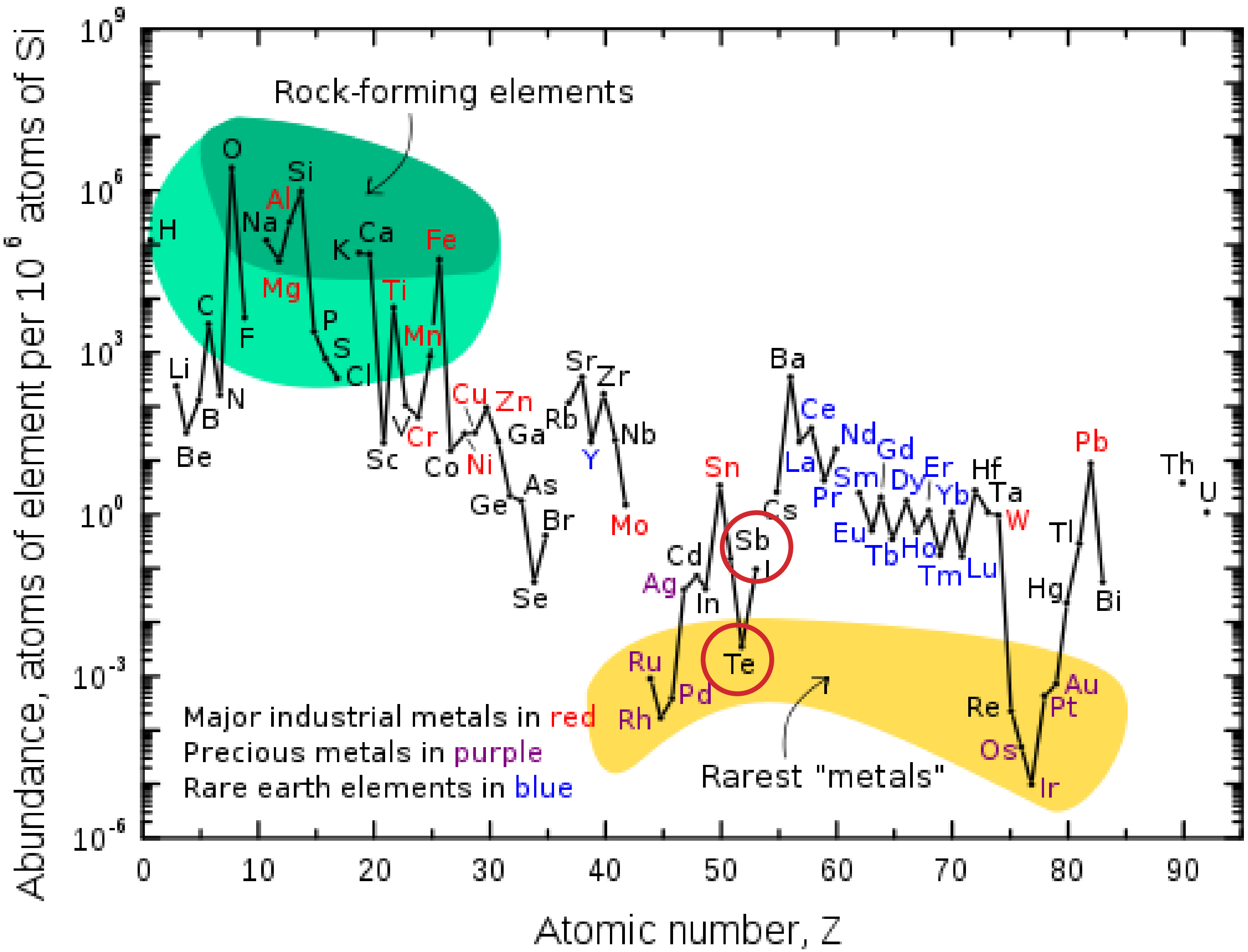
- installation (power) costs

TEGs for civilian use	10 €/W (actual) - 1 €/W (target)
TEGs in aerospace	100-200 €/W (+ launch costs)
Coal power plant	1.64 €/W
Solar panel	0.55 €/W

- energy costs

TEGs for civilian use	0.0016 €/Mjoule (lifetime of 20 years)
household electric supply	0.04-0.08 €/Mjoule (*price*)
battery	30 €/Mjoule (*price*)

Abundance


Rock-forming elements
Major industrial metals in red
Precious metals in purple
Rare earth elements in blue
Rarest "metals"
Abundance, atoms of element per 10^6 atoms of Si
Atomic number, Z

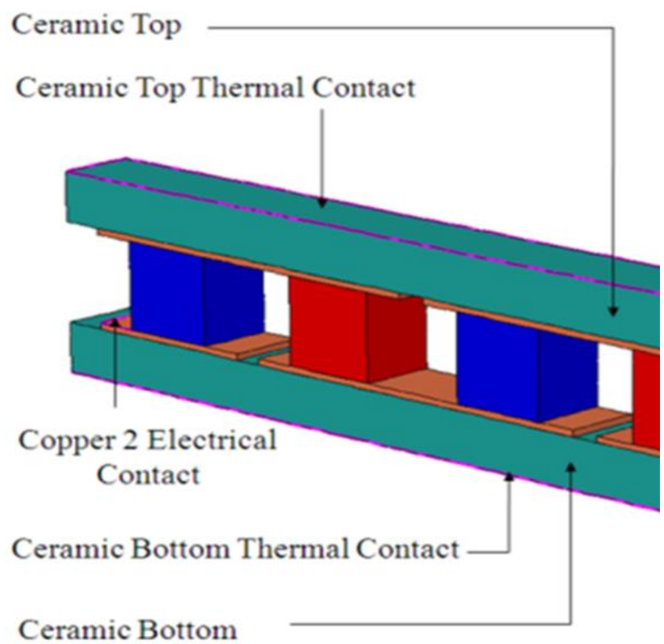
Power consumption

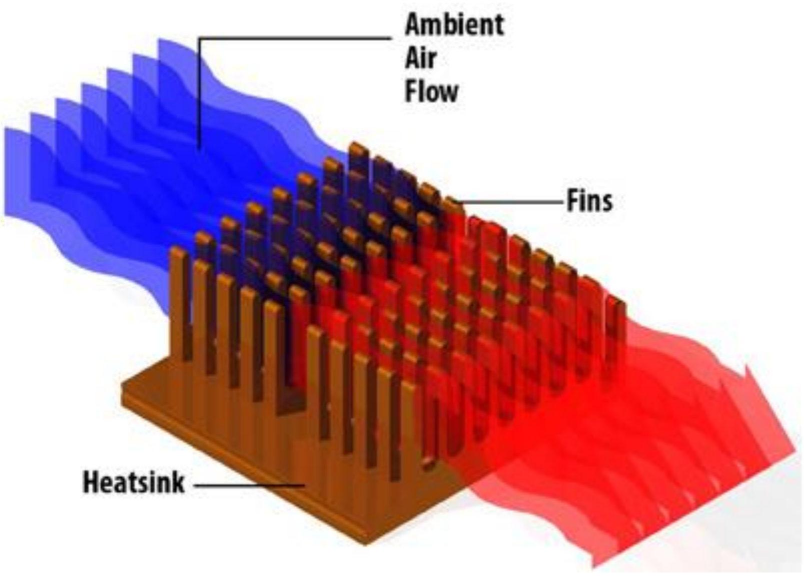
World generation capacity	4 TW	10^{12} W
Power station	1 GW	10^{9} W
House	10 kW	10^{4} W
Light bulb	100 W	10^{2} W
Laptop, human heart	10 W	10^{1} W
Cellphone	1 W	10^{0} W
Wireless sensor	1 mW	10^{-3} W
Wristwatch	1 μW	10^{-6} W
Cellphone signal	1 nW	10^{-9} W

vs. 1-10 μW/cm^2 (low ΔT range)
1-100 mW/cm^2 (high ΔT range)

Integration

- The rush for the high *ZT* is being replaced by the urge of the largest power density
- *ZT* = 1 is acceptable for industrial applications
- Power output depends also (and often: especially) on
  - device architecture
  - thermal chain (contact resistances)
  - mechanical stability





Treasuring the TEG advantage

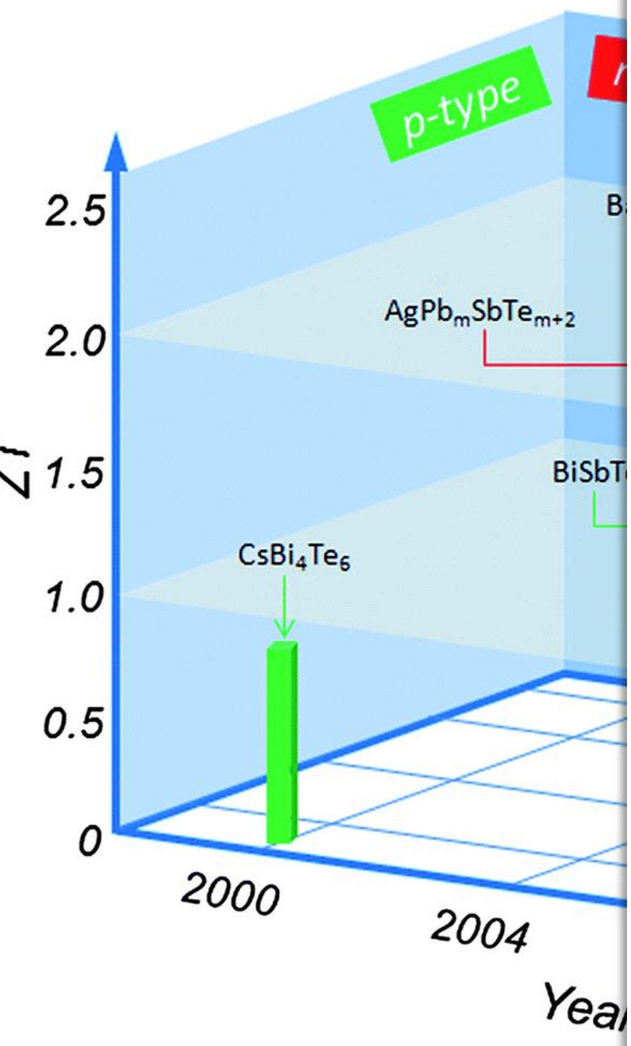
- **Pros**
  - Mobile
  - Lower maintenance
  - Environmentally friendly
  - Higher uptime
- **Cons**
  - Dependent on availability of harvestable energy source
  - Strict power budget
  - Upfront cost may be higher
  - Less mature technology

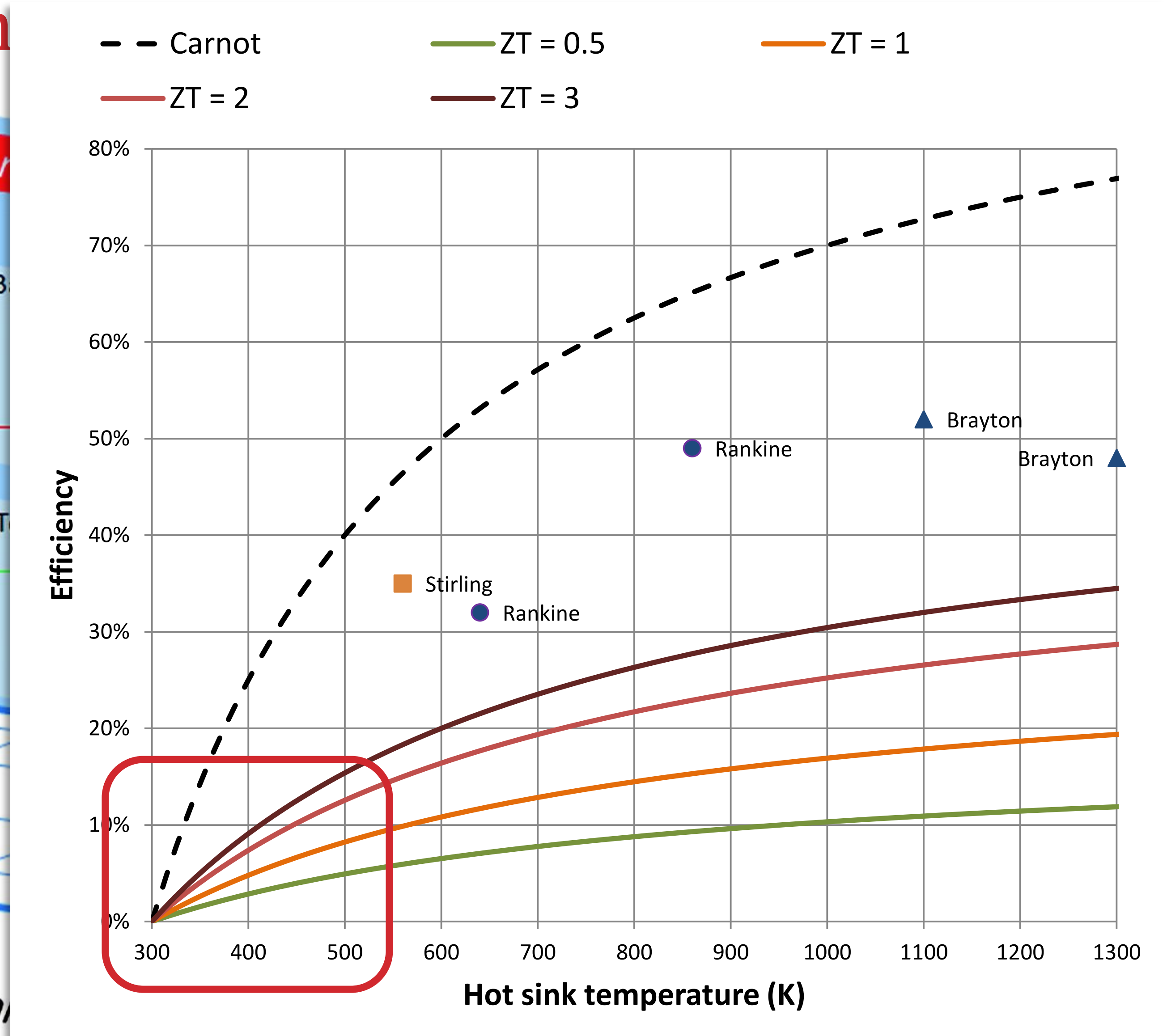
Overall…

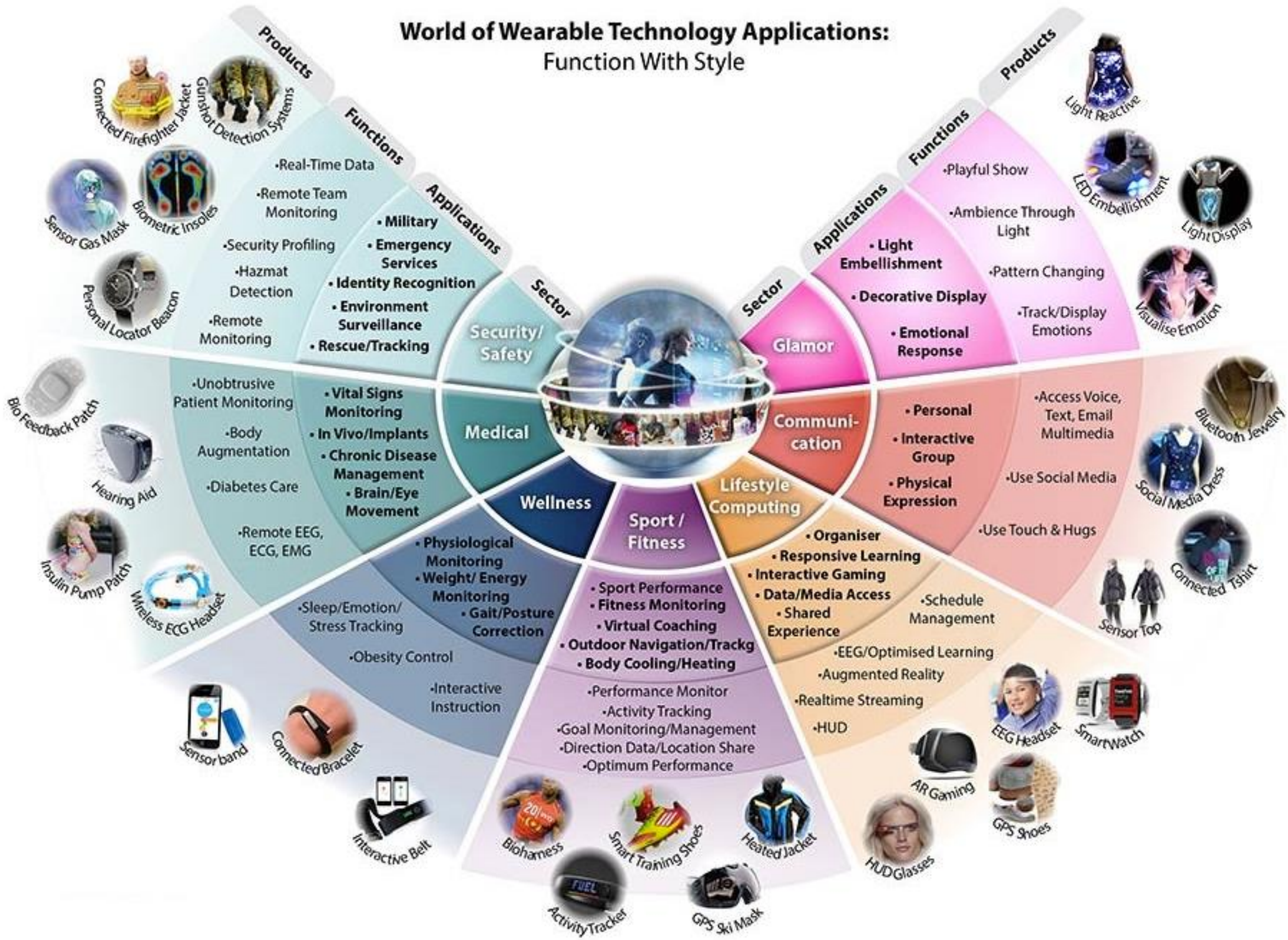
What to target:

- Low data rate
- Low duty cycle
- Ultra-low power
- Mobility
- Mission-critical
- Cost-tolerant

About the tem

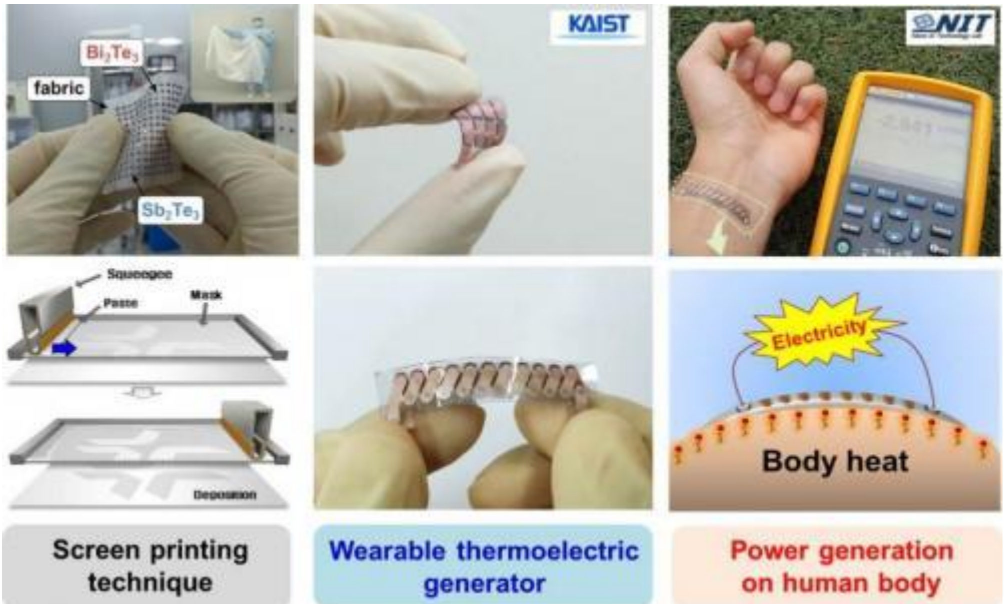






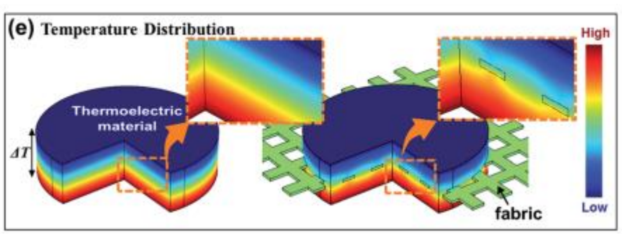
Courtesy of HL7 Standards

Body heat harvesting



because the Al_2O_3 substrate causes thermal energy loss, as illustrated in Fig. 5a. As a result, it leads to 133% enhanced power density (3.8 mW cm^{-2} at a $\Delta T = 50$ K), which is several tens of times higher than flexible TE generators reported to date (Fig. 5c).[30,31] Moreover, in terms of power per unit weight, the glass

shape approximating that of a medical bandage, and applied it to human skin as a body heat energy harvester (Fig. 6). The TE module generates an open-circuit output voltage of 2.9 mV and an output power of 3 μW on a matched external load at an air temperature of 15 °C (Fig. 6b). The measured power density

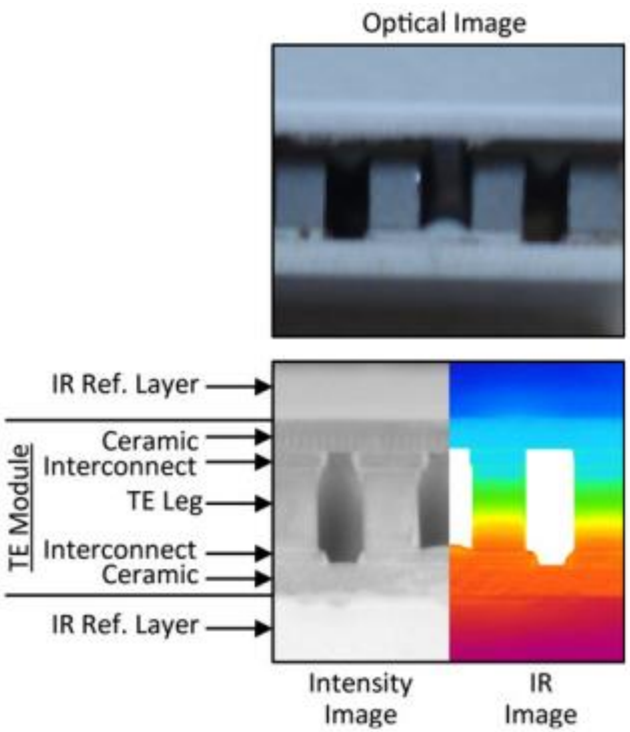


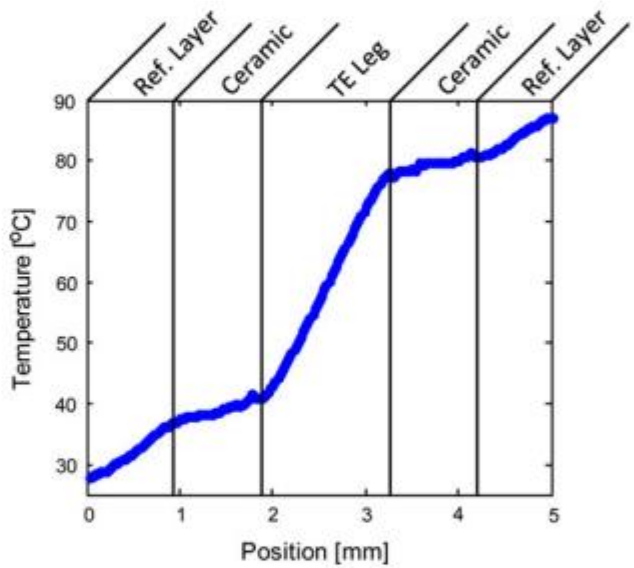
Current limitation is not at the material level but at the device level:

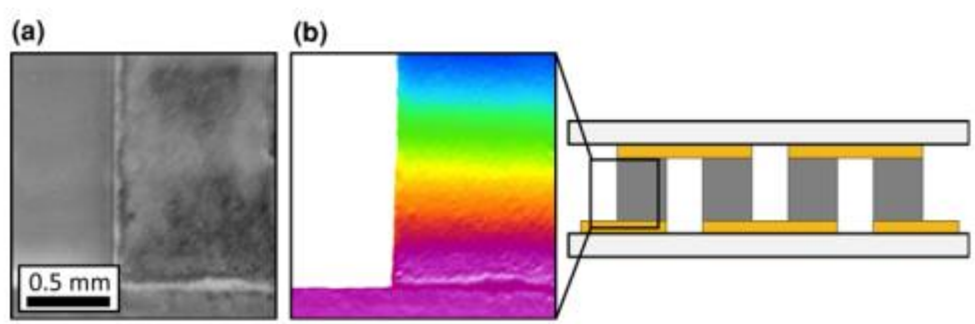
- thermal mismatch
- contact resistance
- effective dissipation

S.J. Kim, J.H. Wea and B.J. Cho, Energy Environ. Sci., 2014,7, 1959-1965

Contact resistance



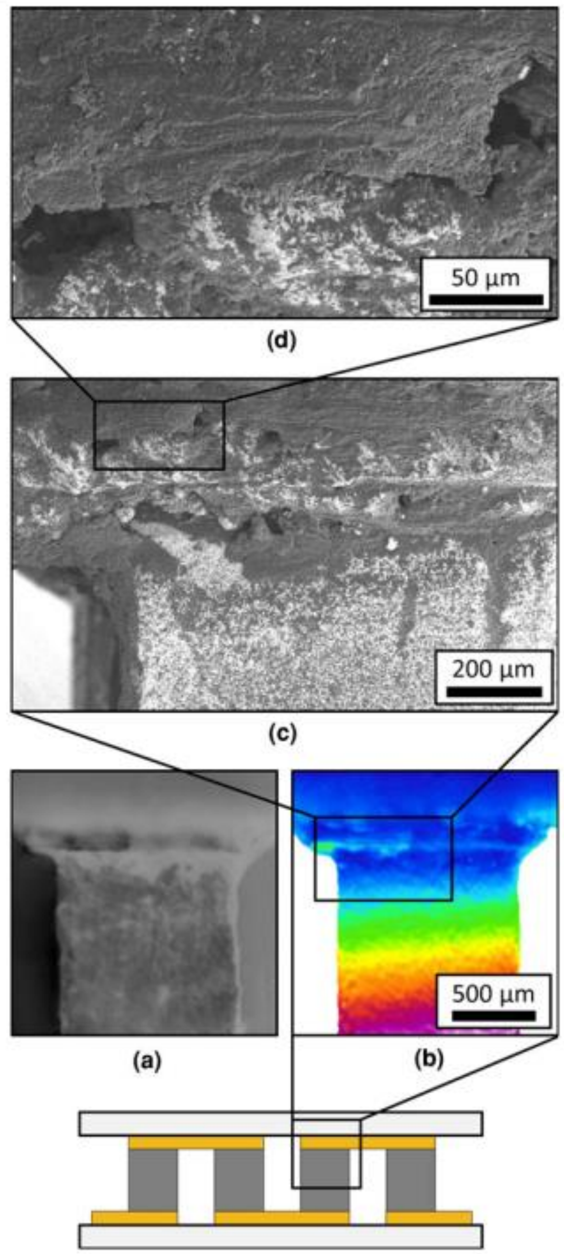




Barako et al., J. Electron. Mater., 42, 2013, 372

Contact stability

- Thermal contacts rule the actual amount of ΔT sensed by the TE legs
- In contacts to soft surfaces, additional thermal resistances arise
- Furthermore, thermal cycling may cause interdiffusion at metal-TE contacts
- Reliability issues often related to metallurgy

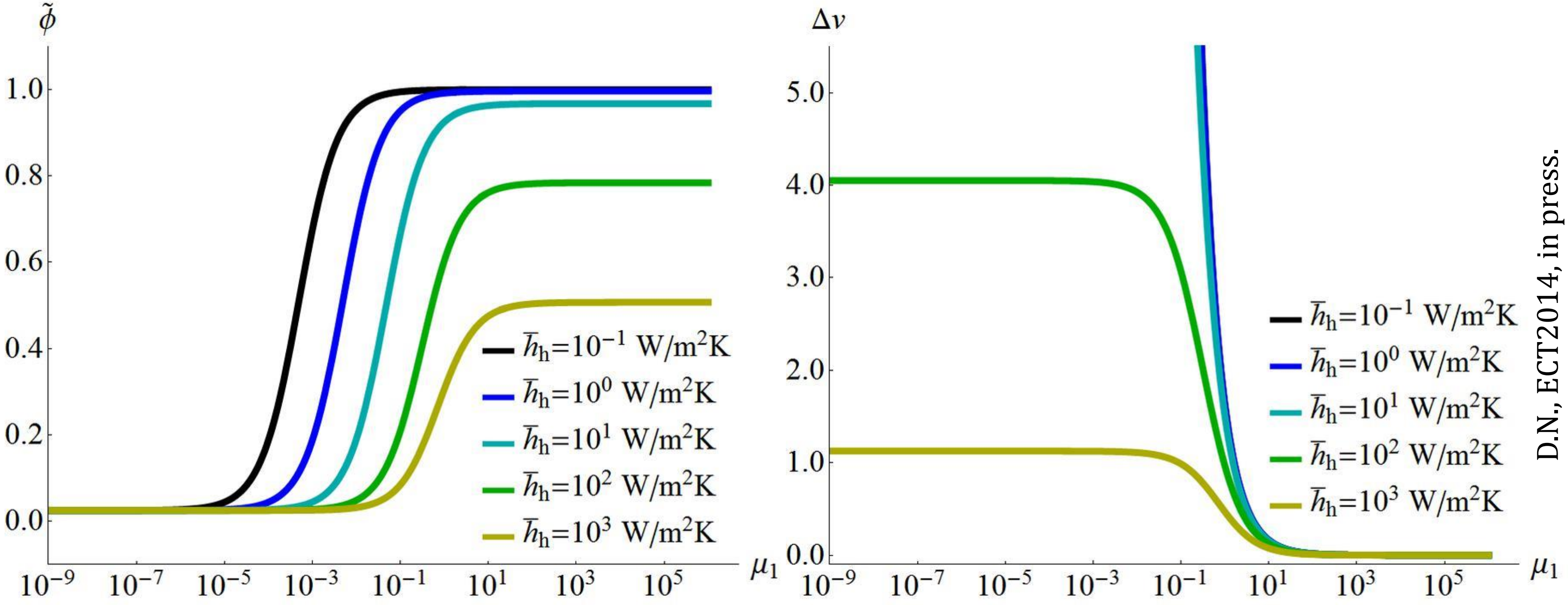


Barako et al., J. Electron. Mater., 42, 2013, 372

Dissipation efficiency

$\mu_1 \equiv d_{\mathrm{H}} / d_{\mathrm{TE}}$

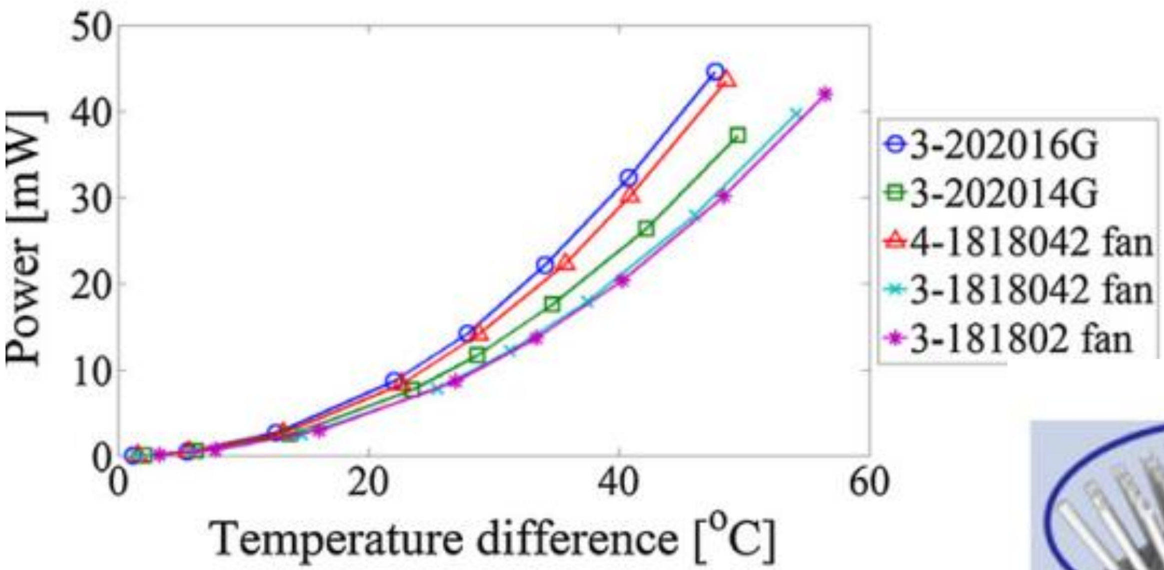
$\Delta v \equiv v_H - v_C = (T_{\mathrm{H}} - T_{\mathrm{C}}) / T_{\mathrm{a}}$

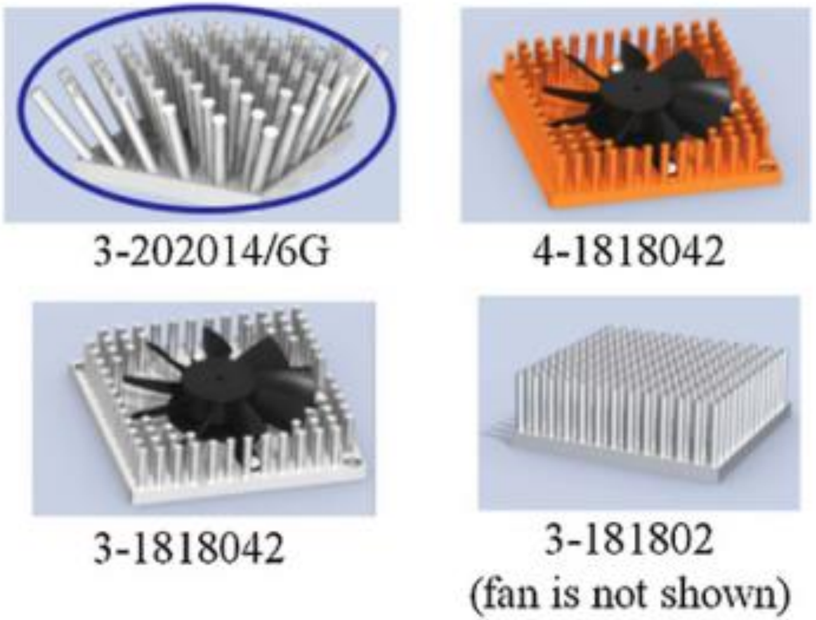


D.N., ECT2014, in press.

If the hot side is not perfectly insulated (or the heat source strength decreases) constant temperature/heat flow BCs do not apply around μ_1= 1. Since typical μ_1 for TEGs are between 10^{-1}- 10^{1} (bulk) and 10^{6} (micro/nano), application of standard analyses may mislead optimization of leg lengths.

Dissipation efficiency





P Gambier et al , Meas. Sci. Technol. 23, 2012, 015101

Conclusions

- Nanotechnology breakthrough enabled new applications for TEGs
- It induced a rethinking of material research on TE:
  - Raw material issues
  - Cost factors & integration
  - Strict correlation between material development and device design
- Take-home message
  - 'Side' issues in material technology are central to TEG design
  - TEG is not a one-size-fits-all kind of technology
  - The bridge over the Valley of Death possibly stands on careful selection of scenarios where TE points of strength can be fully appreciated
  - Internet of (Mobile) Things may be a suitable workbench if applications are realistically selected (e.g. body heat harvesting) and technology is accurately tailored