



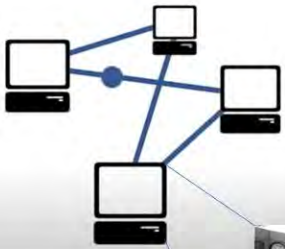
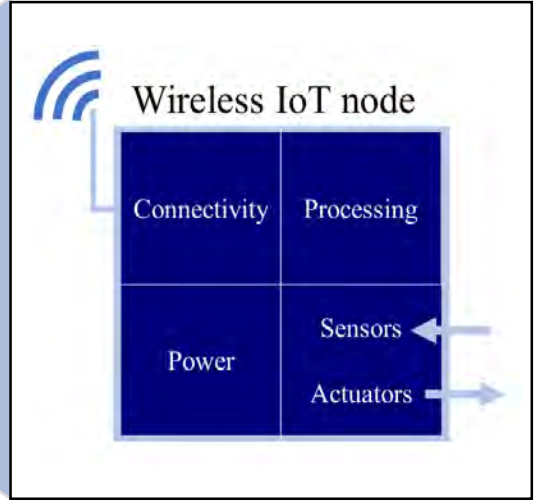
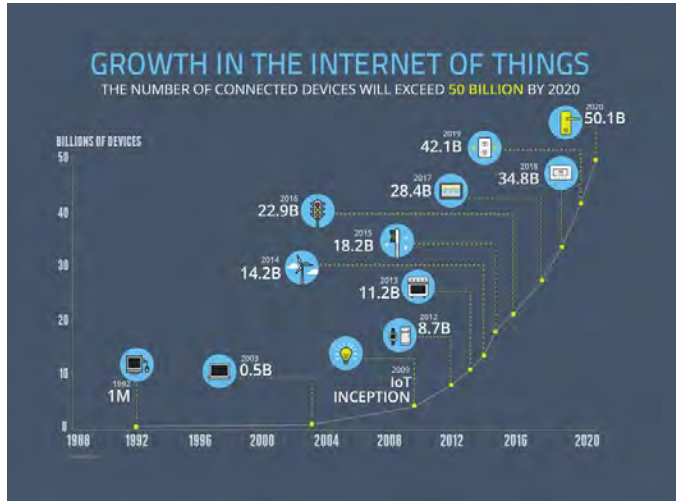
Shaping Energy for a Sustainable Future

# Nanostructured thermoelectric materials

Alex Morata, Jose Manuel Sojo Gordillo, Carolina Duque Sierra, Denise Estrada Wiese, Marc Salleras, Luis Fonseca, Albert Tarancón

# Introduction The boom of the Internet of Things (IoT)

Info obtained from *opte.org*

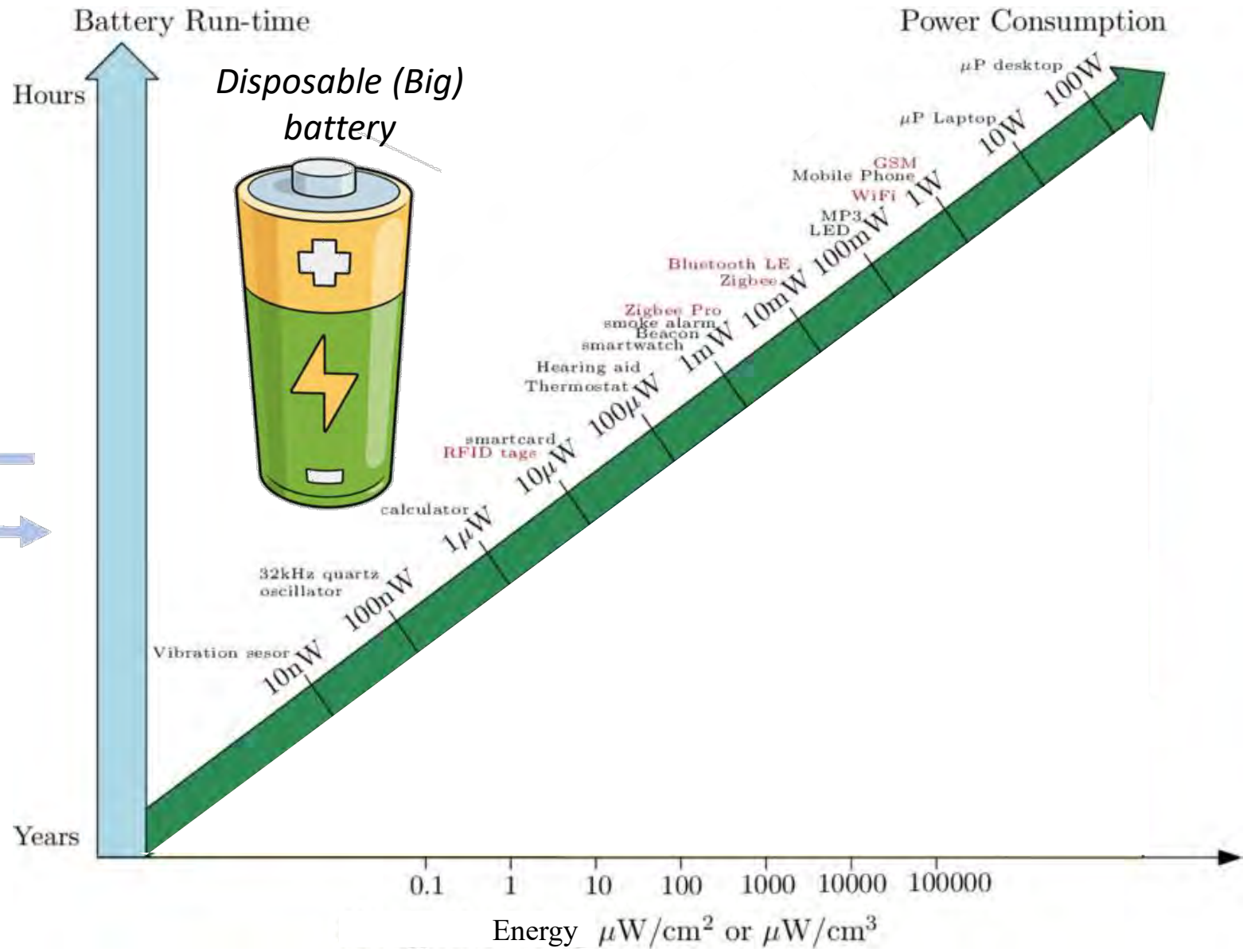
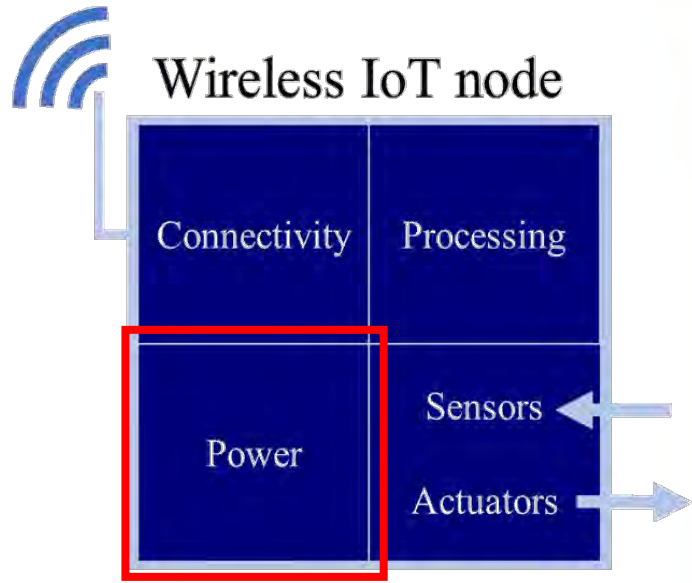


1960

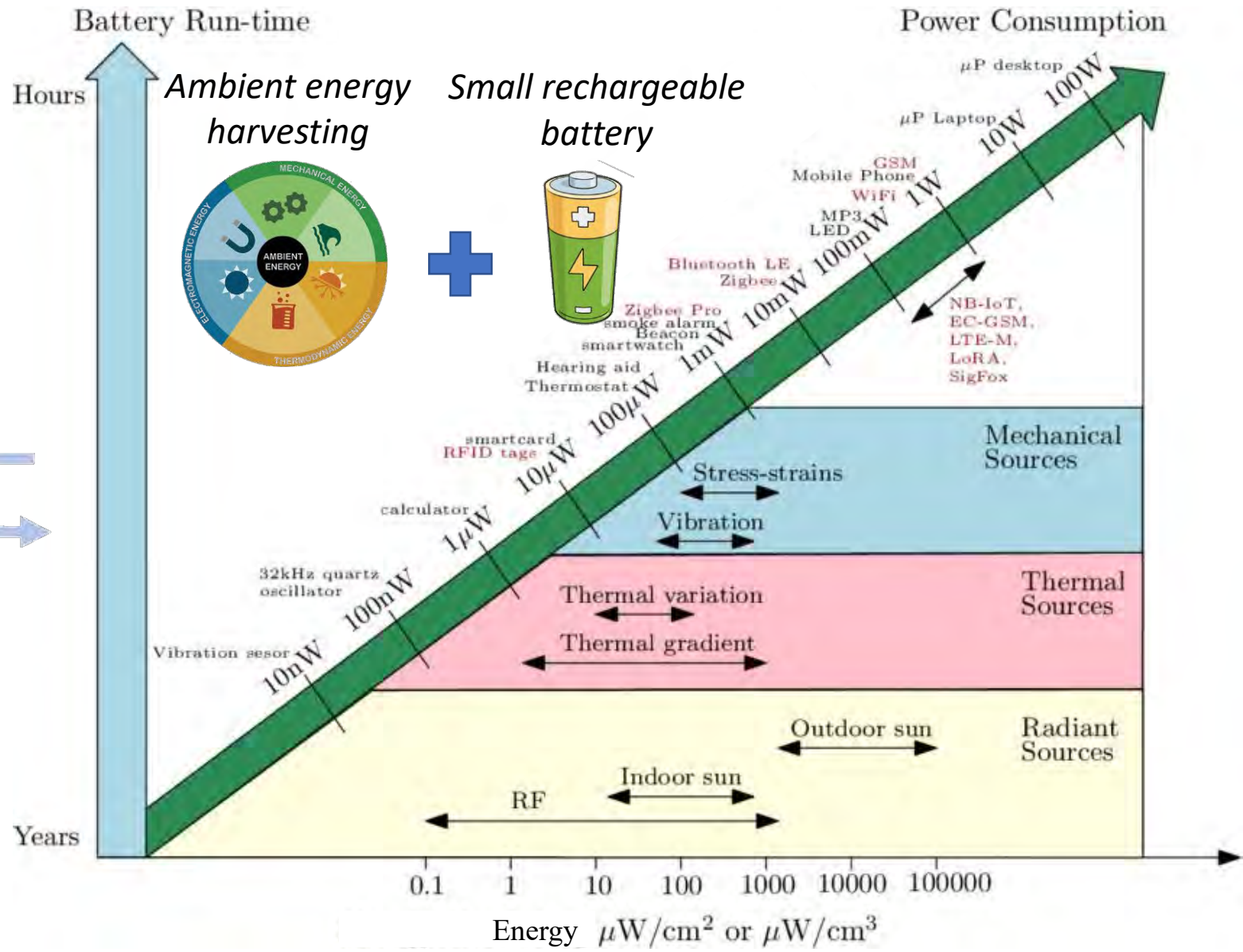
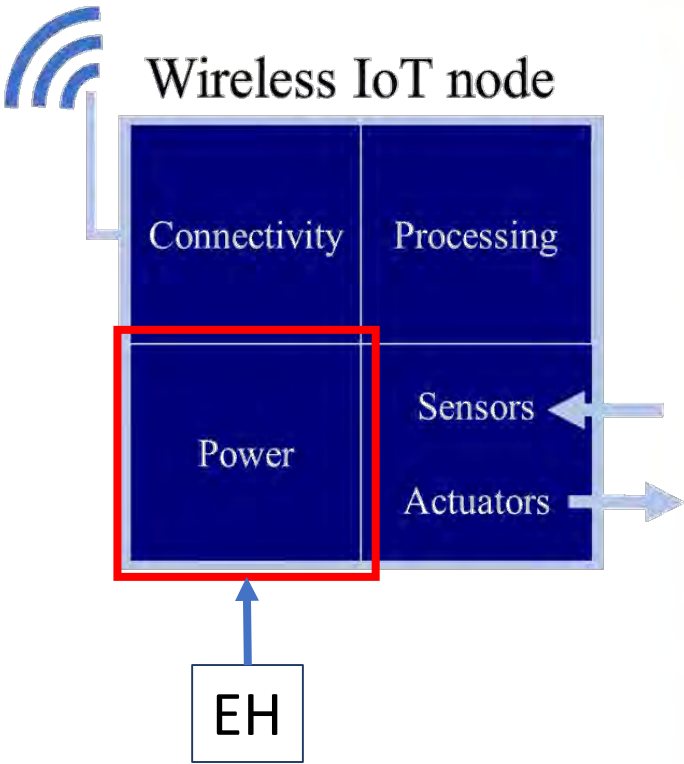
2020

- The number of connected devices is growing exponentially
- The powering of IoT nodes is a major challenge
- Environmentally friendly solution is urgent

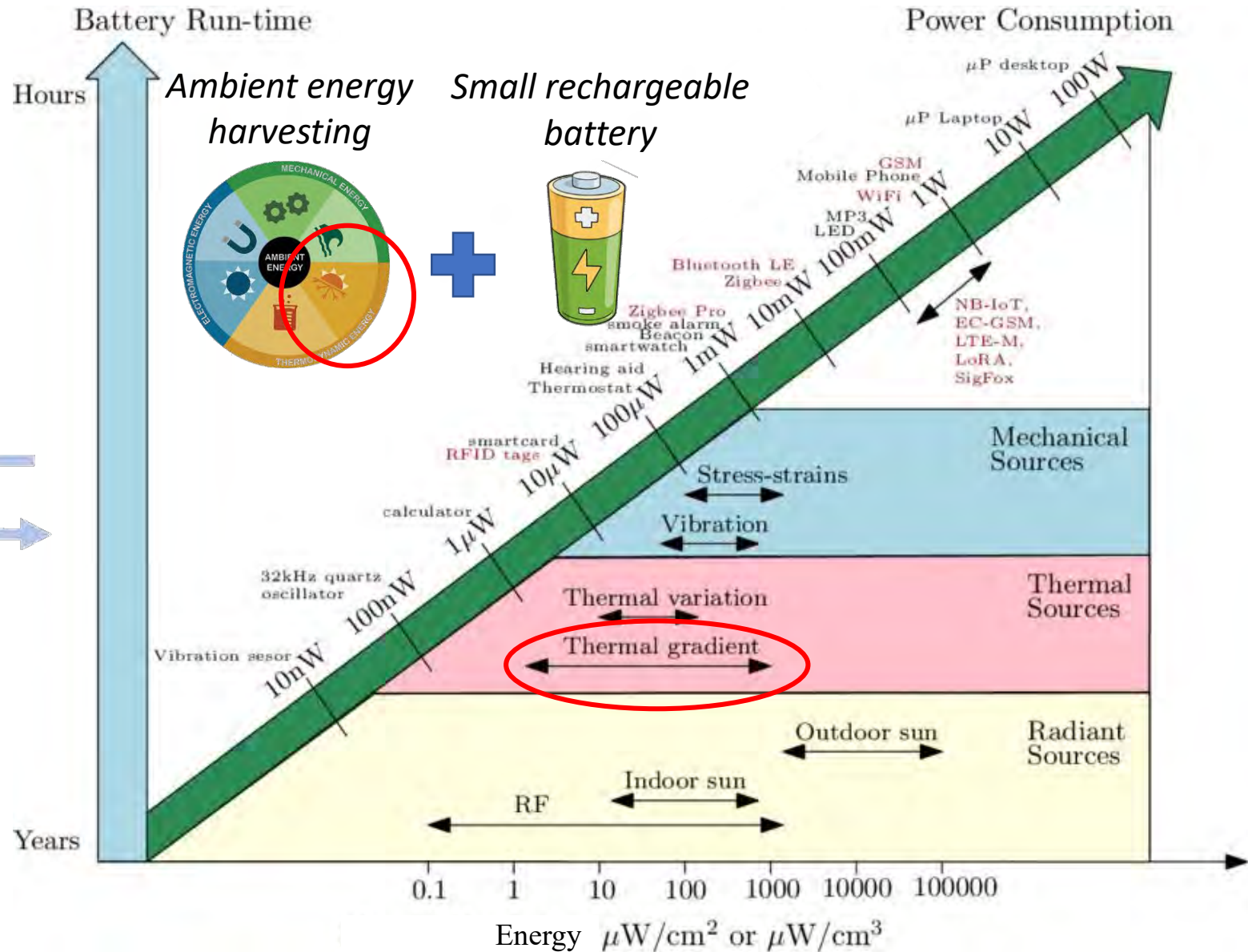
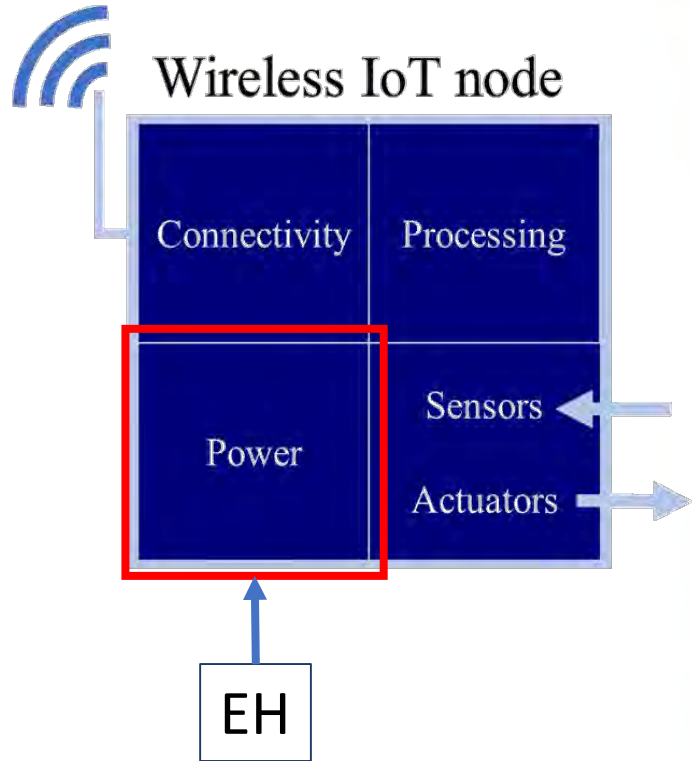
# Introduction Energy supply for IoT nodes



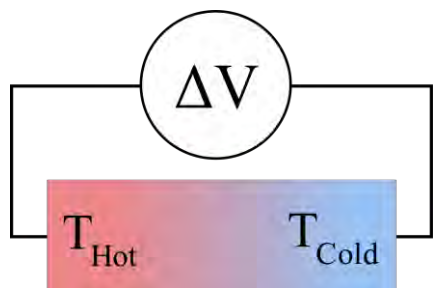
# Introduction Energy supply for IoT nodes



# Introduction Energy supply for IoT nodes



*Thermoelectricity: direct conversion of heat into electricity by means of Seebeck effect*

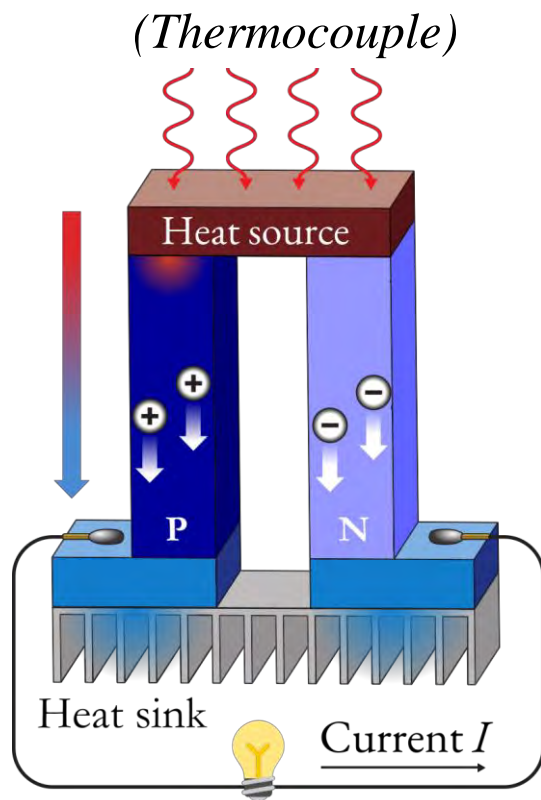


$$\Delta V = S \cdot \Delta T$$



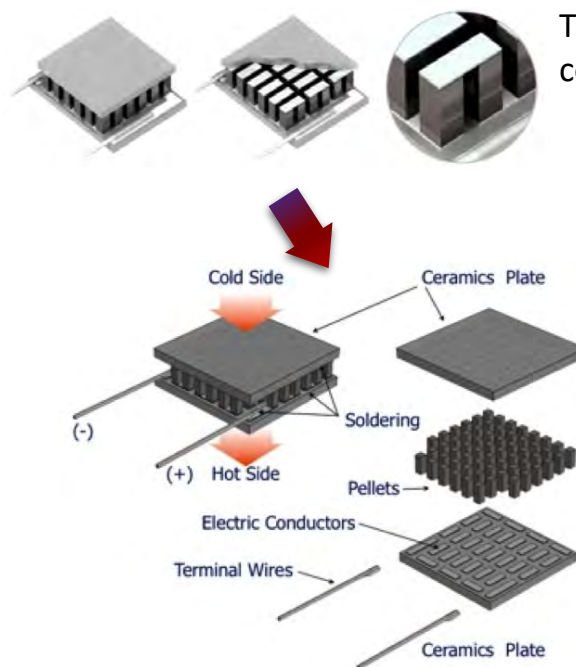
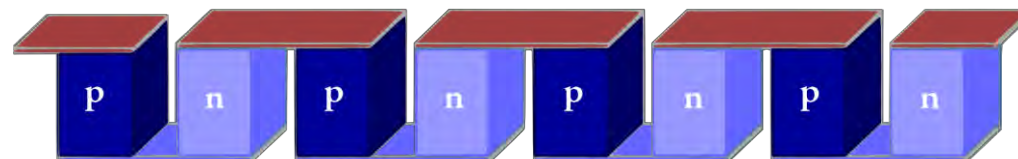
Thomas Johann Seebeck

## Thermoelectric generator

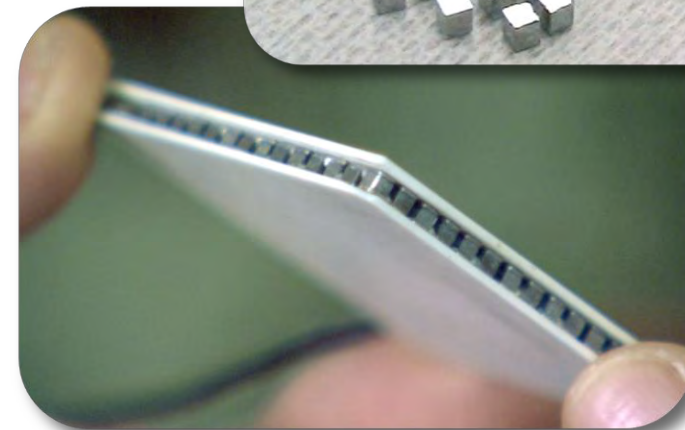
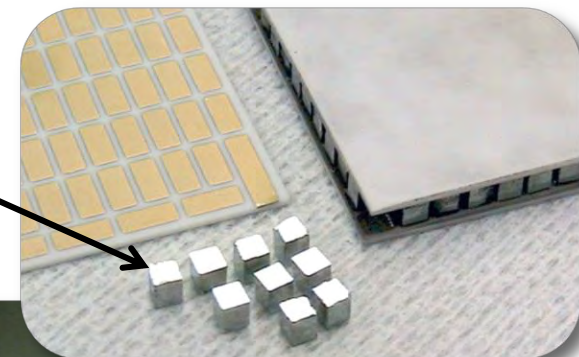


## Thermoelectric modules

Conventional  $\pi$  module



Thermoelectric couples



A commercial thermoelectric module

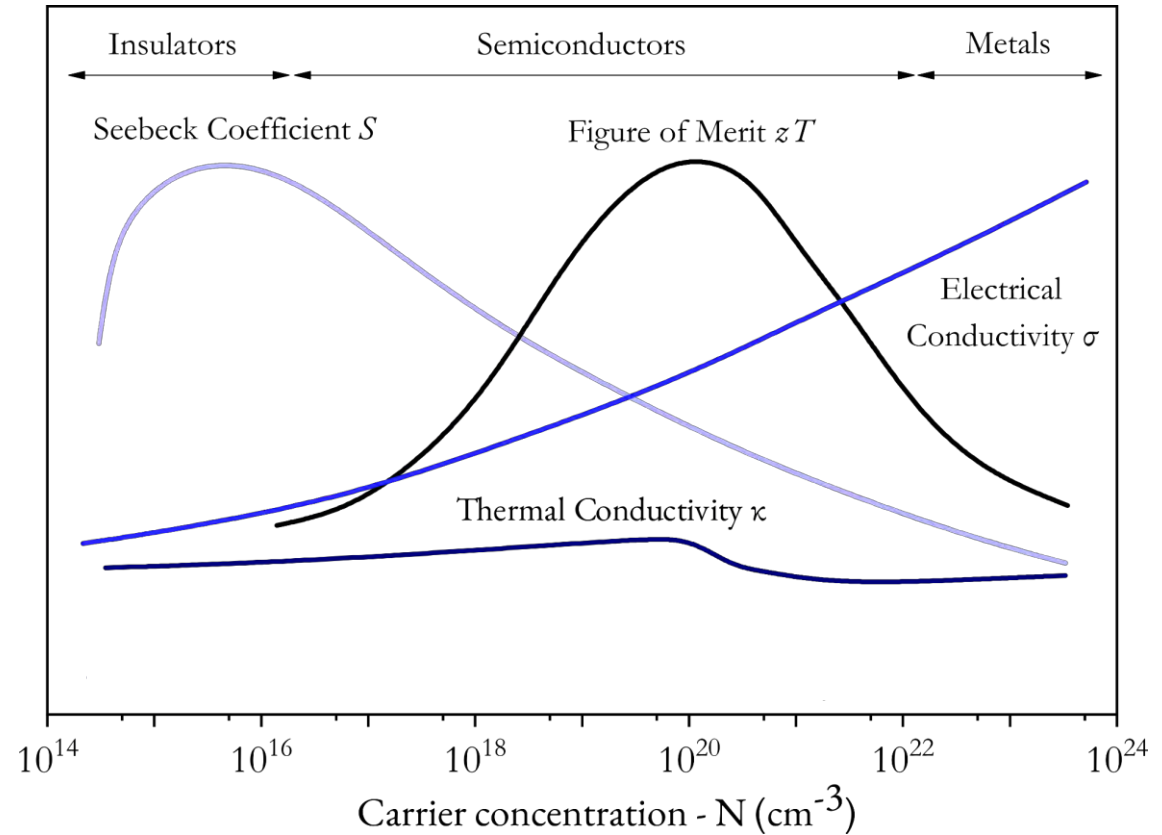
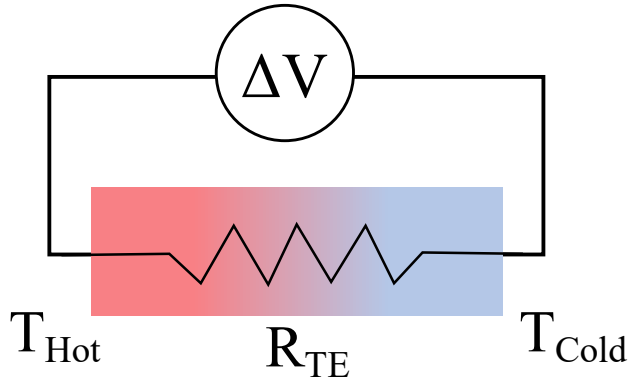
### Thermoelectric efficiency

$$zT = \frac{\uparrow S^2 \sigma \uparrow}{\kappa \downarrow} T$$

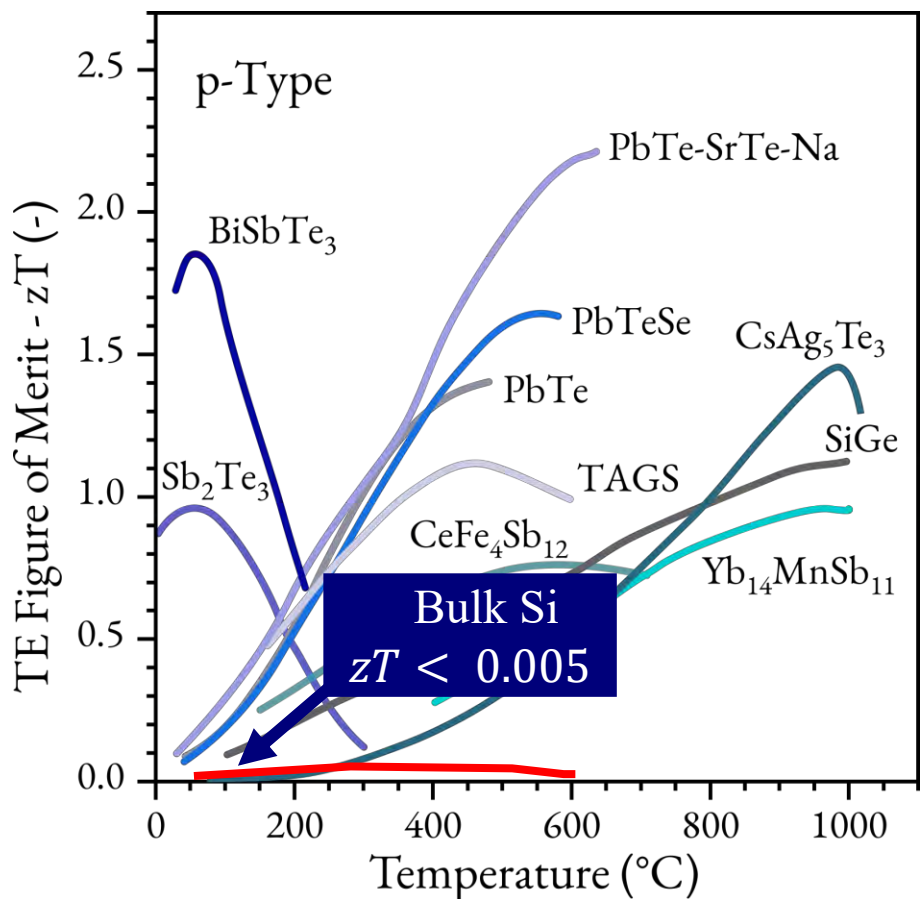
↑  $S$ : Increase output voltage

↑  $\sigma$ : Decrease internal resistance

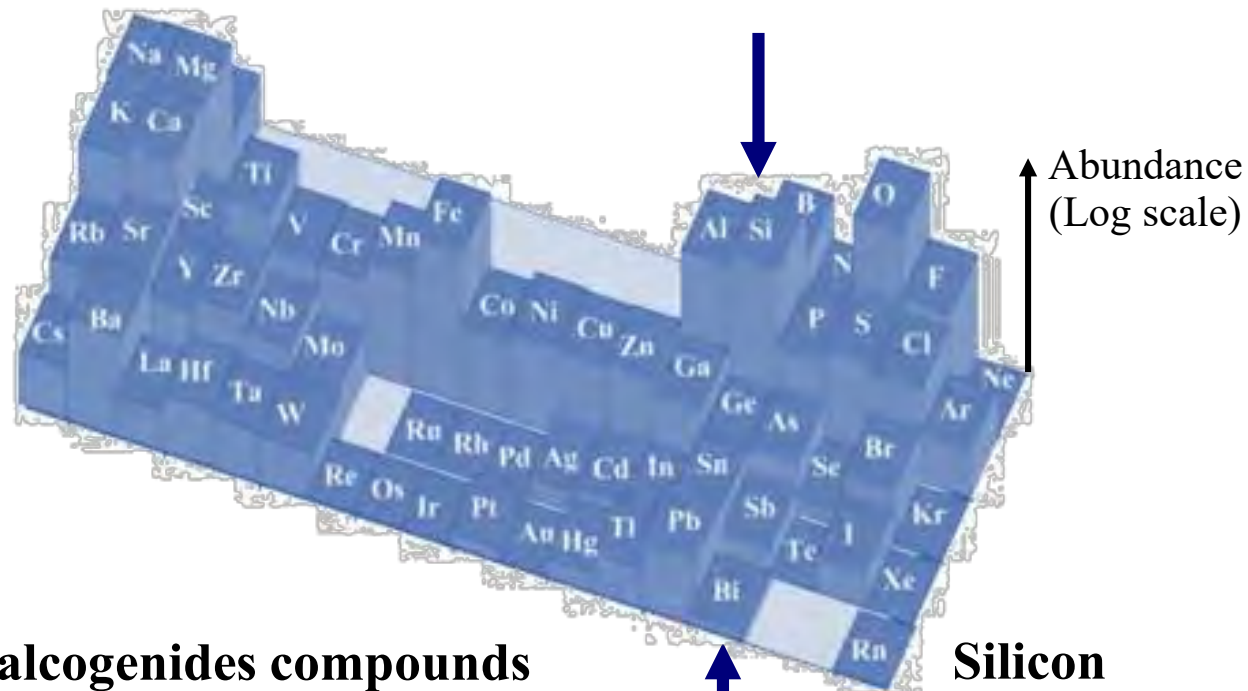
↓  $\kappa$ : Sustain larger thermal gradients



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



*Abundance of elements in earth crust*



### Chalcogenides compounds

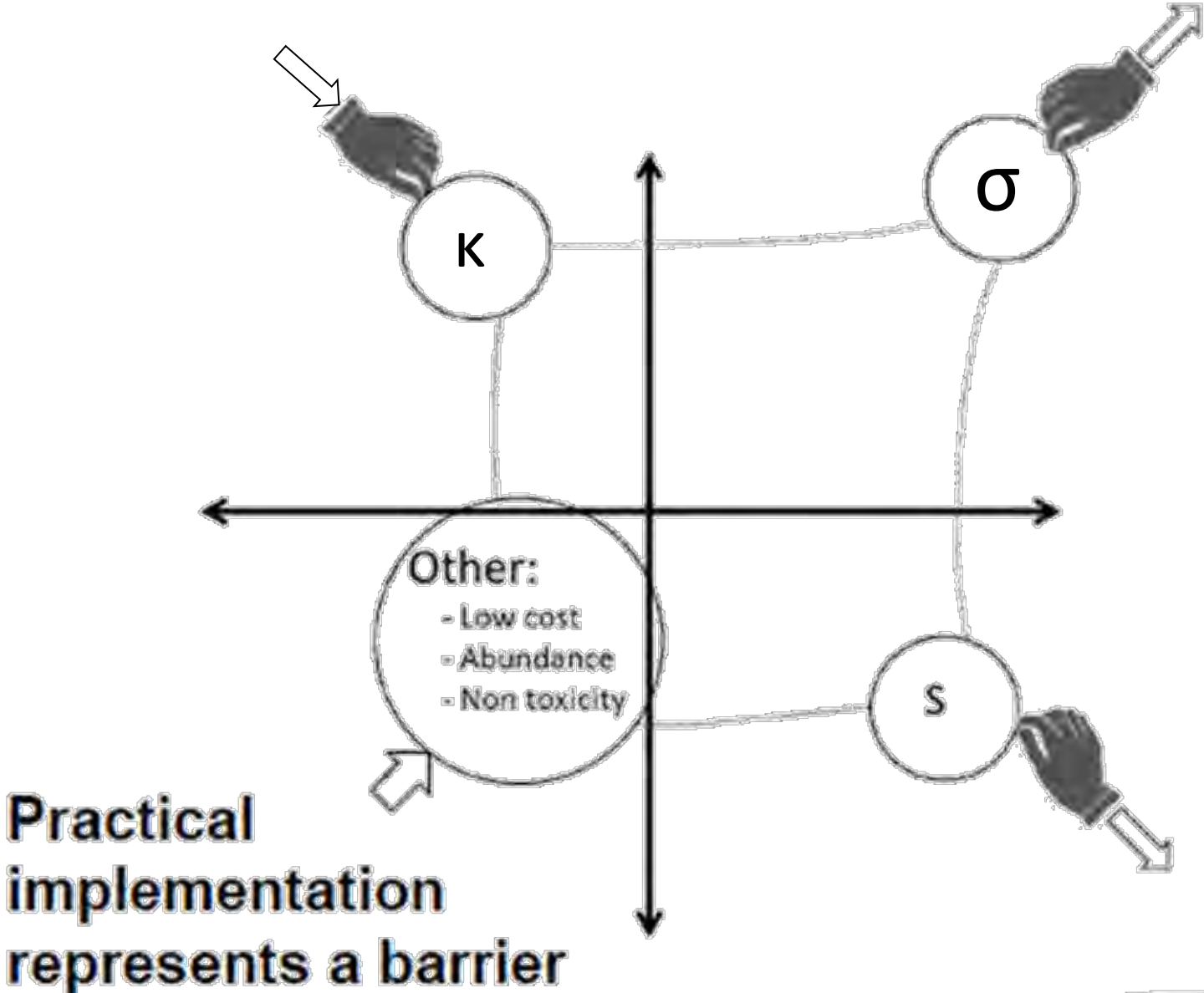
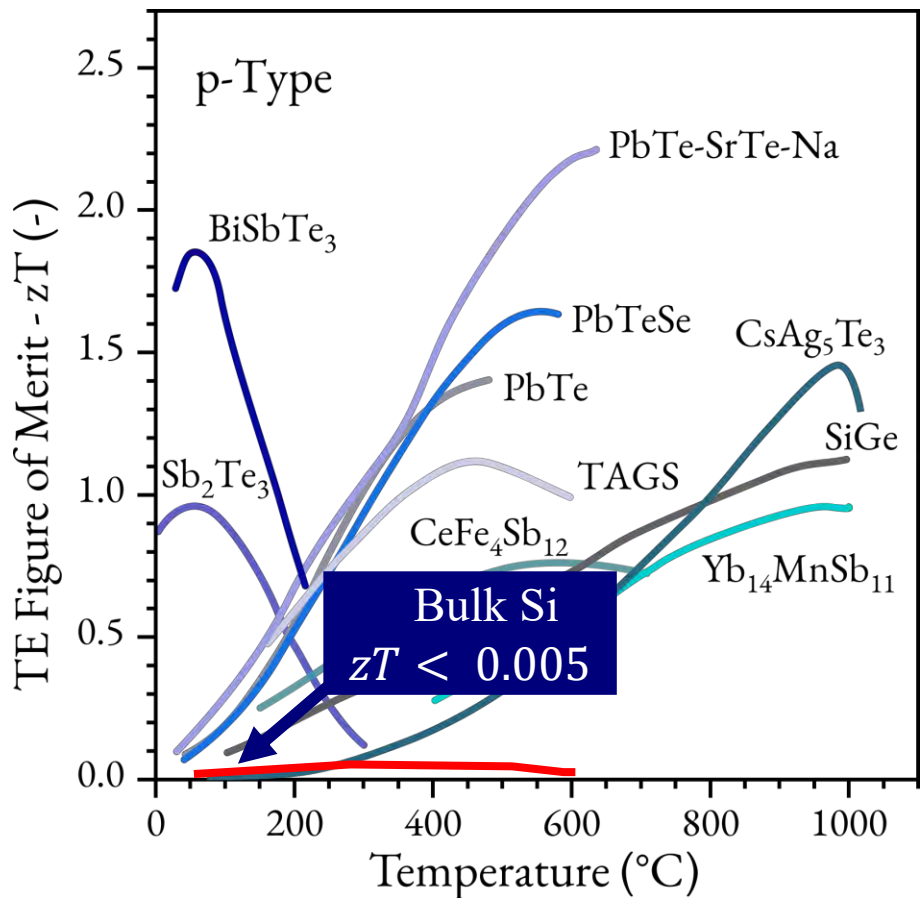
- Scarce → Expensive
- Toxic
- Non-scalable fabrication

- Abundant → Economic
- Biocompatible
- Environmentally friendly
- Integrable in microelectronics



# Introduction Thermoelectric materials

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



# Introduction Nanostructuring of thermoelectric materials

$$zT = \frac{S^2 \sigma}{\kappa} T \quad \text{Maximization of } zT$$

Already good power factor if doped  $S^2 \sigma \propto N$

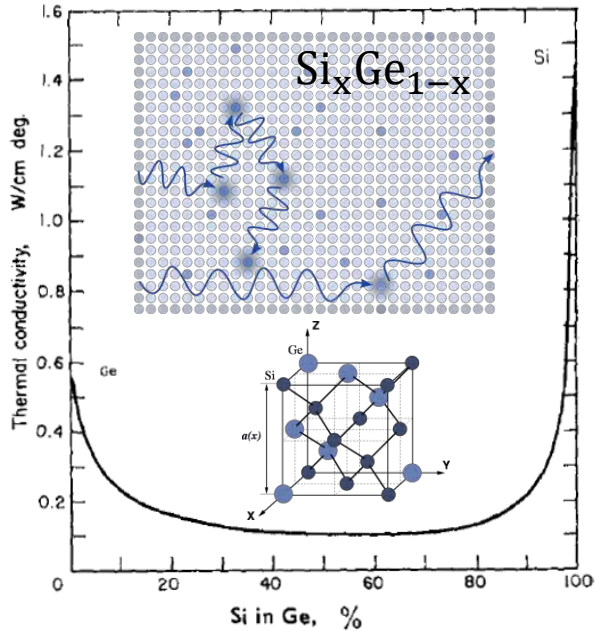
Tailor the thermal conductivity  $\kappa \downarrow$

$\kappa_e$	Electronic	$\propto \sigma(N)$
$\kappa_{ph}$	Phononic	$\propto \lambda$

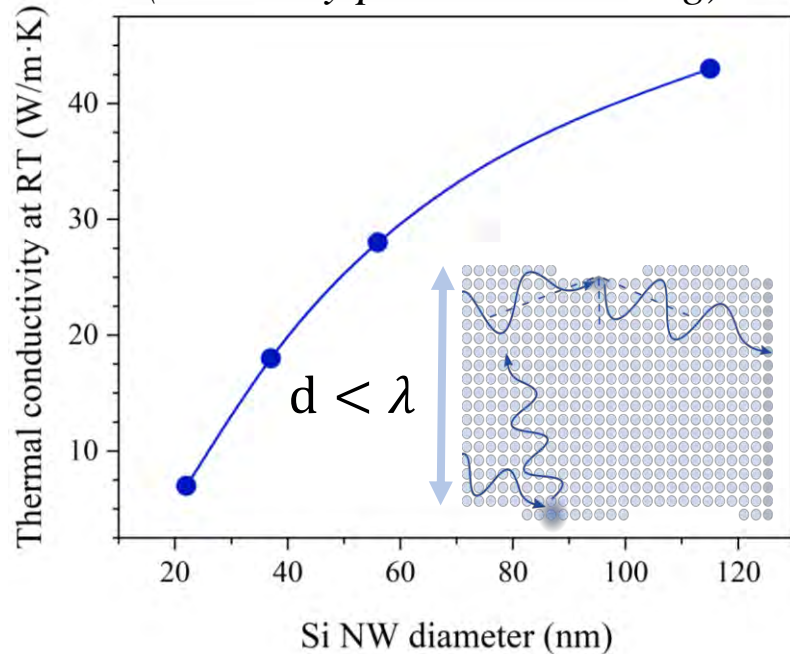
Mean free path  $\uparrow$

**Increasing impurities (alloying)**  
*(mass difference phonon scattering)*

**Reducing size**  
*(boundary phonon scattering)*



Maycock, *Solid. State. Electron.* **10**, 161, (1967)



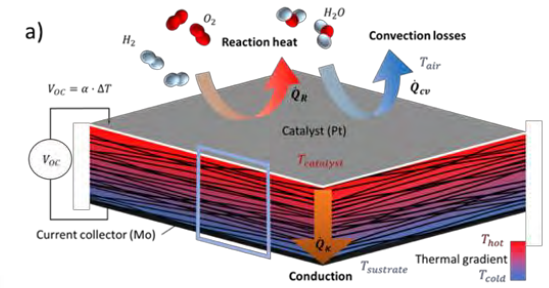
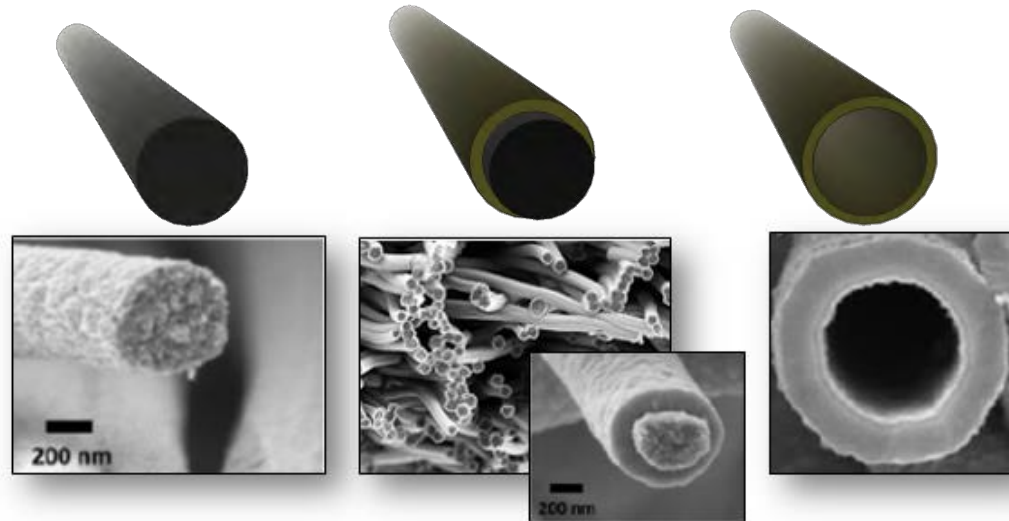
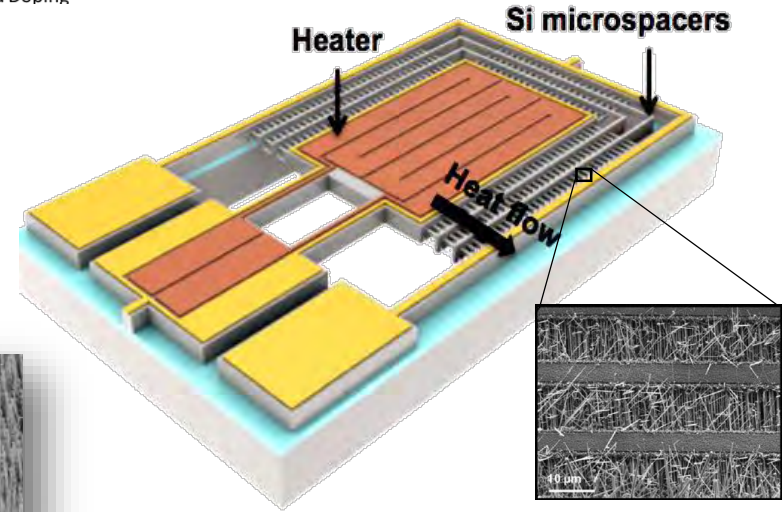
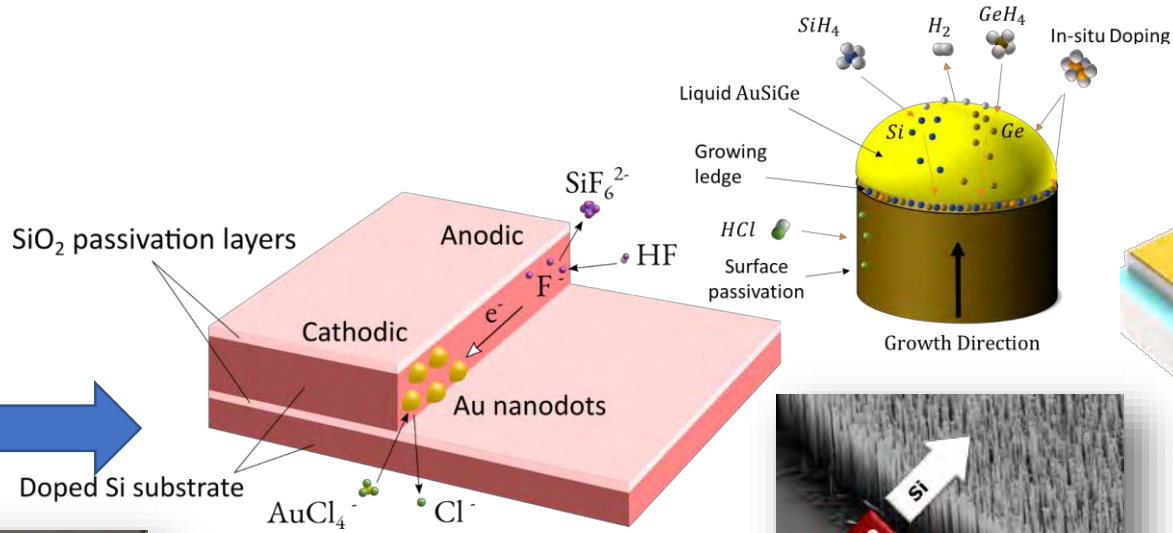
D. Li, *et al., Appl. Phys. Lett.*, **83**, 2934 (2003).

**Nanofabrication challenge**

Scalability

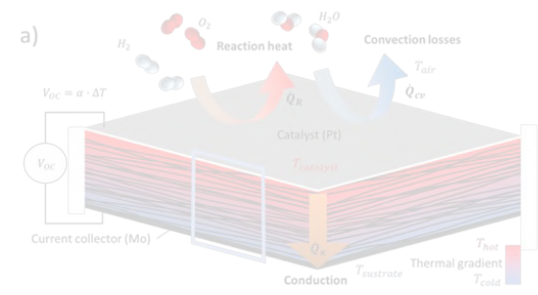
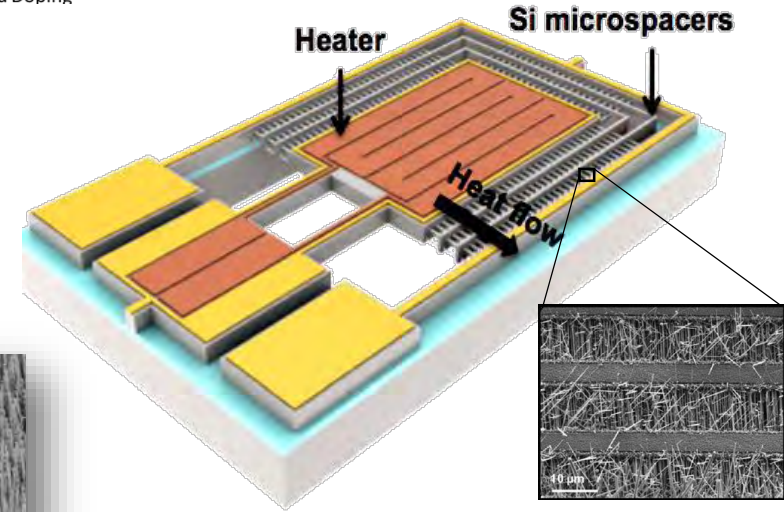
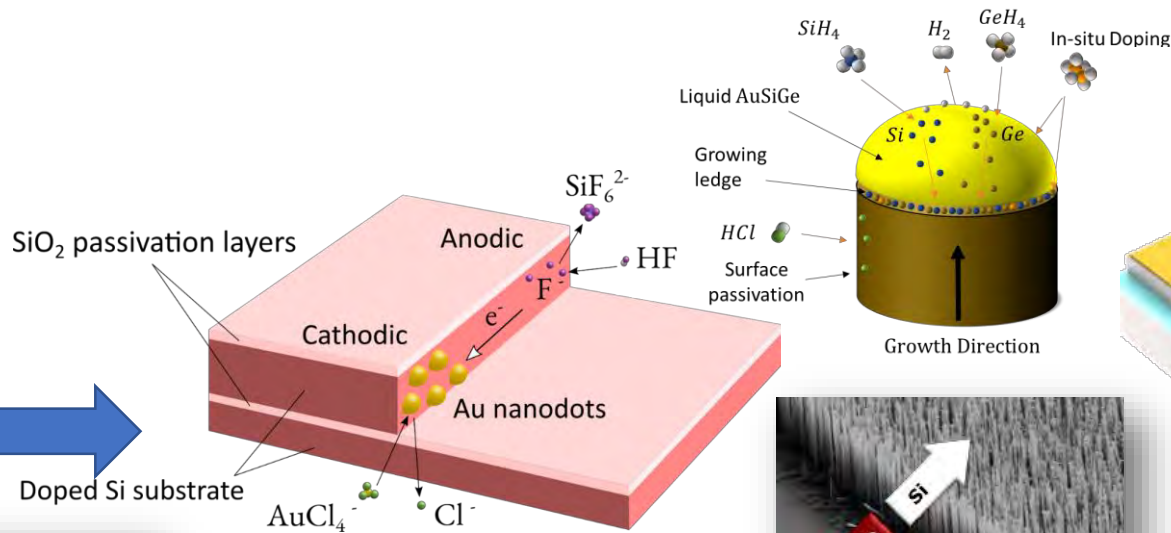
- Integration into microelectronics
- Self-supporting nanostructures

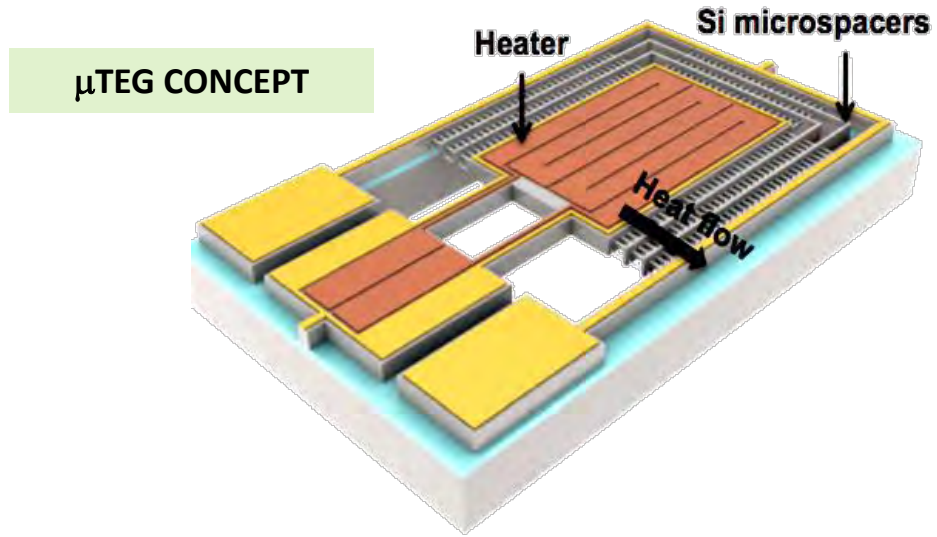
CVD REACTOR

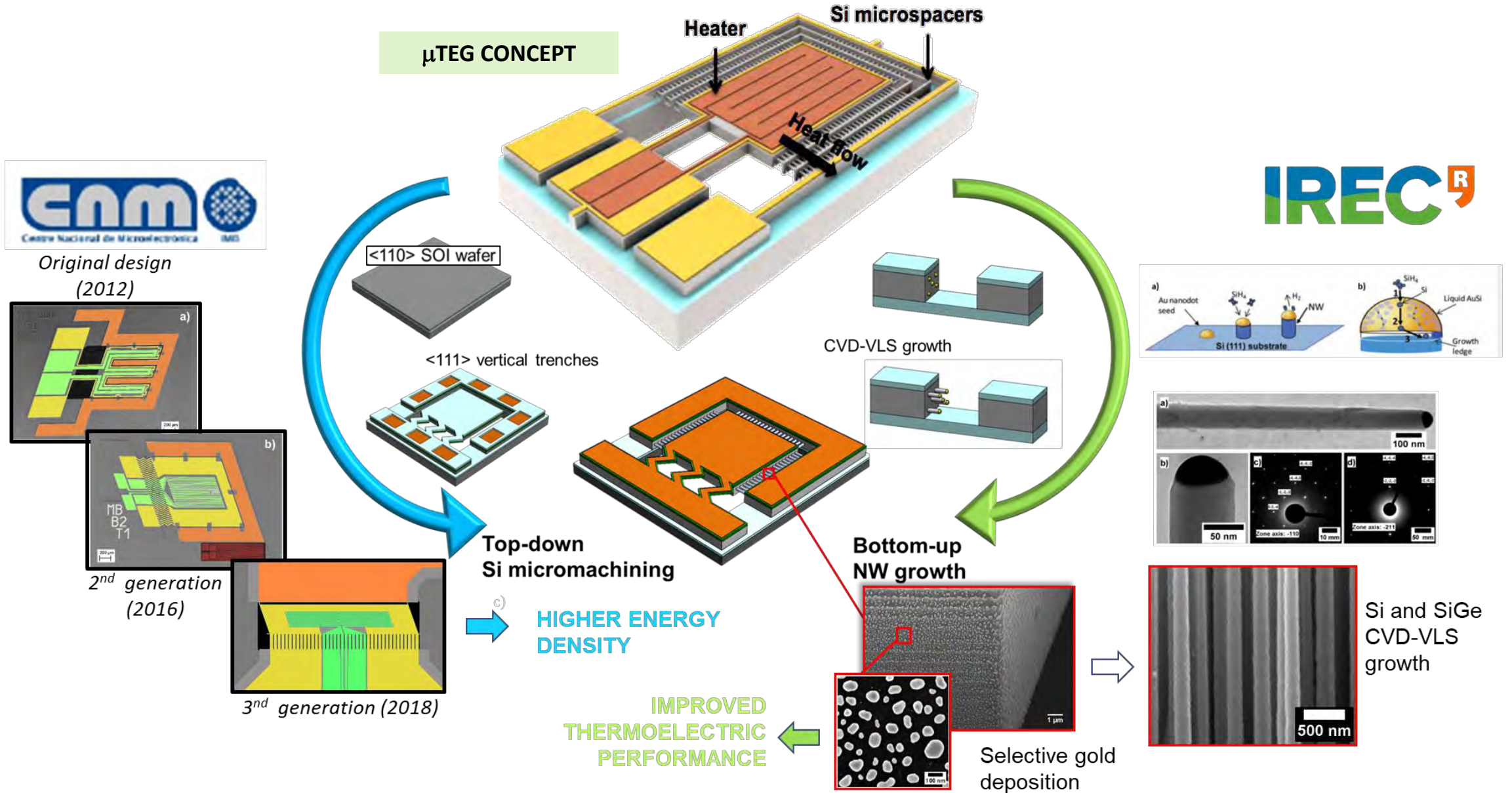


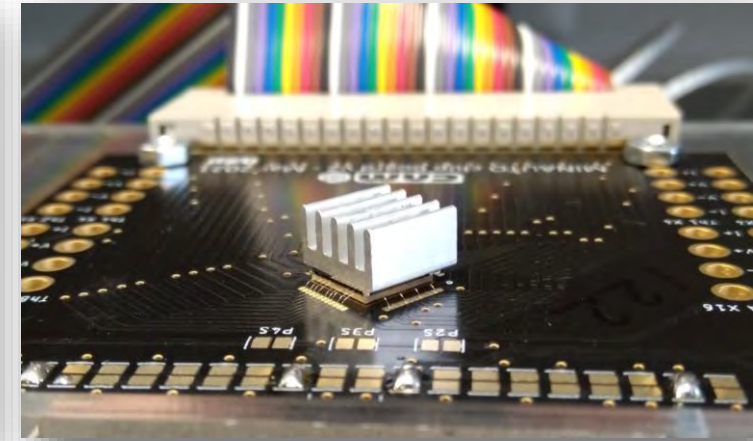
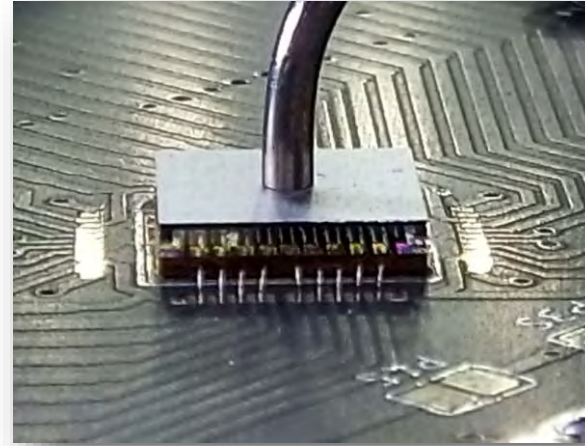
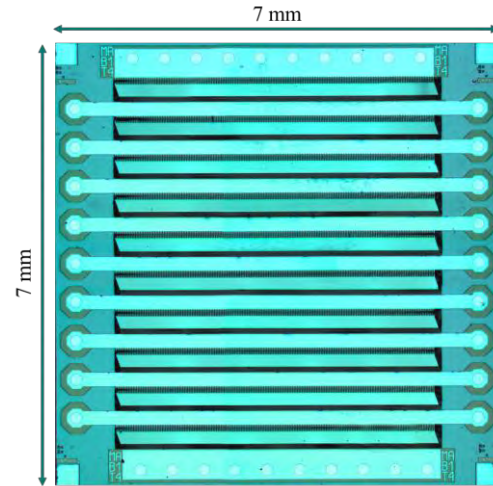
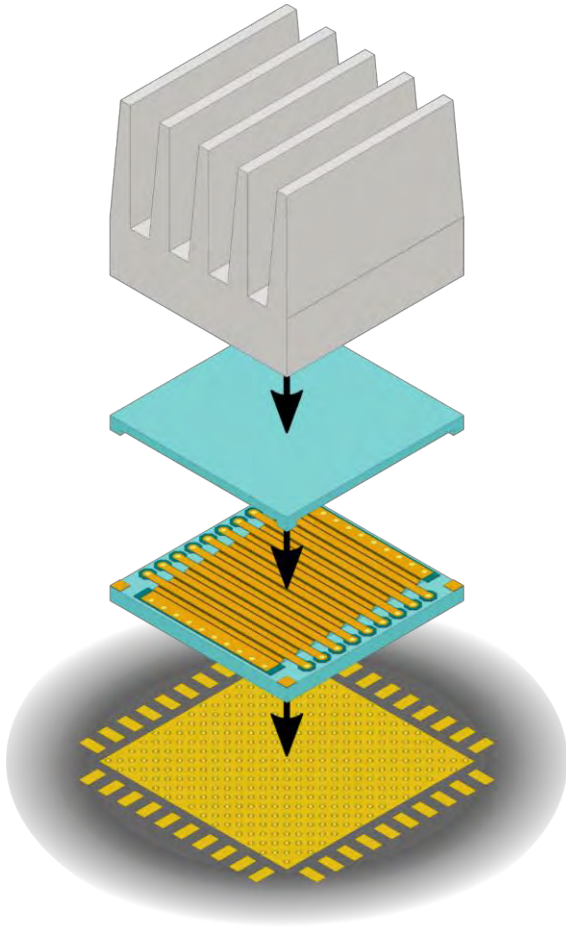
# Introduction Nanostructured thermoelectric materials at IREC

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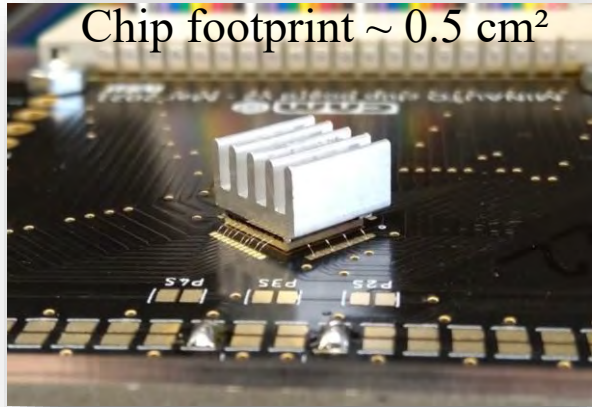








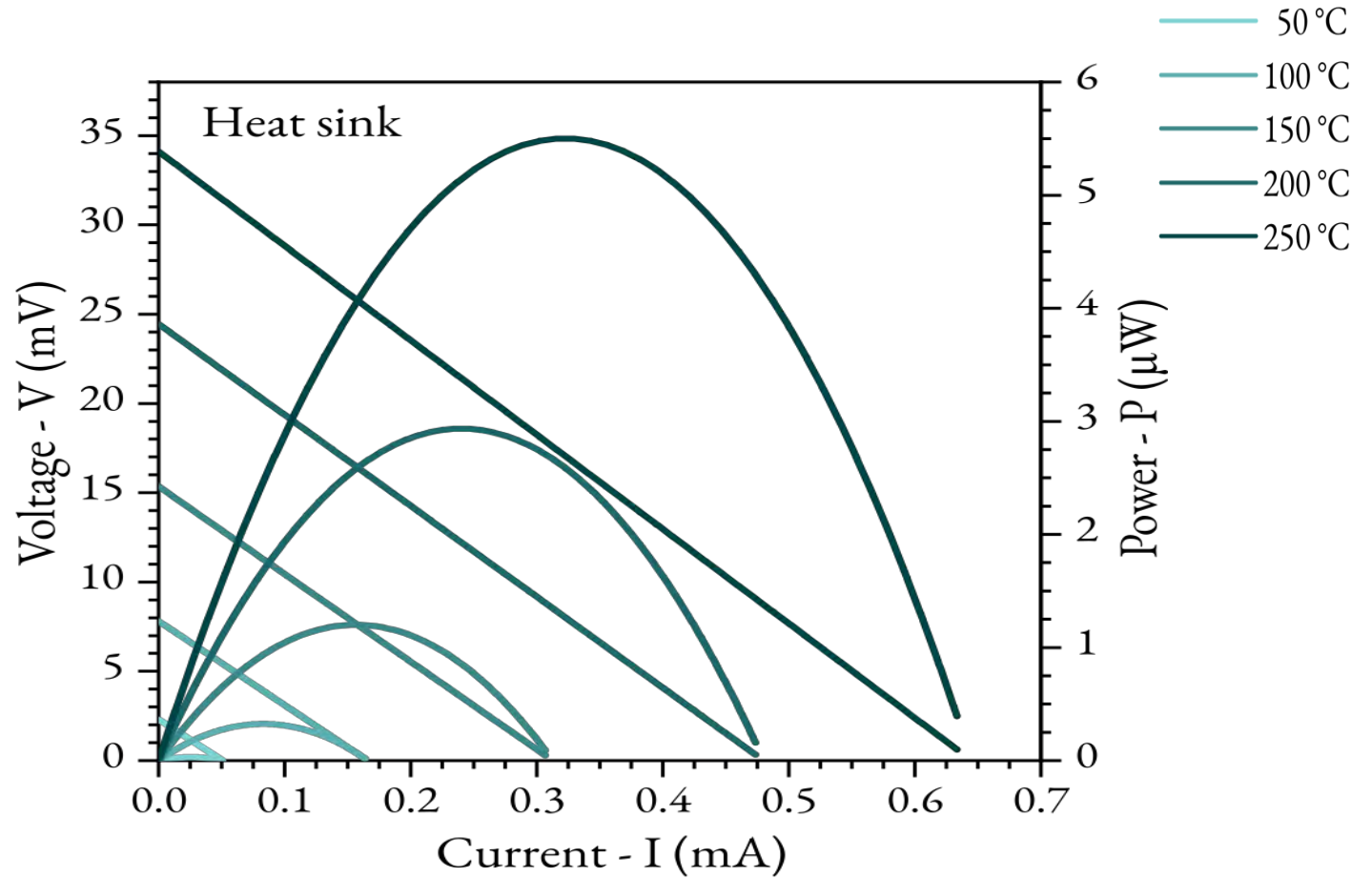
- Large number of microthermocouples
- Designed to be refrigerated by a heat sink



Chip footprint  $\sim 0.5 \text{ cm}^2$

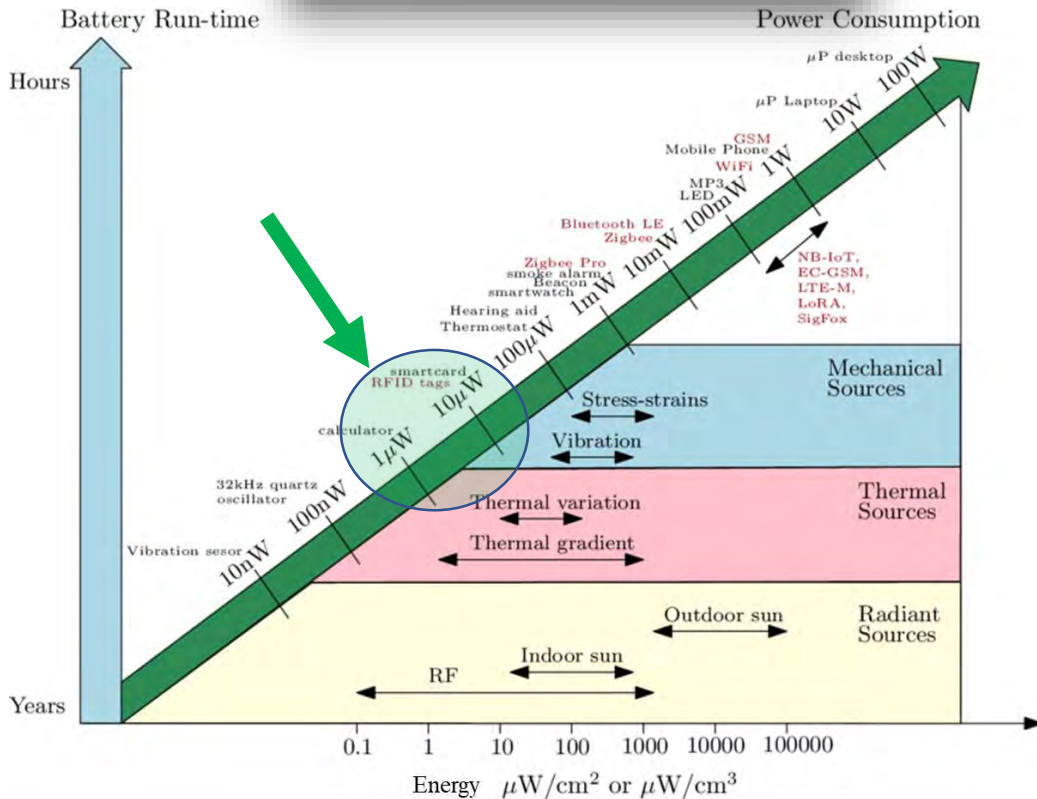
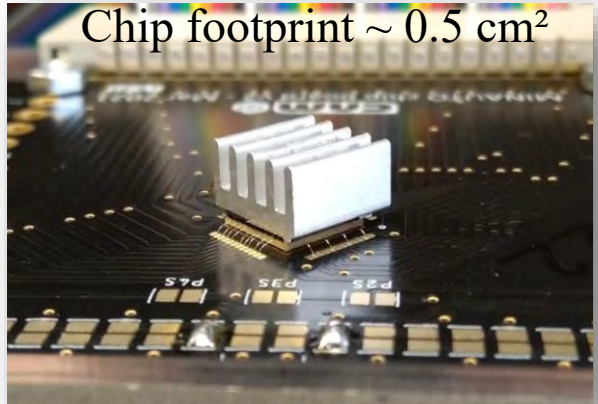


Heat sink:  
Free convection regime

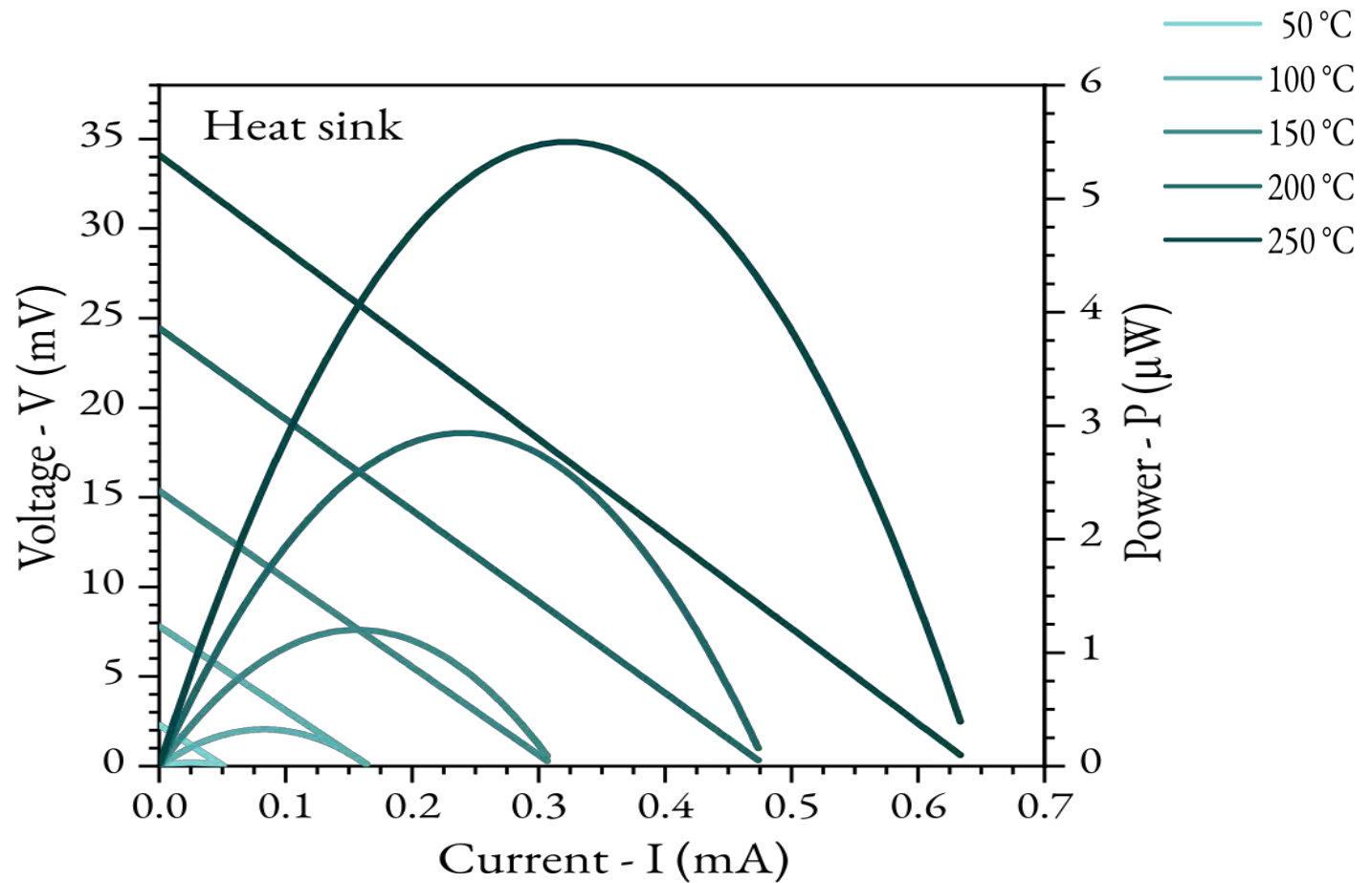


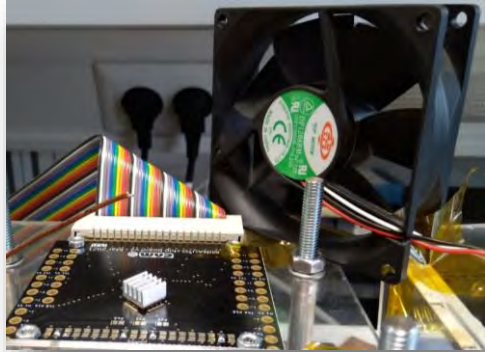


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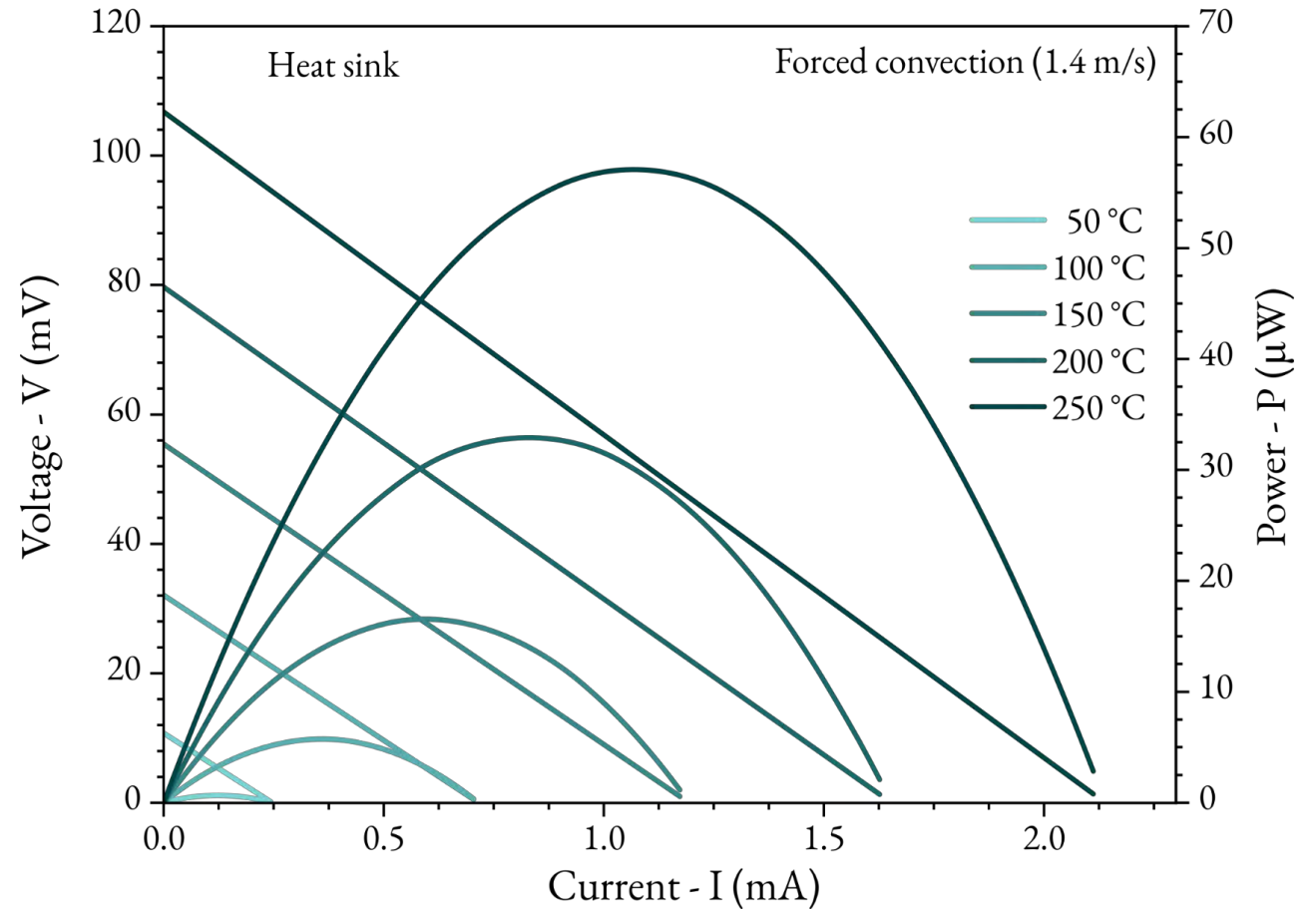
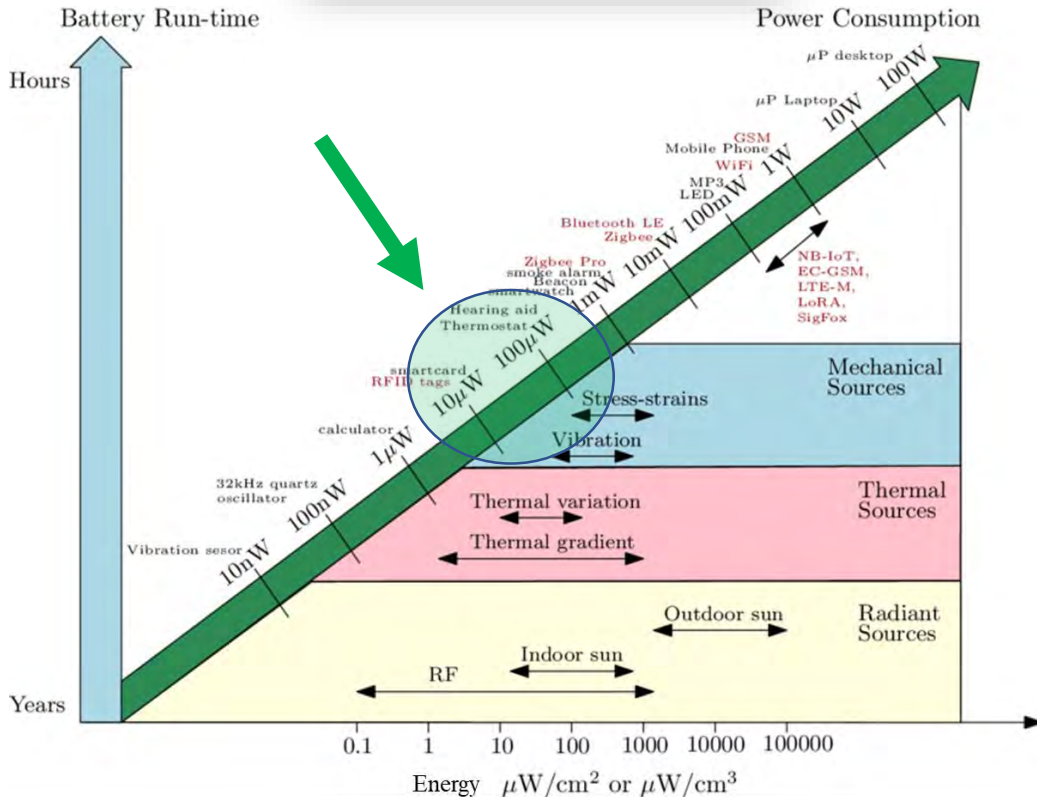


Heat sink:  
Free convection regime





Heat sink:  
Forced convection regime



Group/ Company	Thermoelectric material	T <sub>Hot</sub> (K)	V <sub>OC</sub> (mV)	ΔT (K)	P <sub>max</sub> /A (μW/cm <sup>2</sup> )
Uni Tokyo	CMOS Si NWs	301	0.1	0.65	9.4
Uni Tokyo	Holey poly-Si thin film	335	0.35	40	0.012
Texas instruments	CMOS SiGe nanoblades	527	2350	23.2	1.89
Texas instruments	CMOS Si nanoblades	634	4700	33.9	27.5
UAB	PL Si thin film	300	39	5.5	4.1
Waseda	EBL Si NW	298	0.02	0.5	0.0279
CNM/IREC	VLS SiGe NW arrays	395	10	35	45.2
Bare chip	VLS Si NW arrays	525	4.5	2.5	0.5
This work	Heat Sink (Forced CV)	375	32	16	26
	Heat Sink (Forced CV)	525	110	55	260

In *Red*, references that used actively forced gradient (heater)

Zhan *et al.*, *Sci. Technol. Adv. Mater.*, **19**, 445 (2018).

Hu *et al.*, *Nat. Electr.*, **2** 300-3006 (2019).

Dhawan *et al.*, *Nat. Comm.*, **11** (2020).

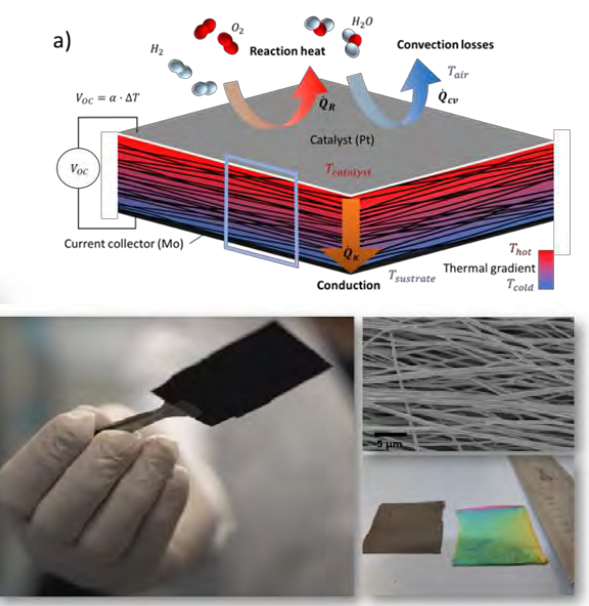
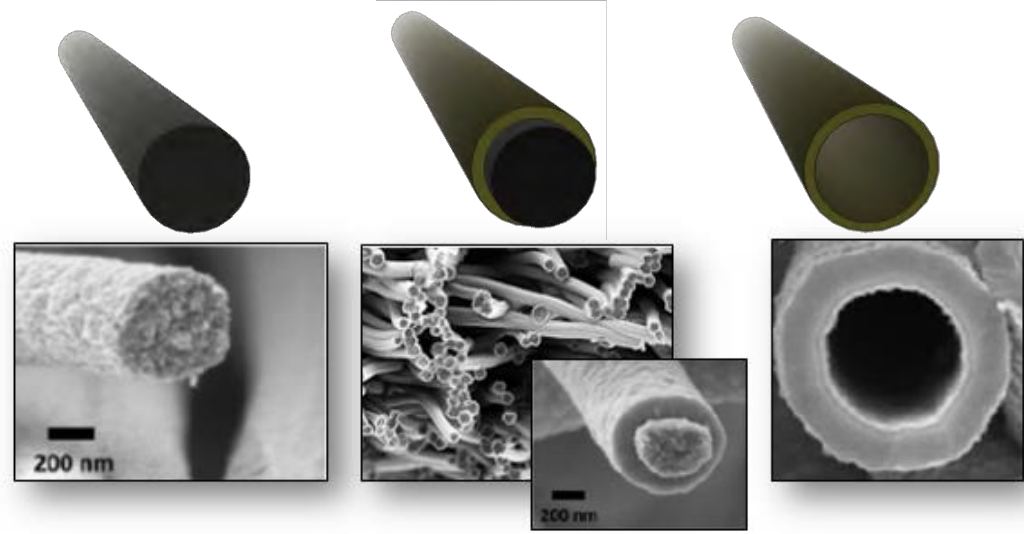
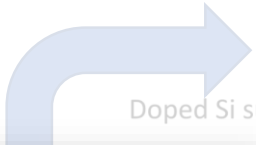
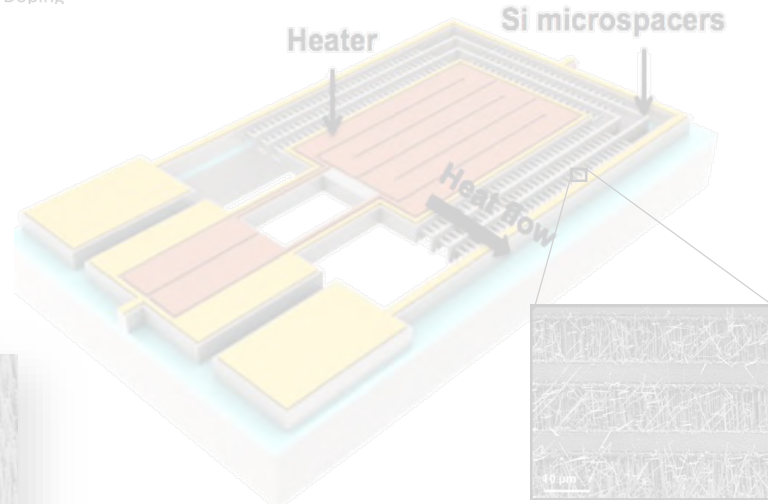
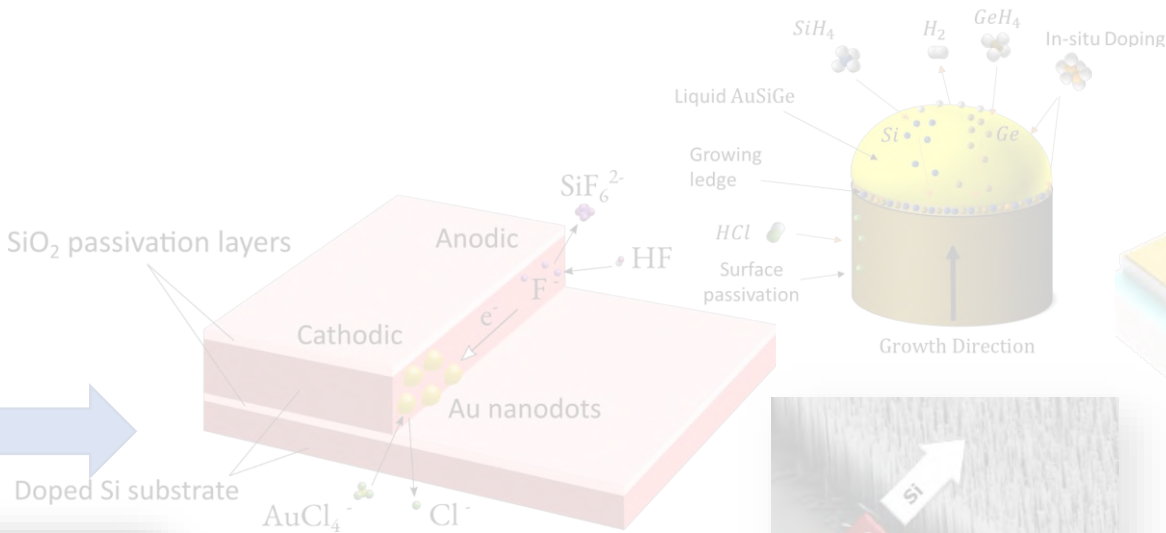
Koike *et al.*, *Jap. J. Appl. Phys.*, **59**, 074003 (2020).

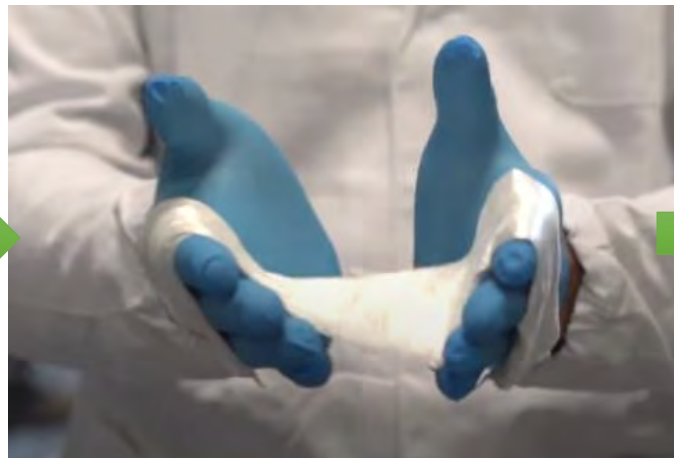
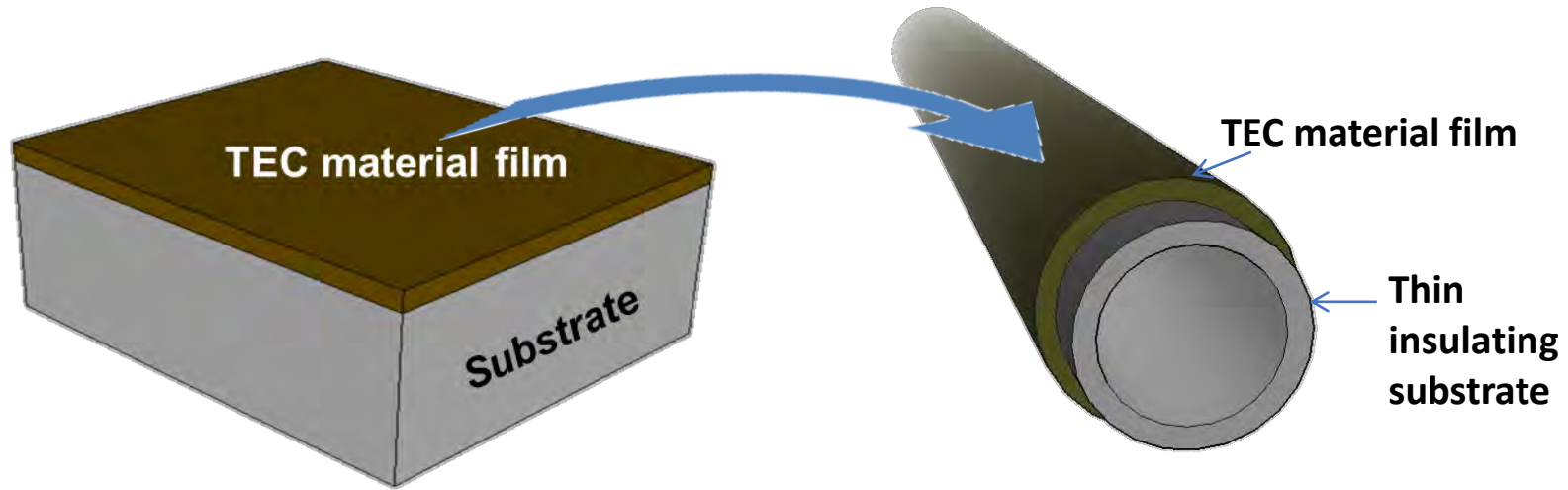
Donmez *et al.*, *Nano Energy*, **57**, 492–499 (2019)

# Thermoelectric nanofibres

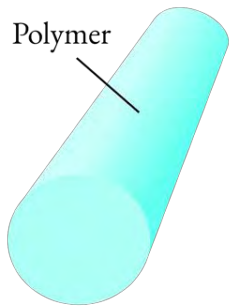
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**CVD REACTOR**

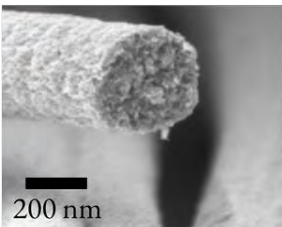
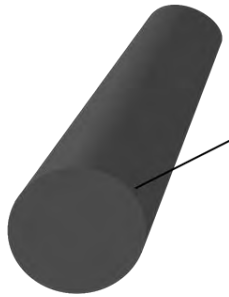




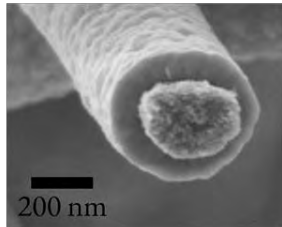
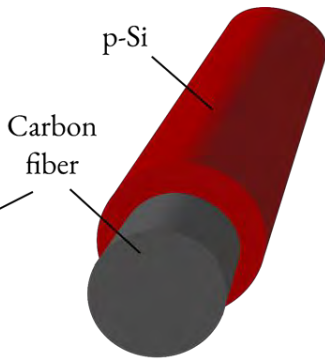
Electrospinning



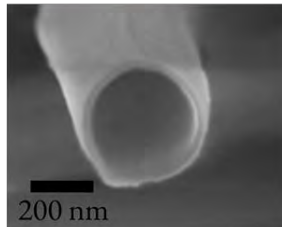
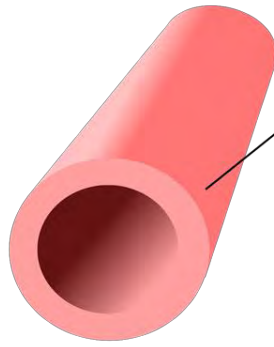
Pyrolysis



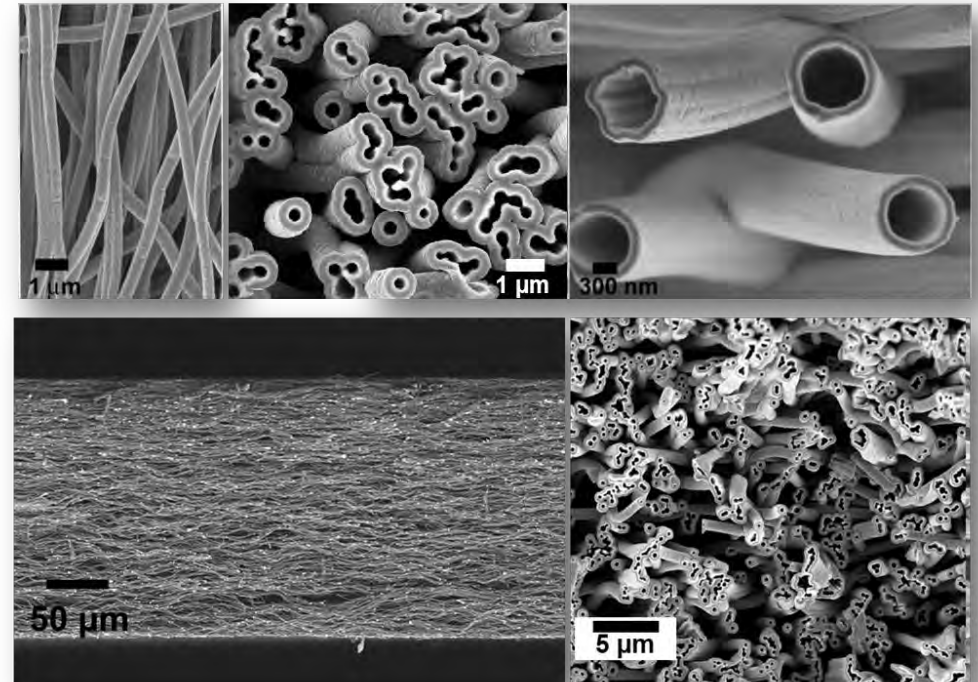
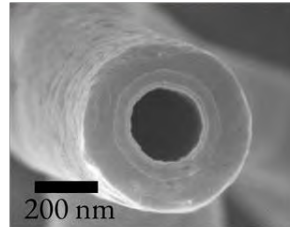
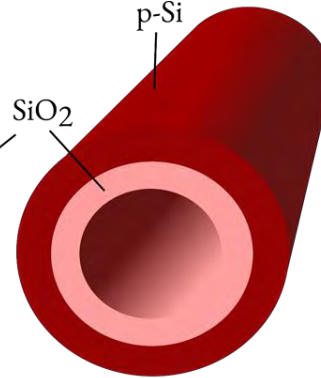
CVD deposition



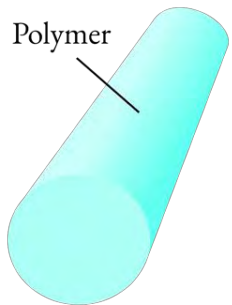
Calcination



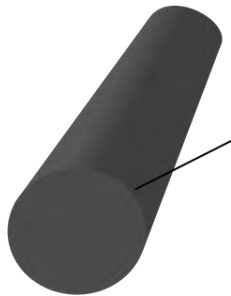
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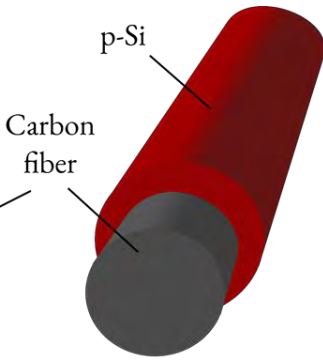
Electrospinning



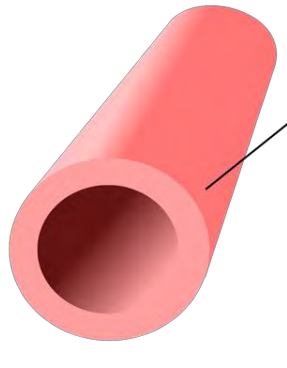
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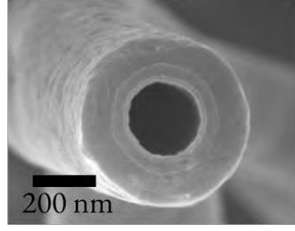
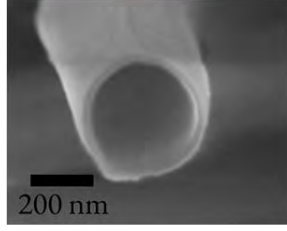
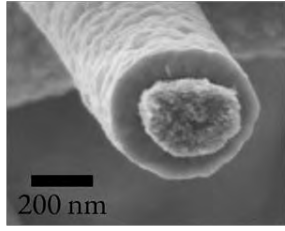
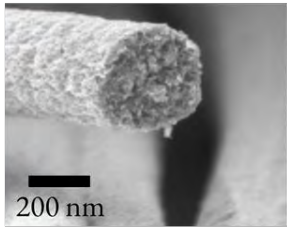
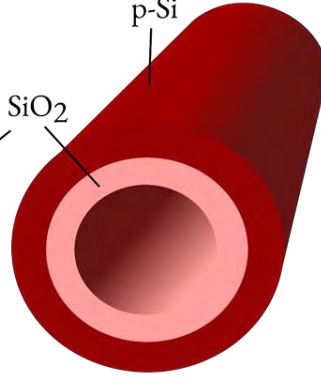
CVD deposition



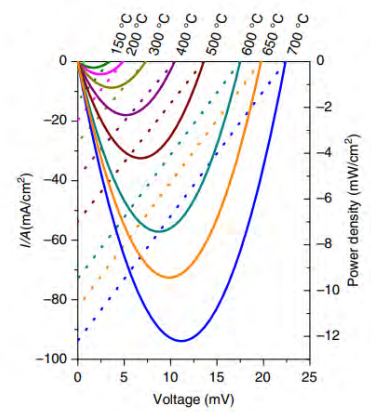
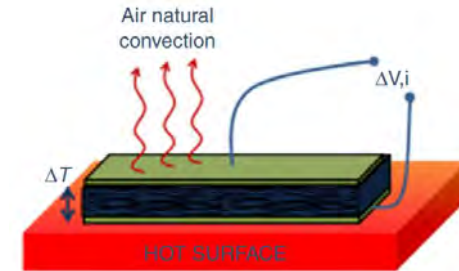
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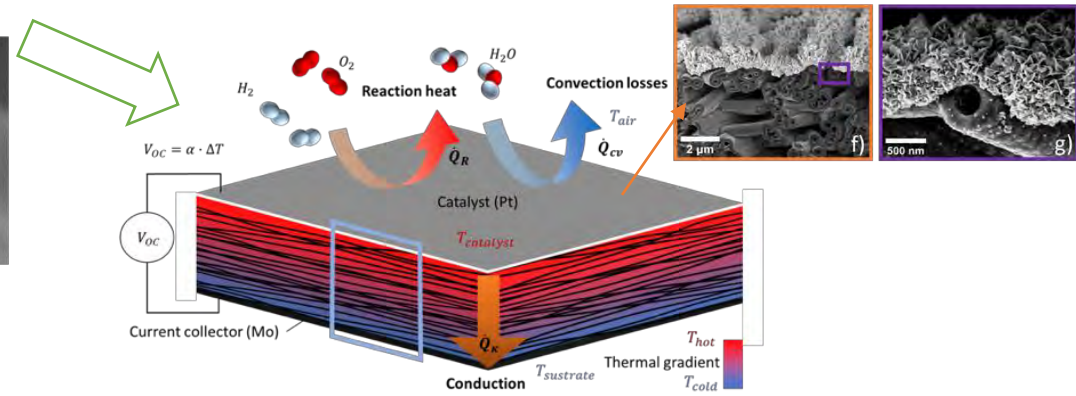
CVD deposition



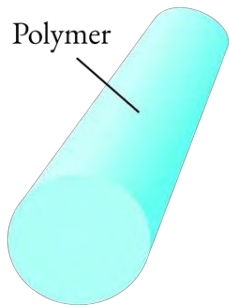
## Thermoelectric generation



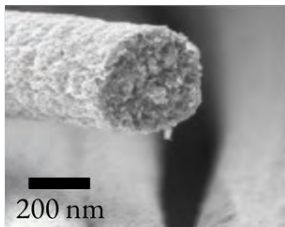
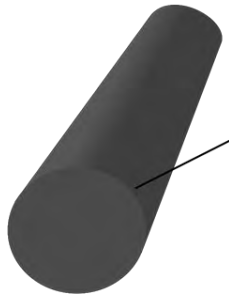
## H<sub>2</sub> sensor



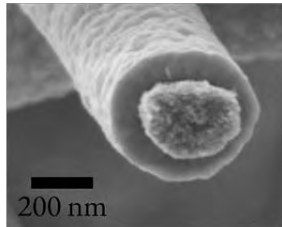
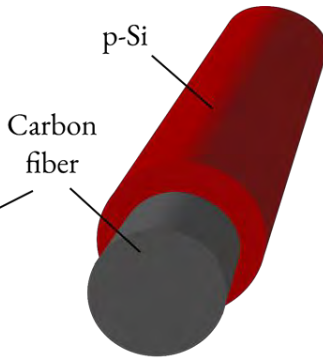
Electrospinning



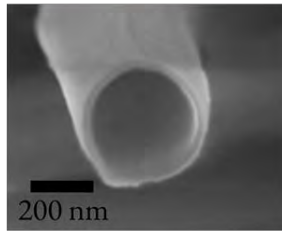
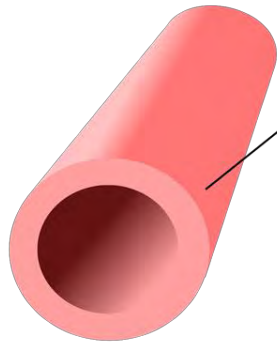
Pyrolysis



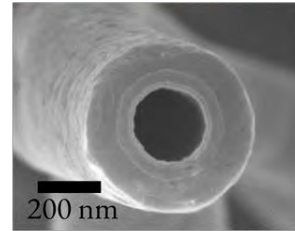
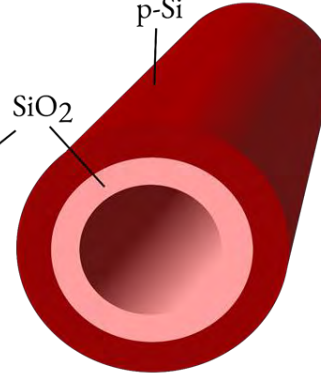
CVD deposition



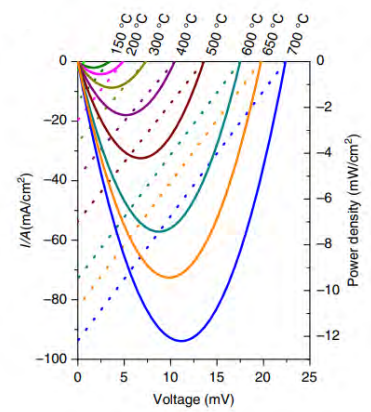
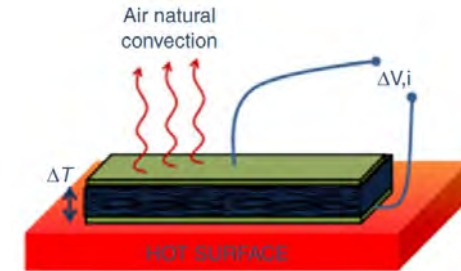
Calcination



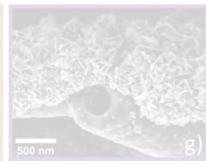
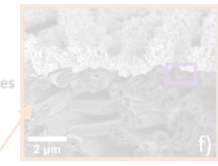
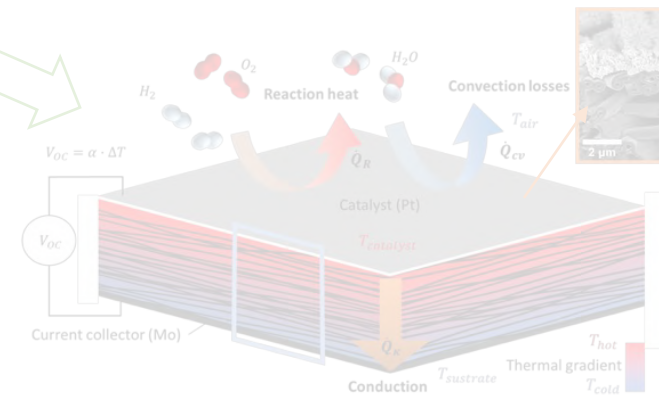
CVD deposition



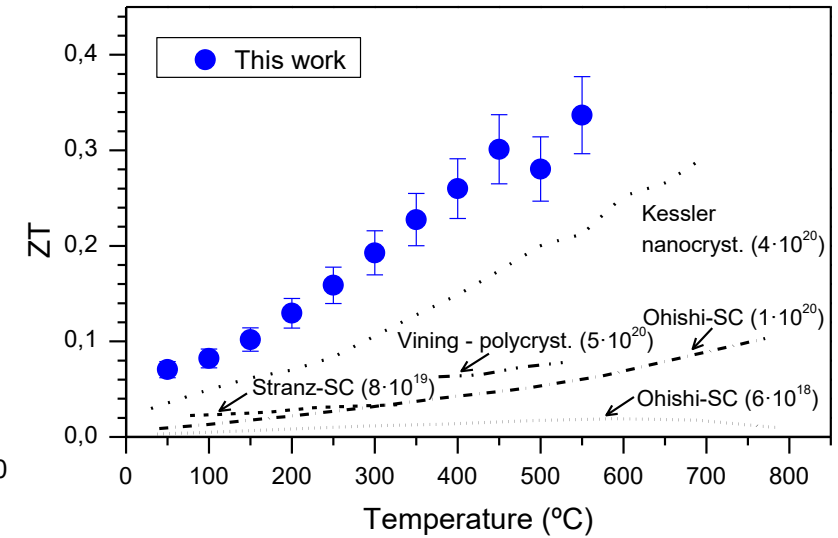
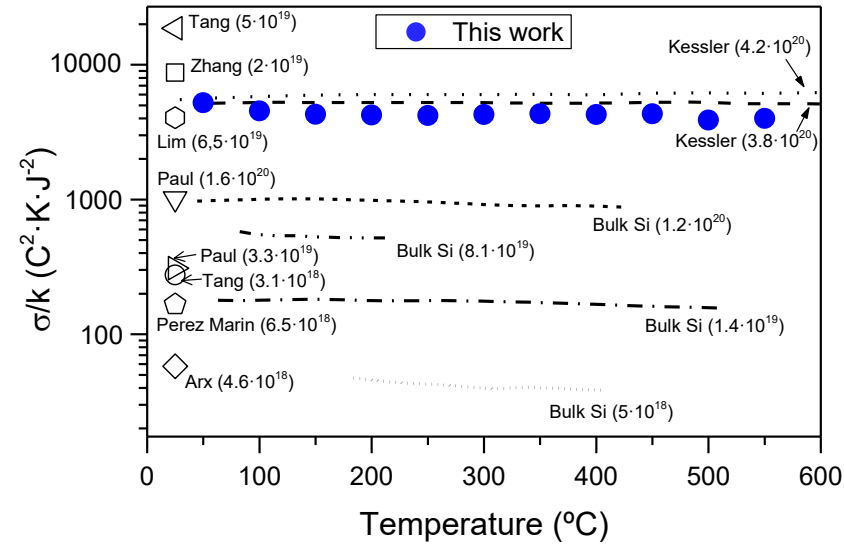
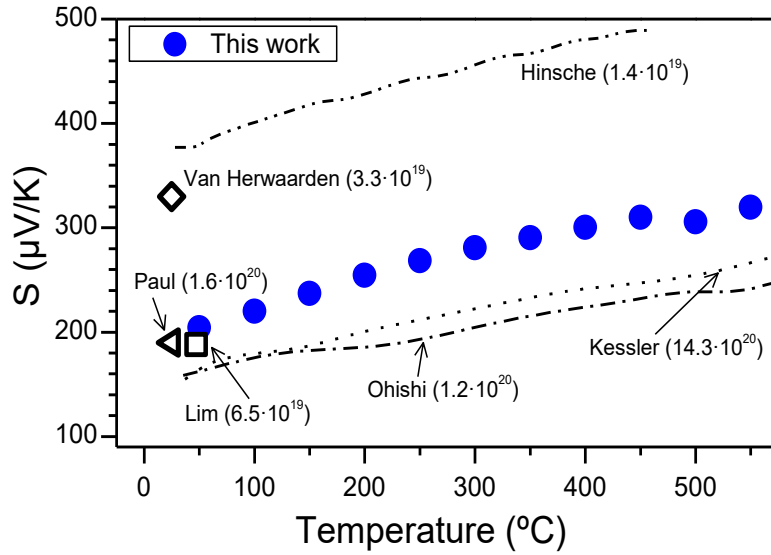
## Thermoelectric generation

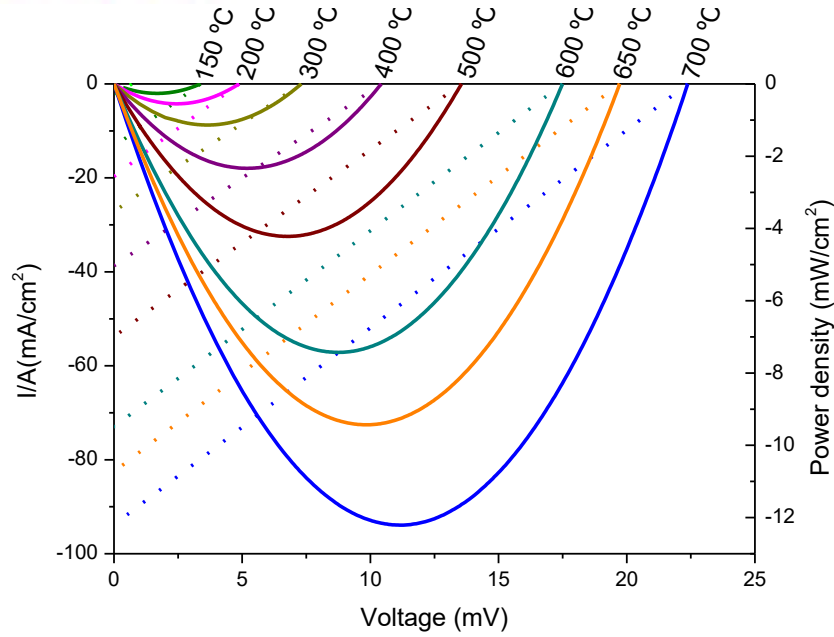
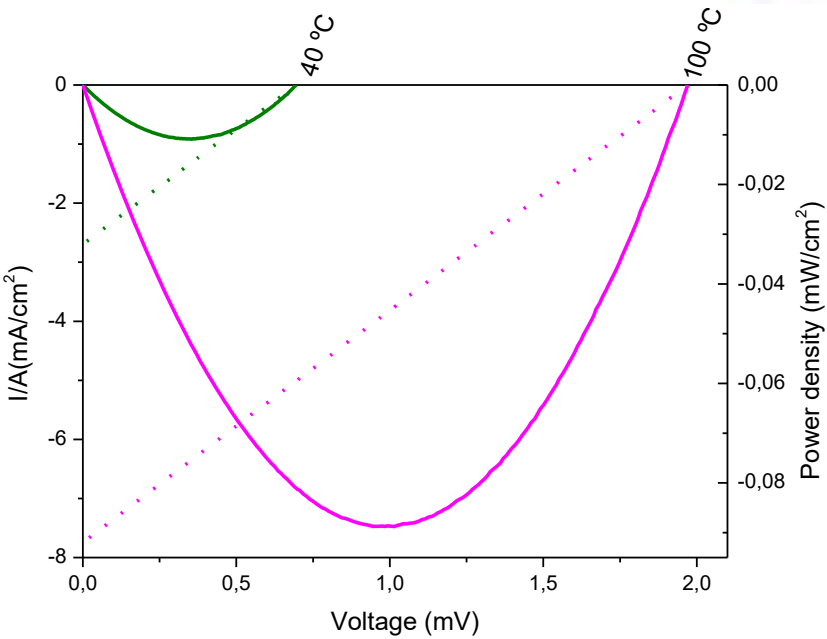
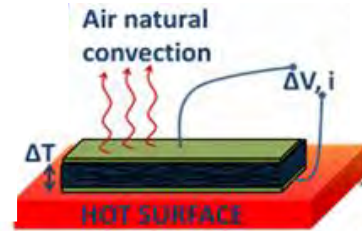


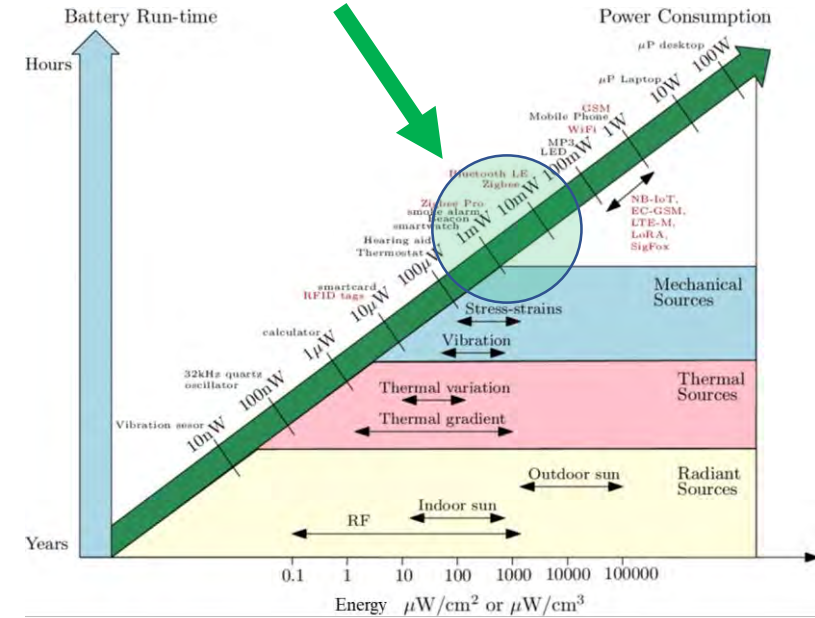
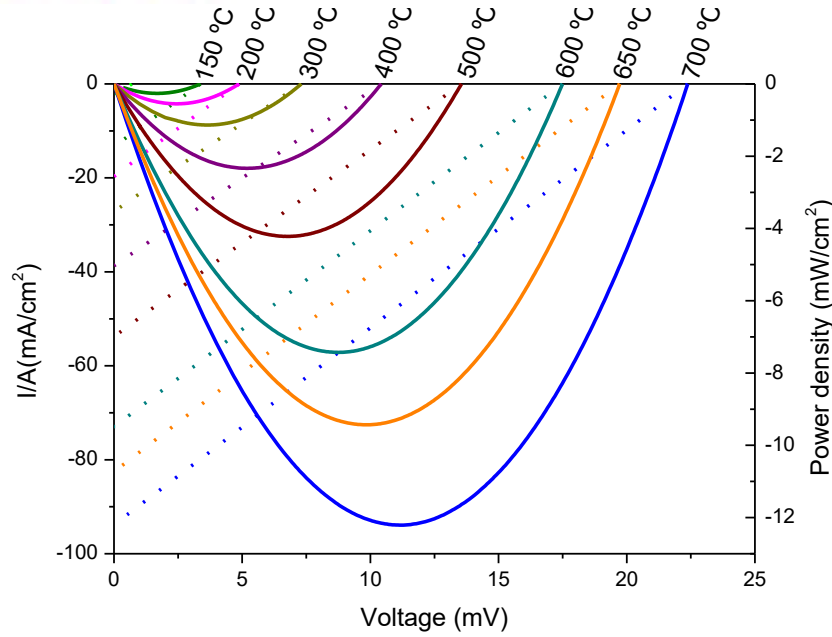
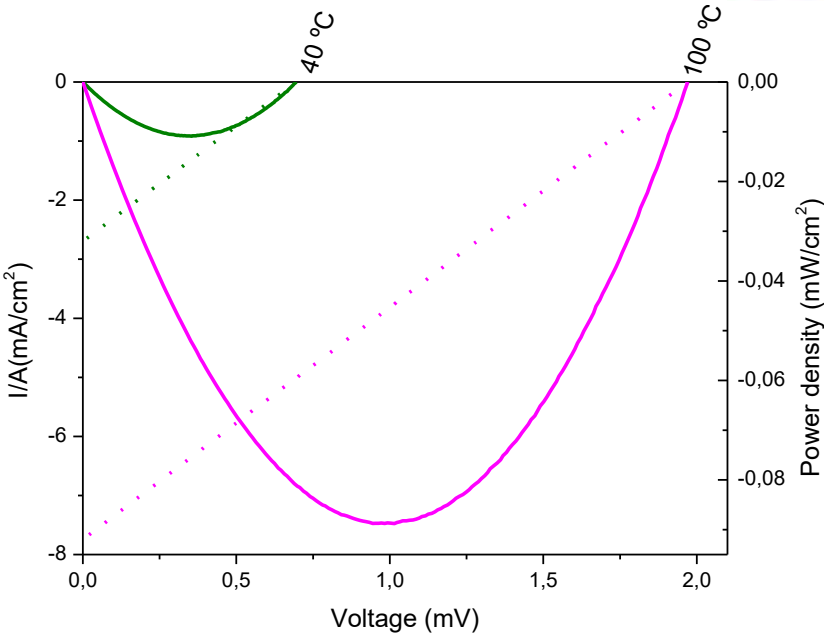
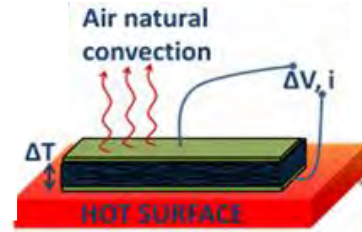
## H<sub>2</sub> sensor

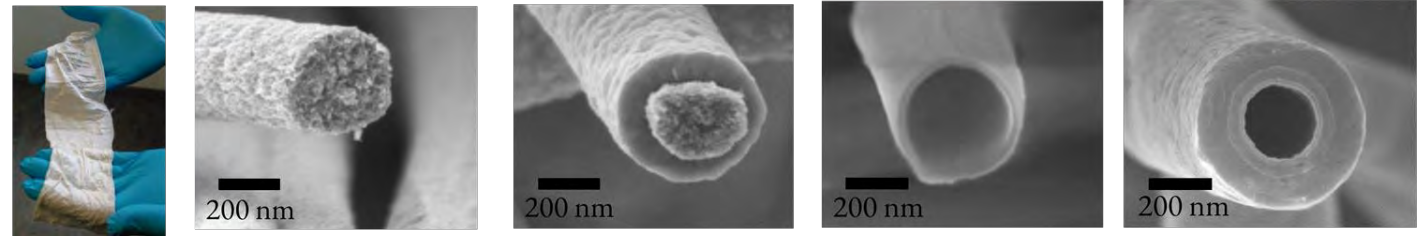
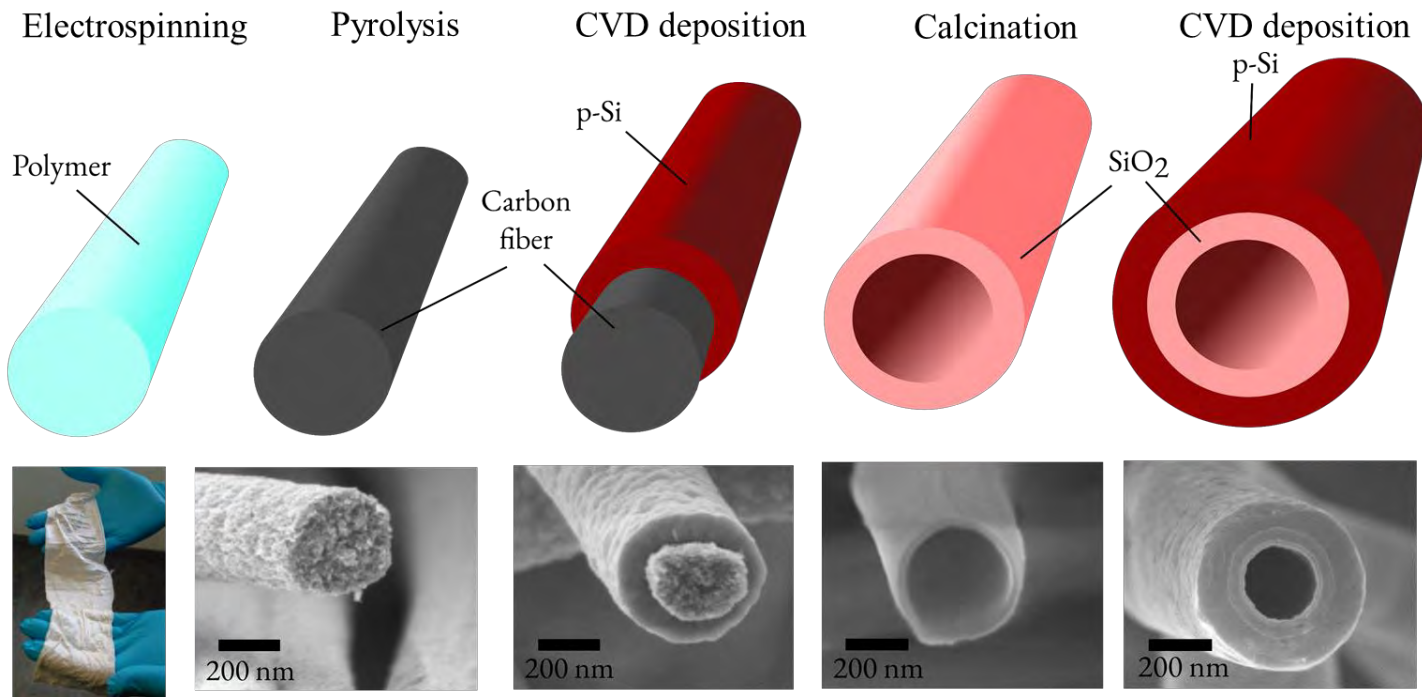
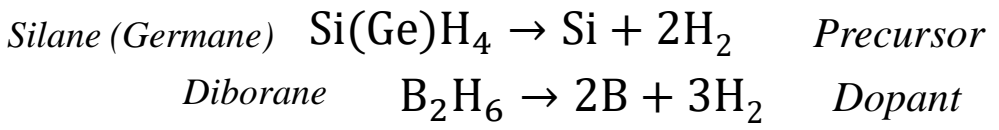




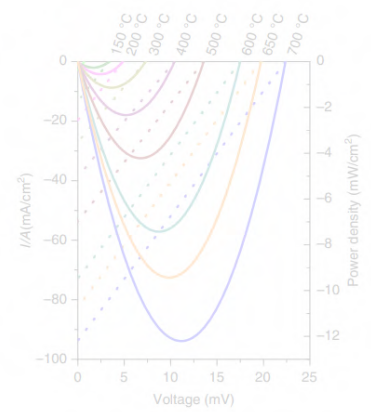
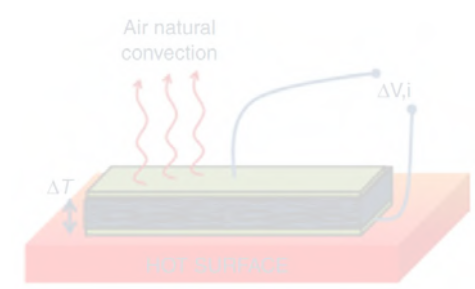




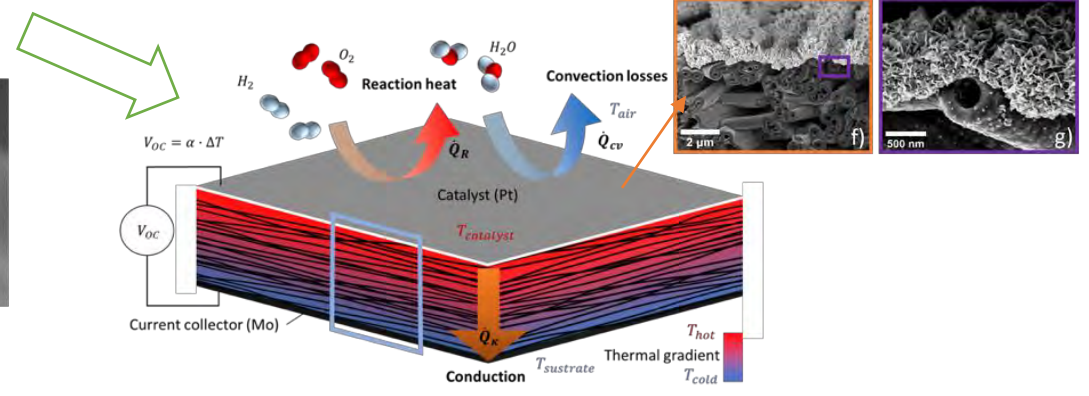


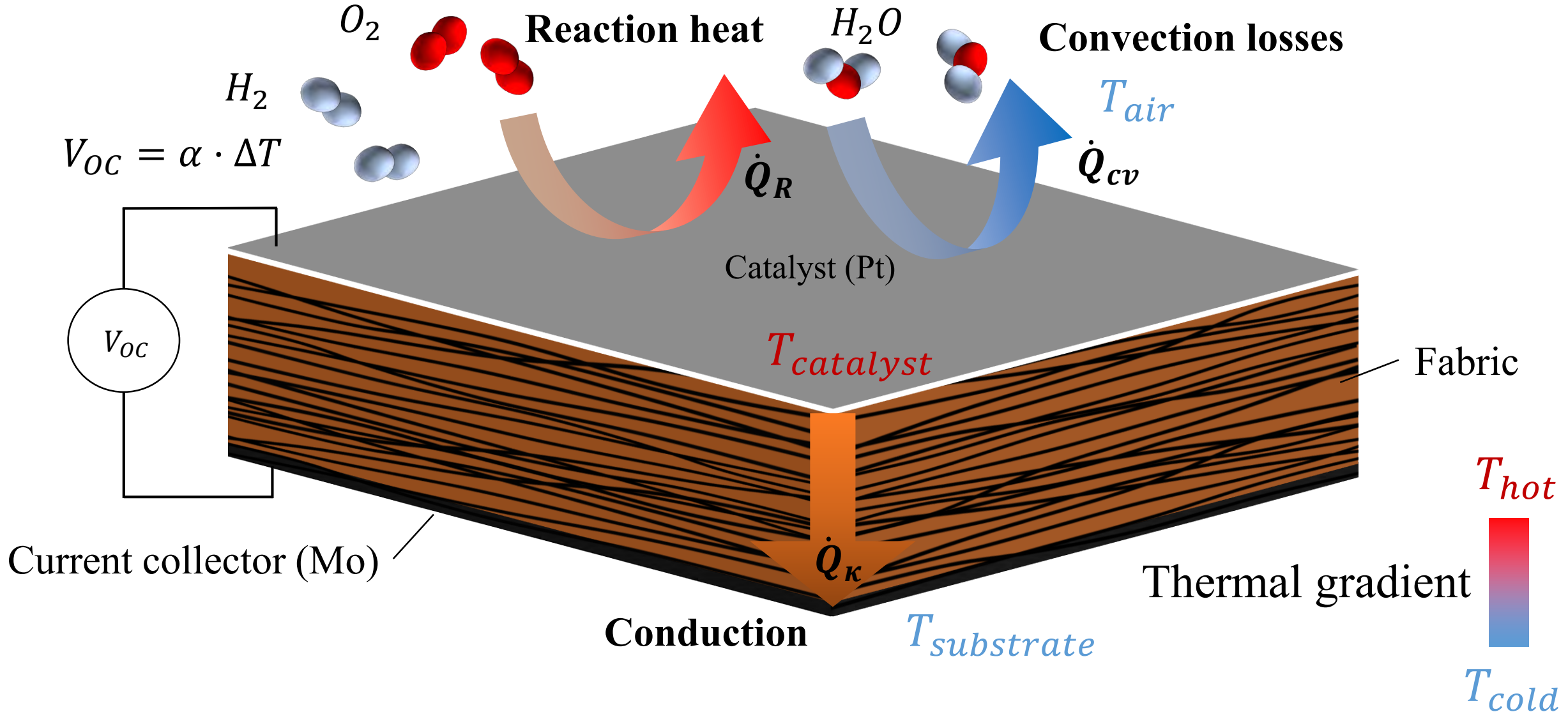


### Thermoelectric generation

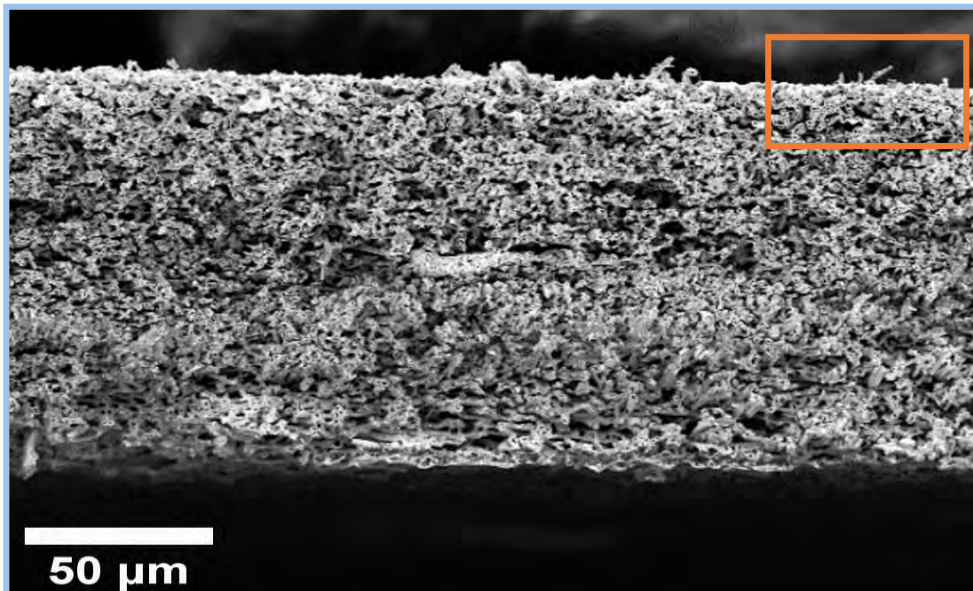
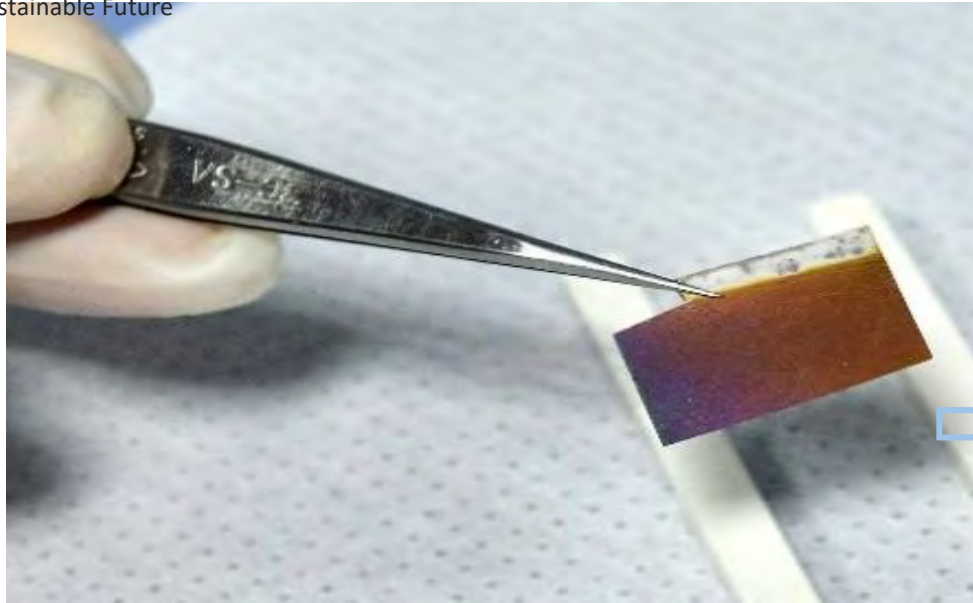


### H<sub>2</sub> sensor

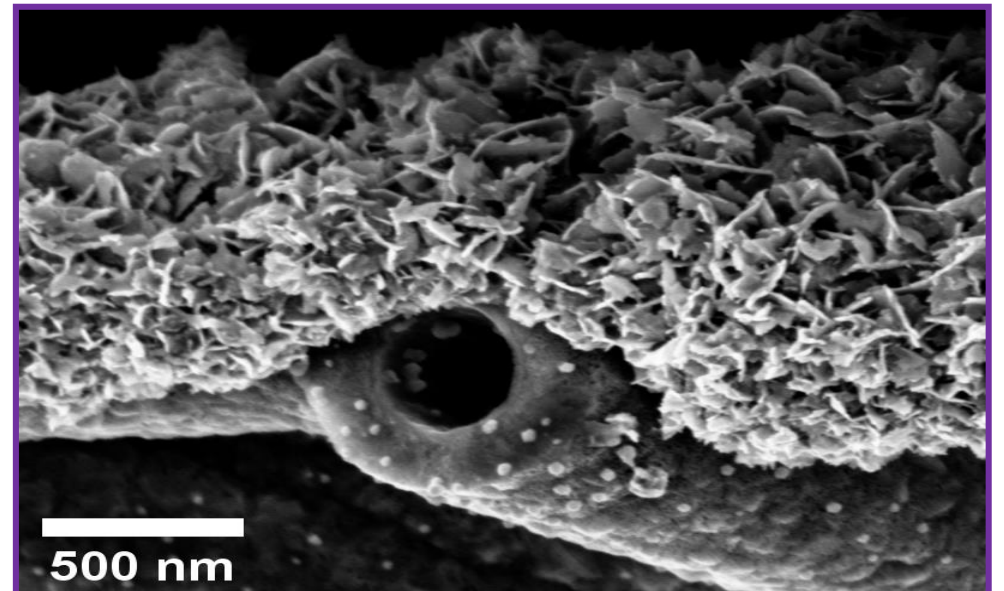
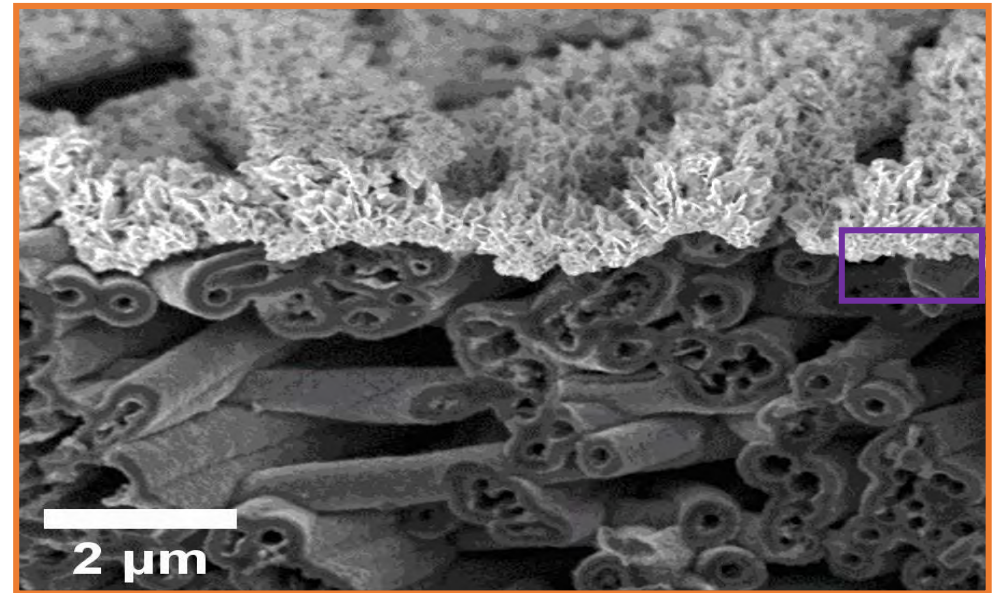


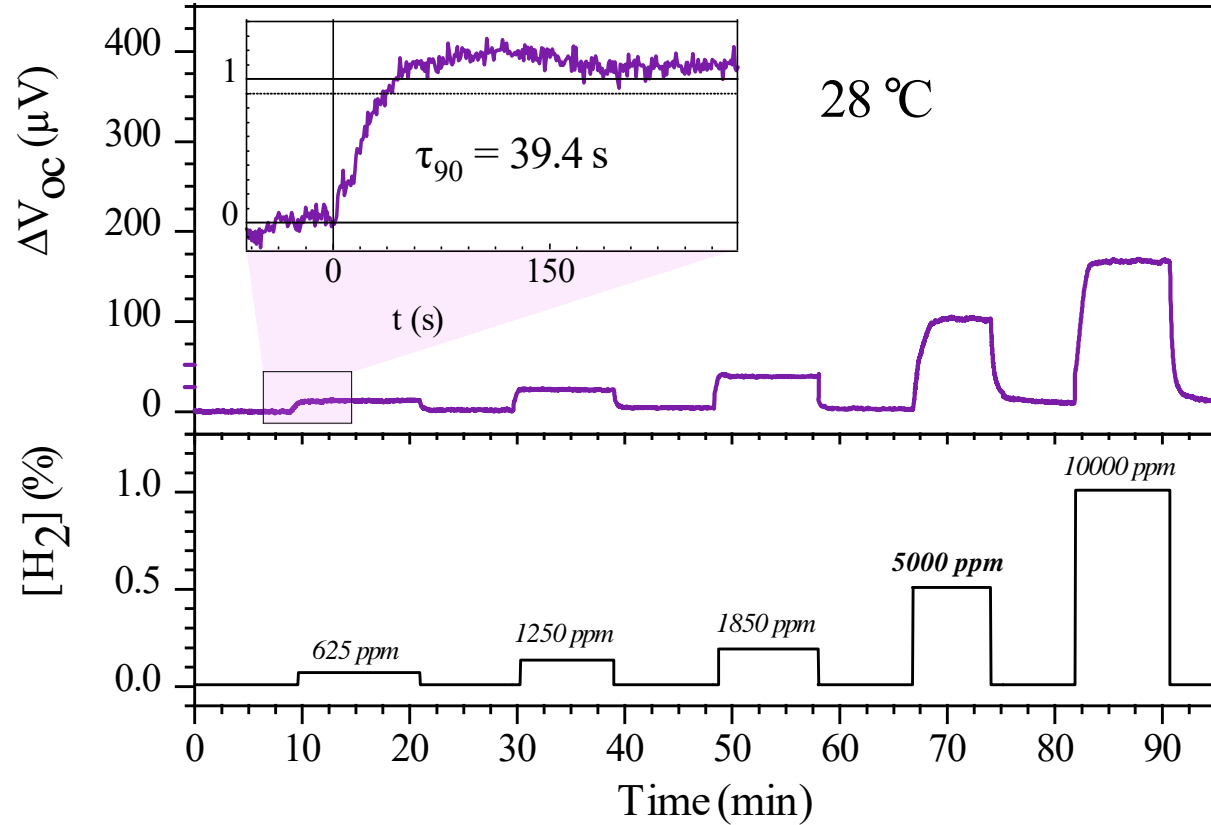


## Thermoelectric nanofibres

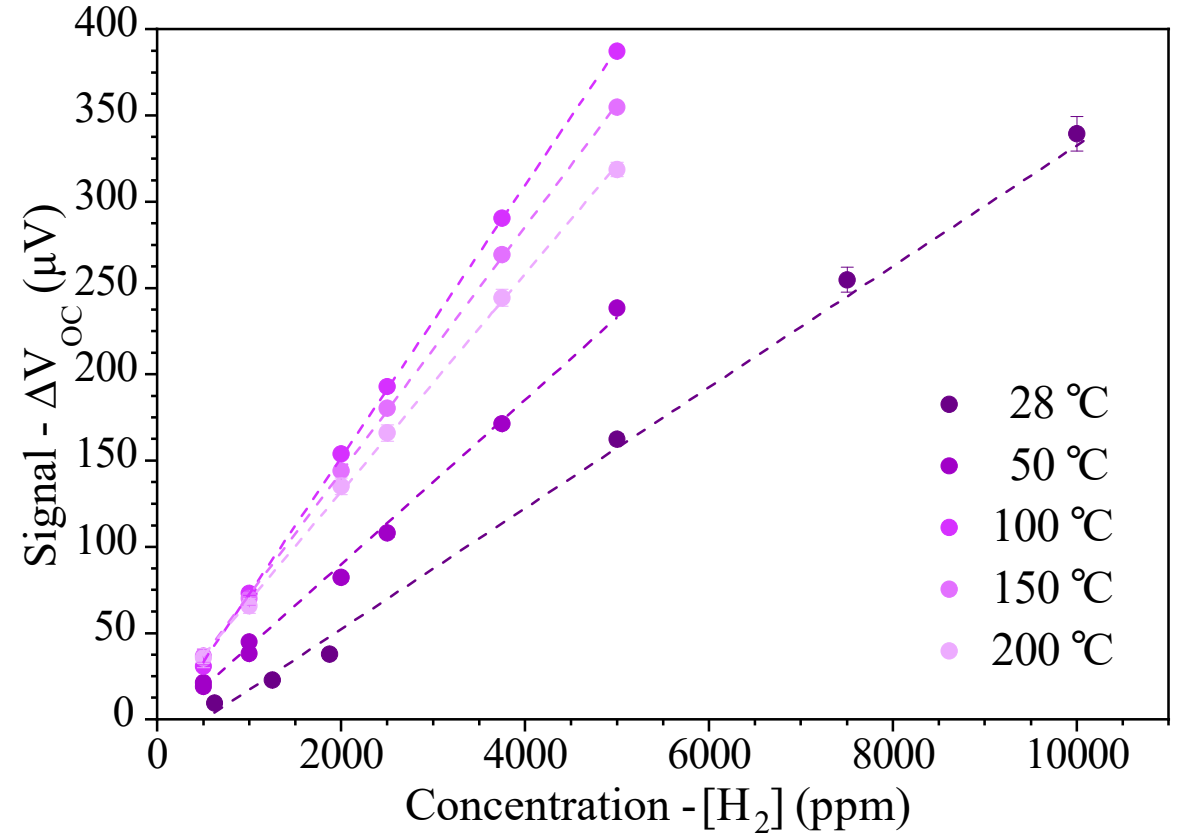


## Thermoelectric gas sensor

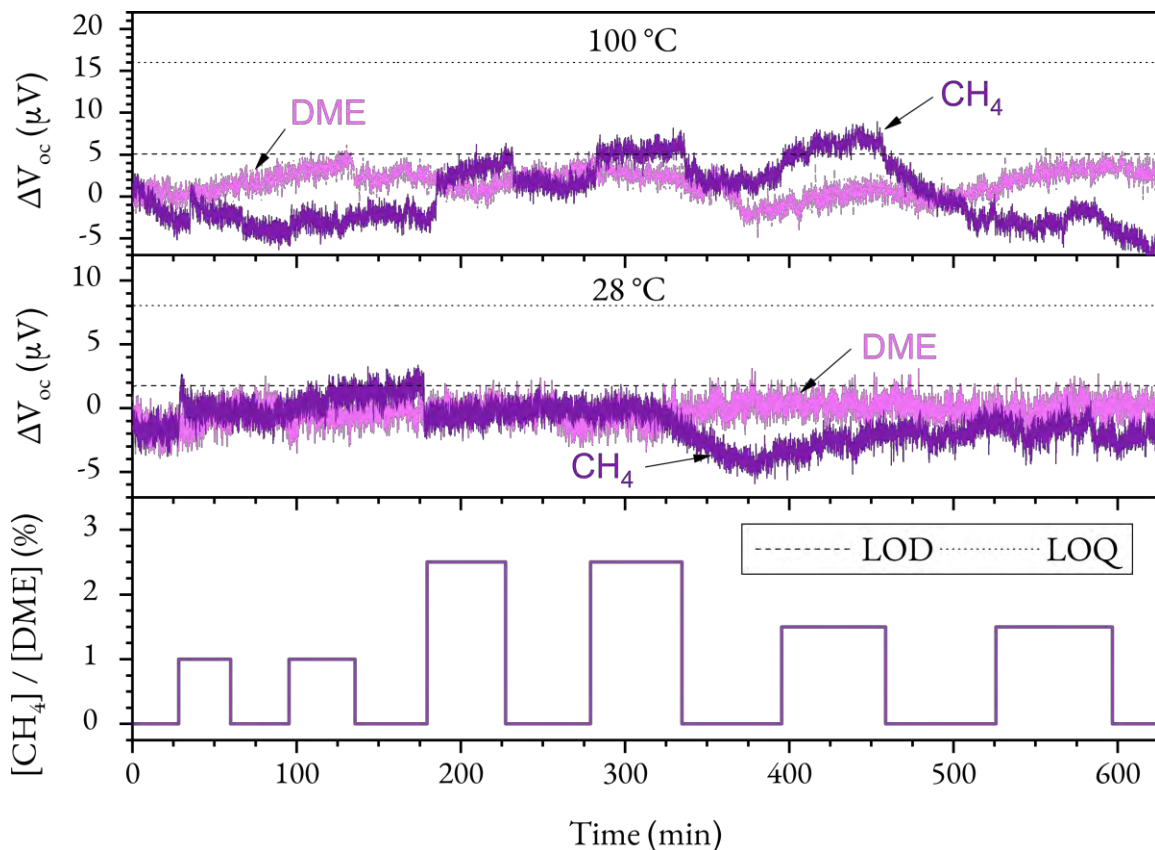




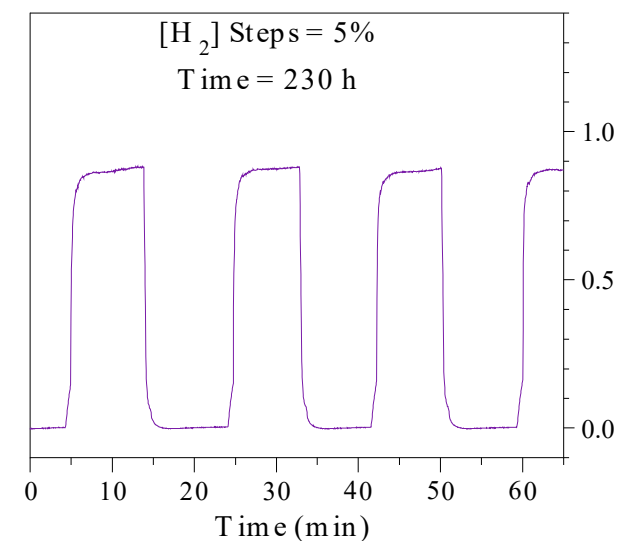
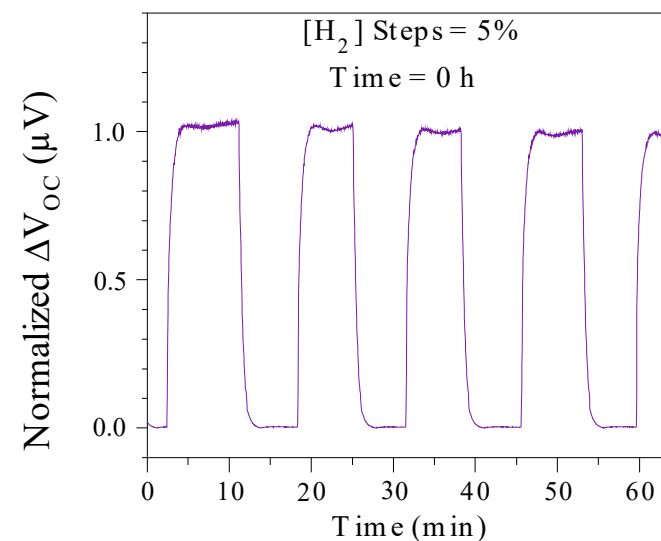
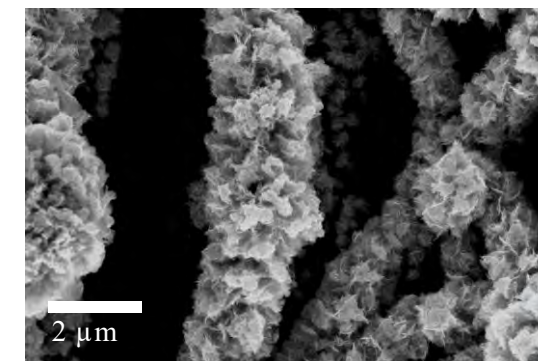
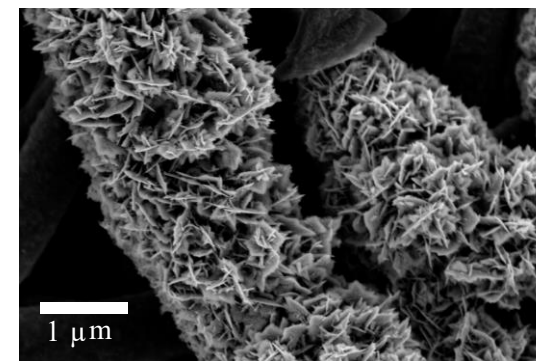
- Passive sensor (no consumption)



- Lower Detection Limit of 250 ppm

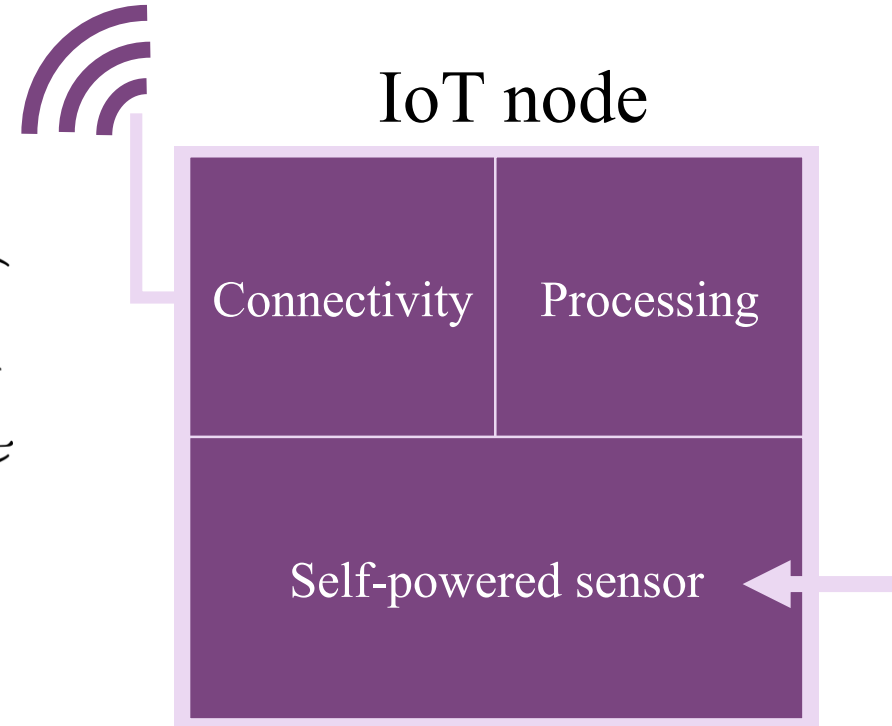
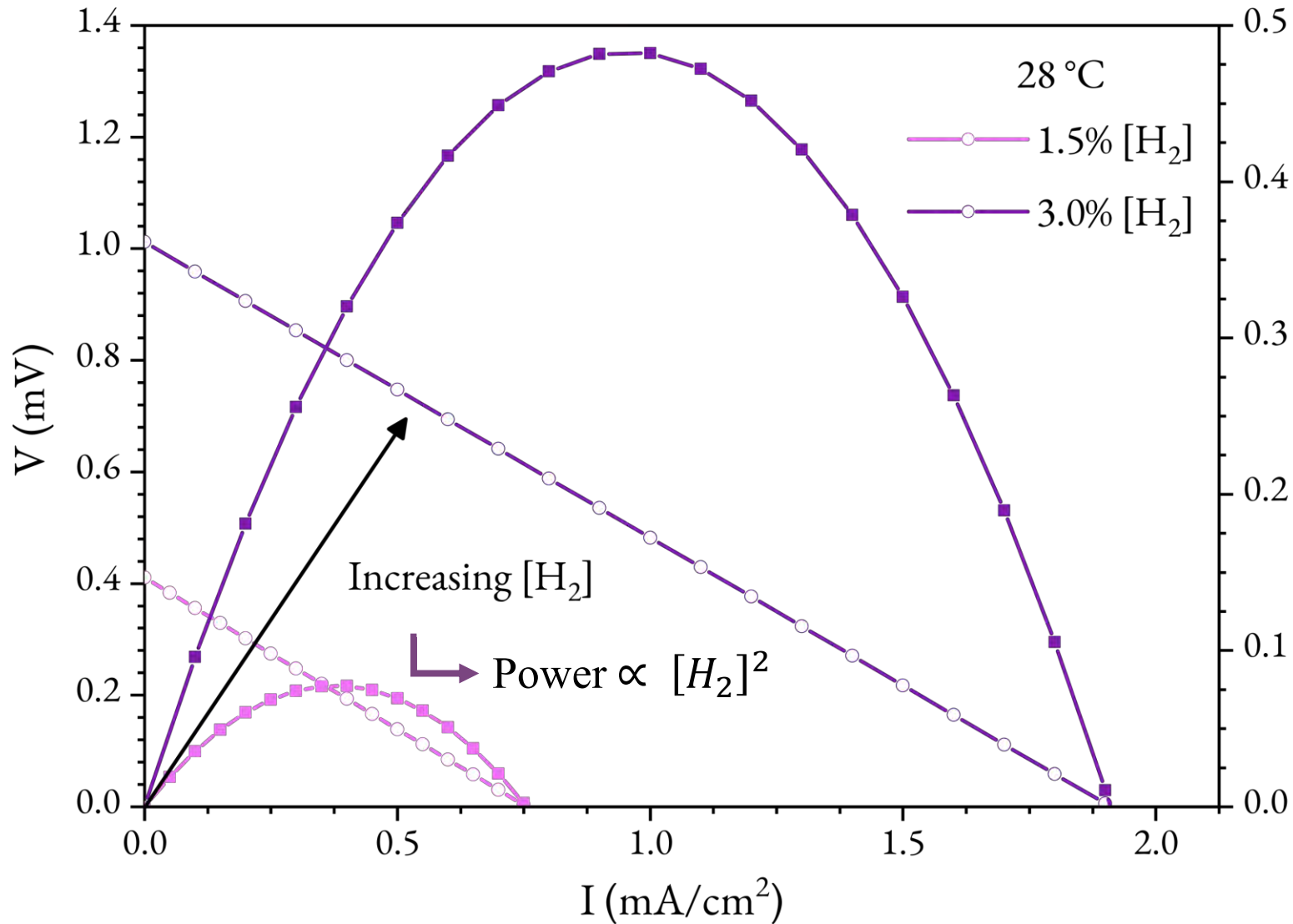


- Selectivity towards CH<sub>4</sub> and DME
- 4.7% variation upon high concentration H<sub>2</sub> steps
- Degradation rate of 200 pV/h ppm<sub>H<sub>2</sub></sub>



Continuous operation at 5000 ppm of [H<sub>2</sub>]





- Two different approaches have been demonstrated for the use of nanostructured silicon as thermoelectric material
- Thermoelectric devices have been developed with power outputs in the range of 1 to 100  $\mu\text{W}$  and from 10 to 100 mV, which is in the range of the requirements of IoT nodes
- A self-powered hydrogen sensor has been developed with good sensitivity (LOD of 250 ppm), good selectivity and very high stability



Shaping Energy for a Sustainable Future

Albert Tarancon's

GROUP

[atlab.es](http://atlab.es)

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