Thermoelectric MEMS Energy Harvesters

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March 2025

History and actual status

- Discovery of the Seebeck principle in 1821

- In 1997, Stordeur and Stark demonstrated one of the first MEMS thermoelectric microgenerators, followed in 1998 with the Seiko Thermic wristwatch, the first commercial body-heat-powered watch:

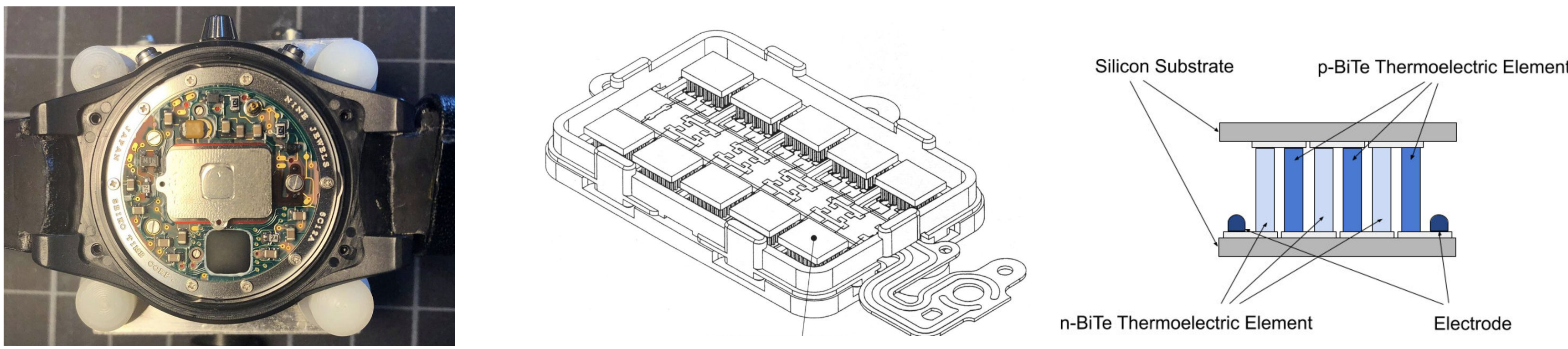


Fig. 2.1 - `Seiko Thermic' body heat-powered watch overview. *Source [1]*

- In 2008, Micropelt GmbH developed the TE-Power Bolt, used in industrial equipment, converting waste heat from machinery into electricity for battery-free IoT sensors.
- Nowadays, research in nanostructured materials and printed and flexible thermoelectrics will allow TEGs to be seamlessly embedded into clothing or medical implants.

Note. ThermoElectric Generators (TEG) will be used interchangeably with ThermoElectric Harvesters

MEMS operation principle

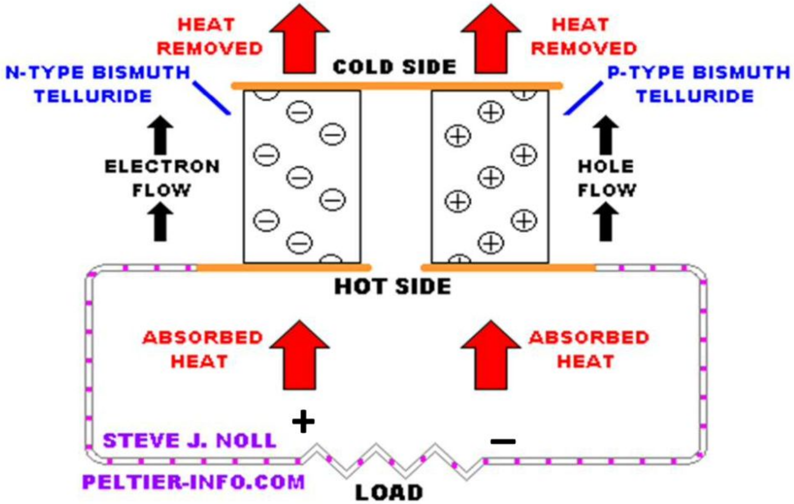


Fig. 3.1 - BiTe-based thermocouple. Source [2]

- Operates on Seebeck effect
- Converts temperature differences directly into electricity using thermocouples (pairs of p-type and n-type semiconductor legs)

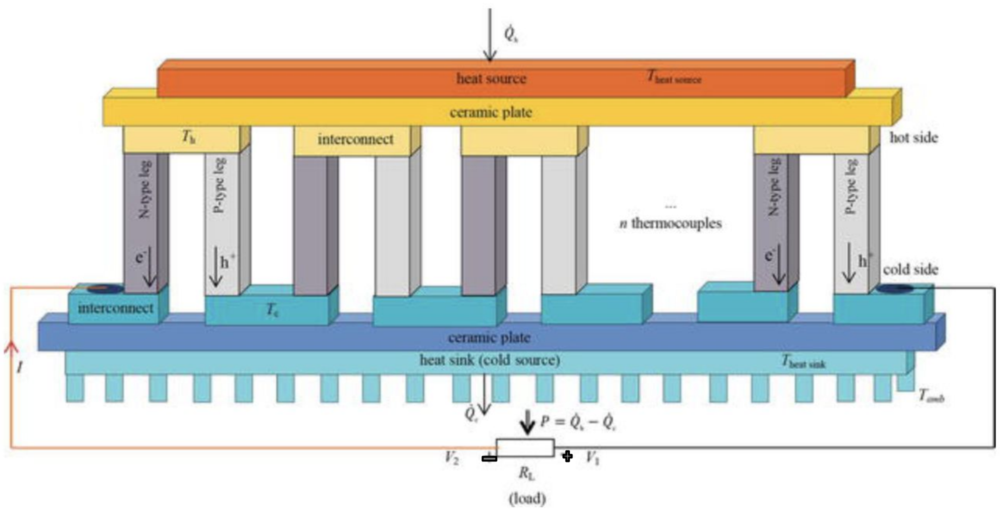
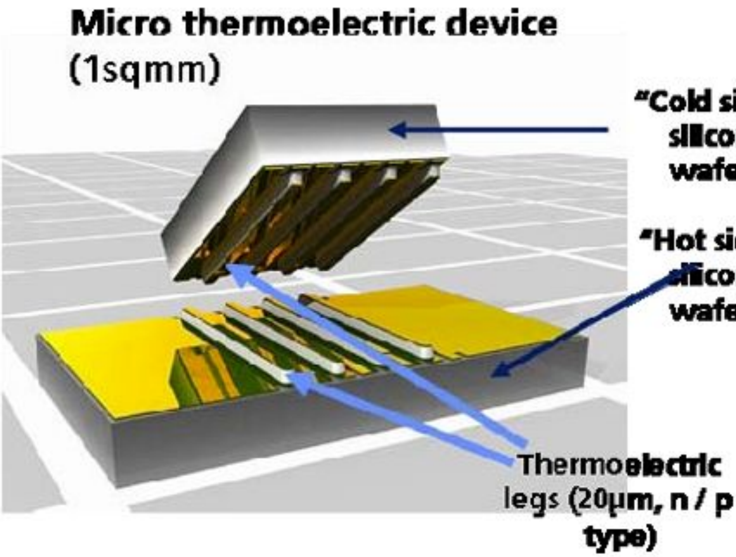


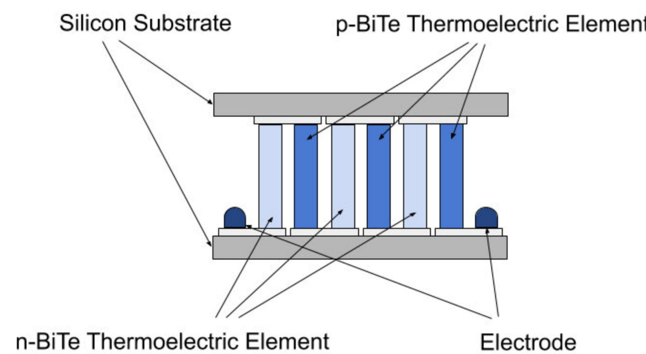
Fig. 3.2 - Thermoelectric Energy Harvesting: Basic Principles and Applications. *Source [3]*

- Thermocouples are connected
  -Electrically in series
  -Thermally in parallel
- $V = (S_p – S_n) \cdot \Delta T \cdot N$

MEMS implementation

- **No established industry standard ⟶ Micropelt TGP 751/651 study case**





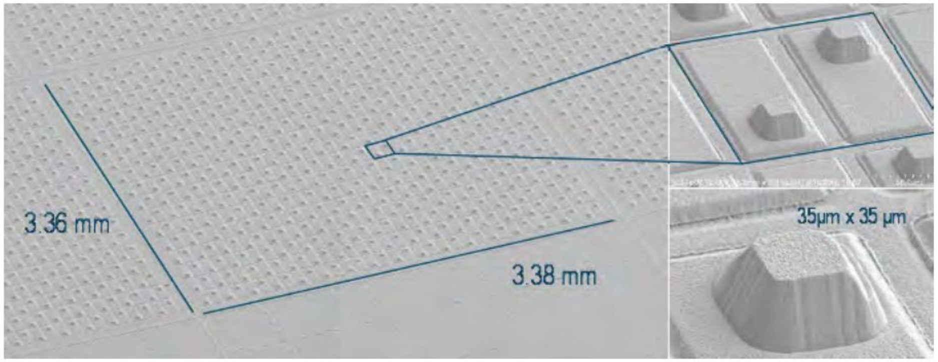


Fig. 4.1 (Top-left) - BiTe Micropelt© TEG CAD view. Source [4]

Fig. 4.2 (Bottom-left) - BiTe Micropelt© TEG SEM view. Source [5]

Fig. 4.3 (Top-right) - BiTe TEG schematic schematic overview. Source [1]

Fig. 4.4 (Bottom) - Performance of Micropelt© MPG-D751. Source [7]

Manufacturer	*Model*	*T_{HOT}* (K)	*T_{COLD}* (K)	*Number of thermocouples*	*Power†* (W)	*Voltage* (V)	*Price§* ($/W)	*Dimensions* Length×Width×Thickness (mm×mm×mm)	*Power density* (W/cm^3)	*Material*
Micr°Pelt	MPG-D751	330	300	540	14×10^{-3}	2.25	~350	4.248×3.364×1.09	0.9	Bi-Te

Characteristics

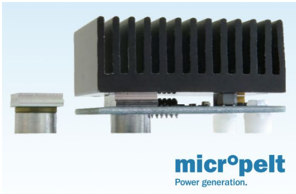
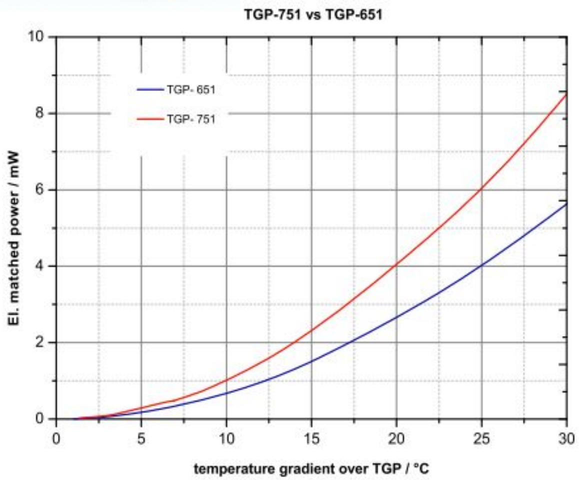
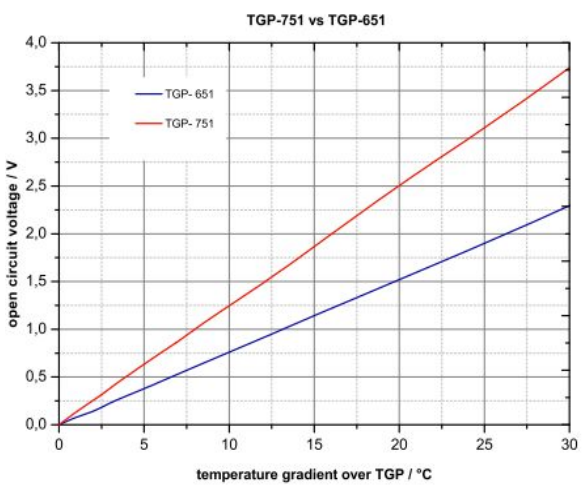


Fig. 5.2 - Typical BiTe Micropelt© TEG CAD view (left) and performance (below). Source [5]





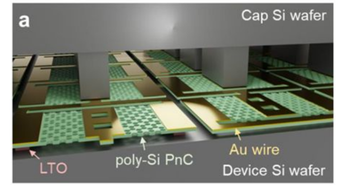
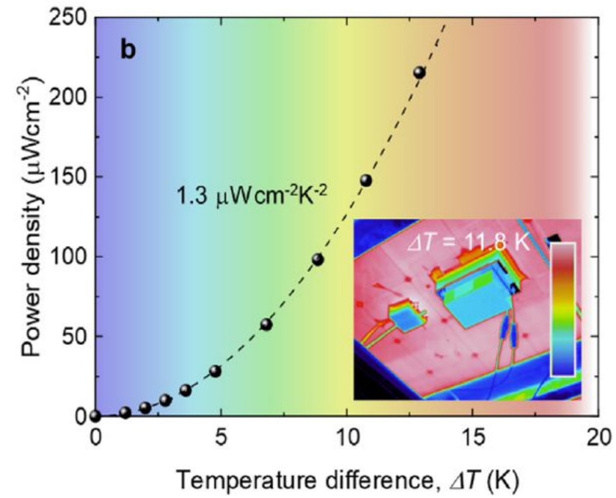
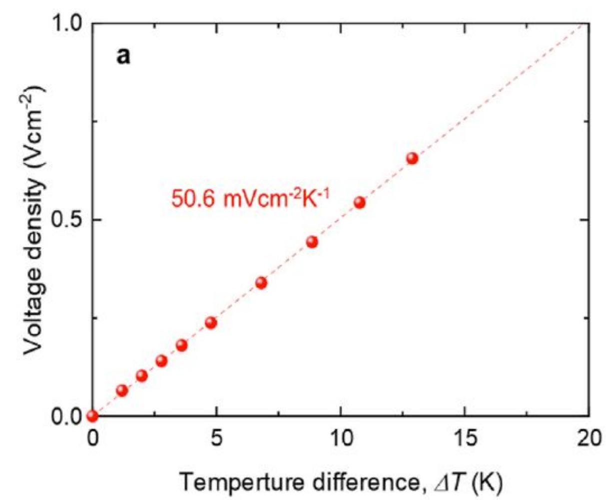
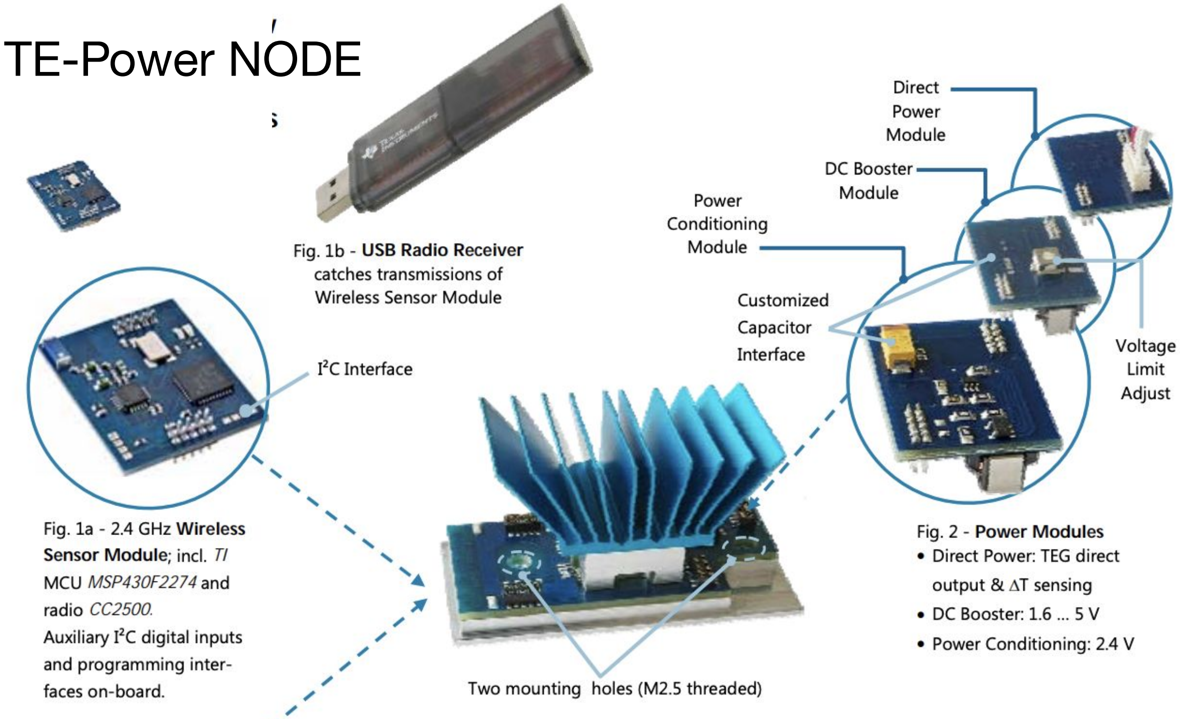


Fig. 5.1 - PolySi Phononic Crystal TEG CAD view (left) and performance (below). Source [8]





TE-Power NODE



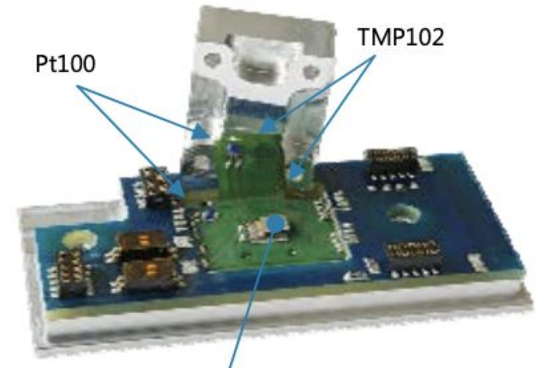
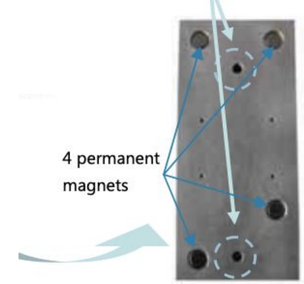


Fig. 6.1 - Schematics extracted from TE-Power NODE Datasheet. Source *[9]*



- Maintaining temperature gradient → Optimal thermal interfaces between the TEG and both heat source and sink
- Robust electrical and mechanical integration → stable connections, protects components, and allows easy mounting on heat sources.

Products and applications

- MEMS TEG still a field of active research, with limited established products commercially available

- Main purpose: powering remote sensors and Internet-of-Things (IoT) applications

- Promising in low-power and long-duty wearable devices (medical implants, space exploration etc.)

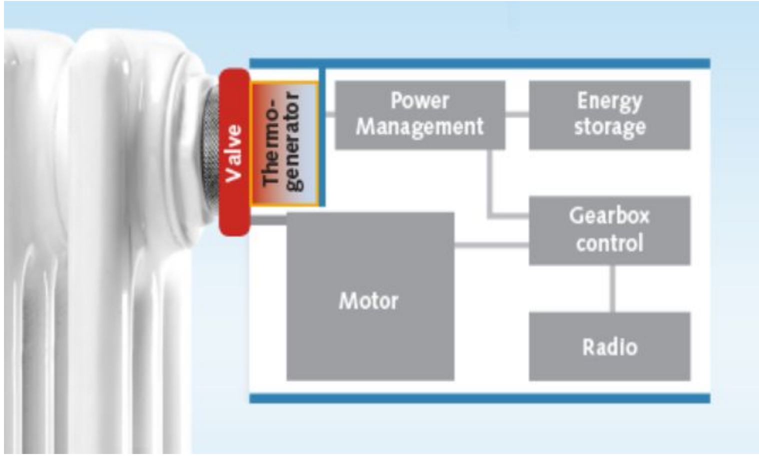


Fig. 7.1 - Use case of Micropelt© TEG in IoT applications: automated heating control. Source - https://www.micropelt.com/en/energy-harvesting

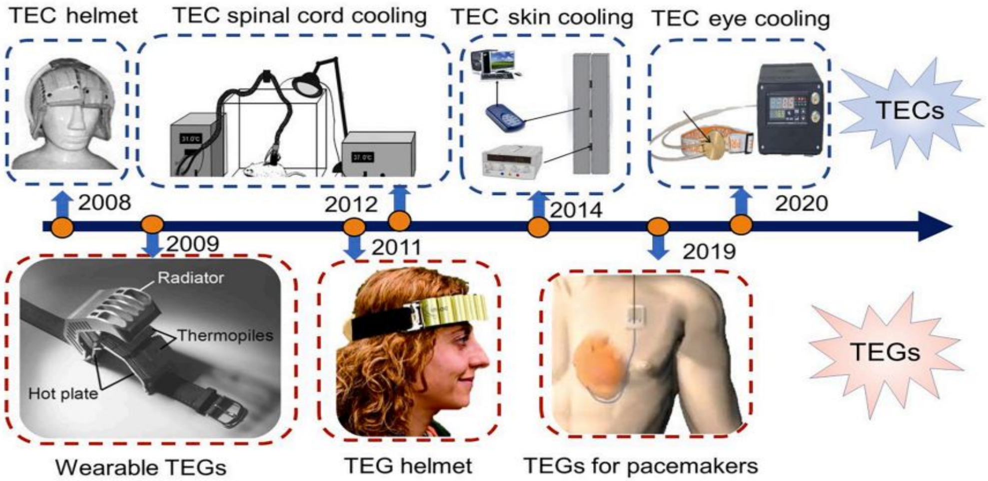


Fig. 7.2 (Above) - Fields of research in TEG applications to medical applications. Source [10]

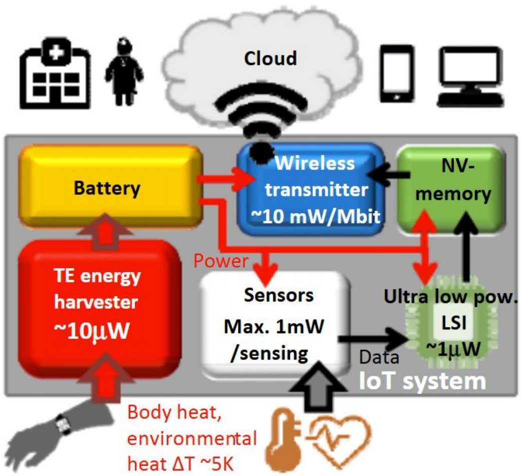


Fig. 7.3 (Left) - Typical TEG-based remote sensing application. Source [11]

References

[1] https://www.plus9time.com/blog/2020/5/30/body-heat-powered-watches-seiko-thermic

[2] Physique des composants semiconducteurs MICRO-312 Besse Pierre-André

[3] https://www.intechopen.com/chapters/65239

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[5] Micropelt TGP 751-651 Preliminary Datasheethttps://www.mouser.com/ds/2/269/thermo_generator_package-2067.pdf

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[7] M. Haras, *Thermoélectricité non-conventionnelle basée sur les technologies silicium en film minces*, Ph.D. dissertation, Univ. Lille 1 Sciences et Technologies, Lille, France, 2016. Available: https://pepite-depot.univ-lille.fr/LIBRE/EDSPI/2016/50376-2016-Haras.pdf.

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[9]https://www.mouser.com/catalog/specsheets/datasheet_te_power_node.pdf?srsltid=AfmBOorPC1pnpjdwDwUt2sVuWYkHL7SguHo5eQxI7Hndx5ydWfDQxcs3

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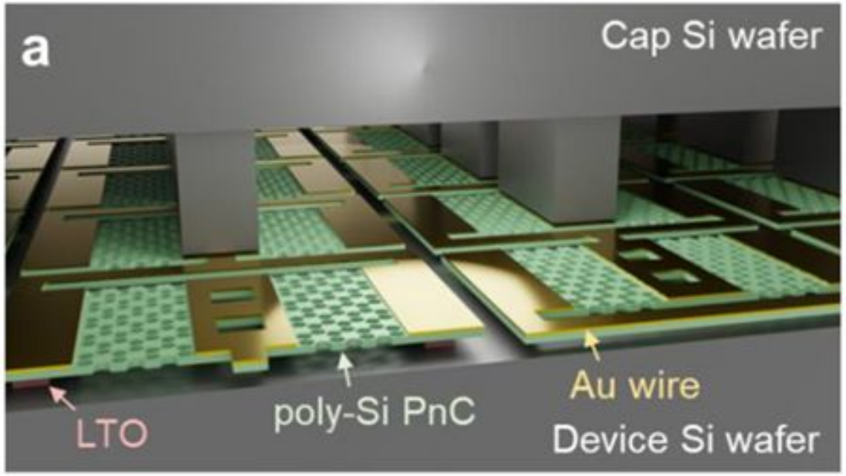
[11] M. Tomita *et al.*, "10μW/cm^2-Class High Power Density Planar Si-Nanowire Thermoelectric Energy Harvester Compatible with CMOS-VLSI Technology," in *Proceedings of the 2018 IEEE Symposium on VLSI Technology*, Honolulu, HI, USA, June 18-22, 2018, pp. 93-94. doi: 10.1109/VLSIT.2018.8510659.

Appendice - MEMS implementation

Advanced TEG principle ⟶ using ‘Nanowires’ Nano-scale effects



- Main process steps
  a. Metal deposition and patterning
  b. Suspended poly-Si Phononic Crystal (PnC) manufacturing
  c. Cap wafer patterning and bonding

Fig. 9 a,c,d,e - Phononic Crystal TEG. (a) CAD render view of device. (c) Focus on energy exchange within a TEG unit area. Scale bar, 20um (d) assembly of units into a TEG device. e) PnC shape close-up view. Scale bar, 500nm. Source [8]