Empa
Materials Science and Technology

From Materials to Devices

The importance of physics in material science & technology for sustainable energy applications

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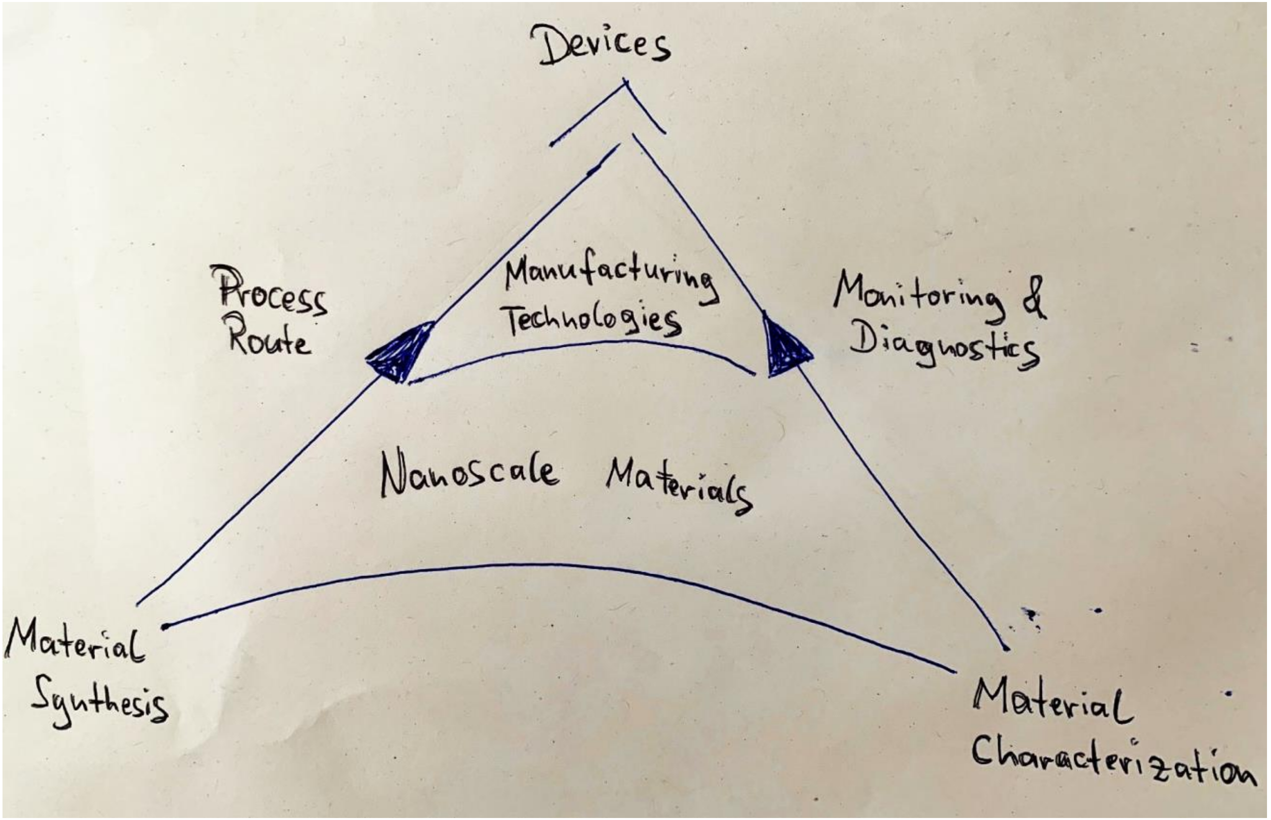
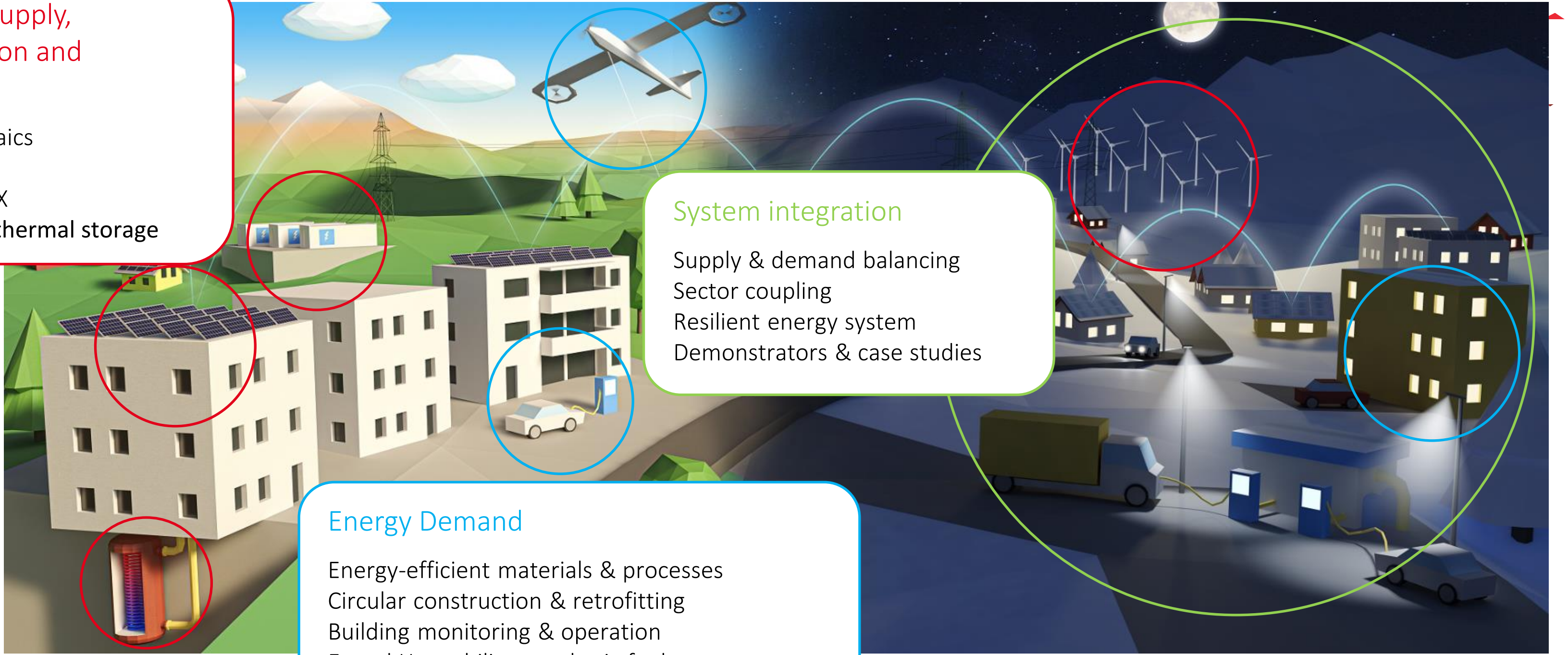
Outline

- Introduction:
  - Concept «Materials to Devices»
  - Physics in Energy-related Materials Science at Empa
- Example 1: High Efficiency CIGS solar cells
- Example 2: Solid state thin film batteries
- Example 3: Quantum heat engines as thermoelectric generators
- Summary

Introduction: From Materials to Devices…





Energy supply, conversion and storage

Photovoltaics
Batteries
Power to X
Seasonal thermal storage

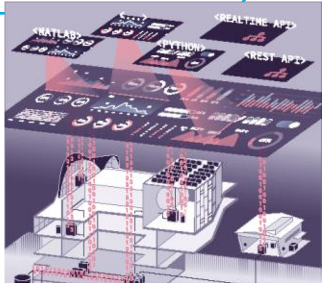
System integration

Supply & demand balancing
Sector coupling
Resilient energy system
Demonstrators & case studies

Energy Demand

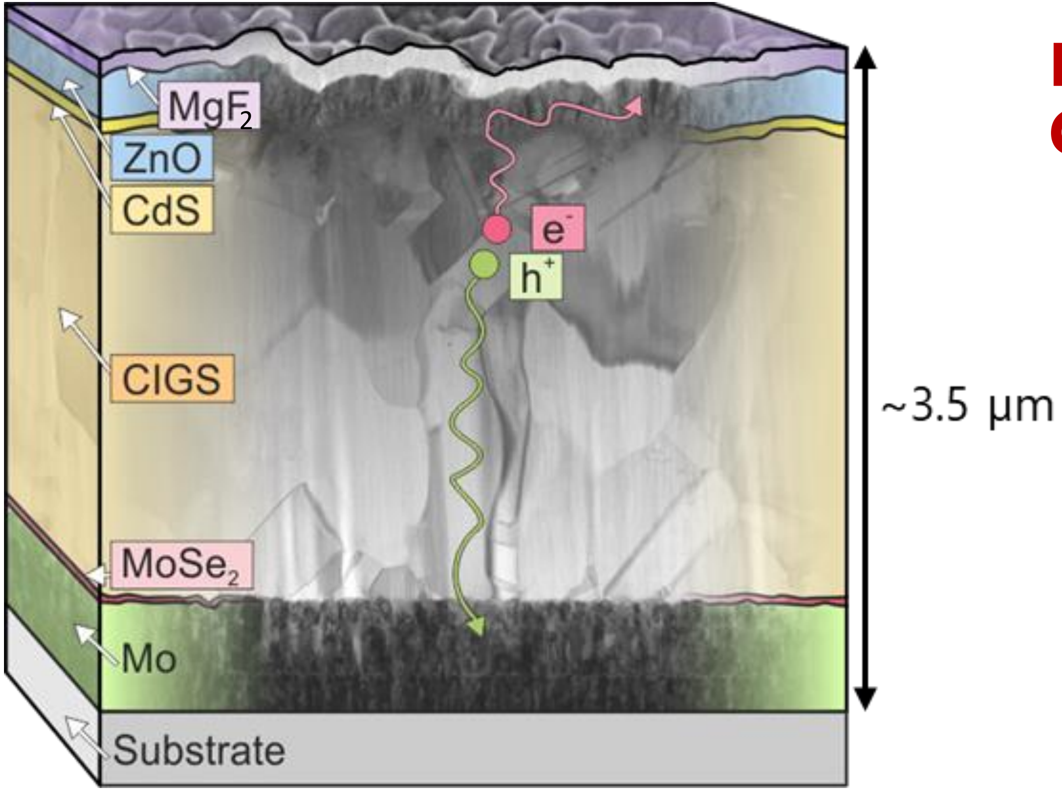
Energy-efficient materials & processes
Circular construction & retrofitting
Building monitoring & operation
E- and H_2-mobility, synthetic fuels

NEST



Energy Hub

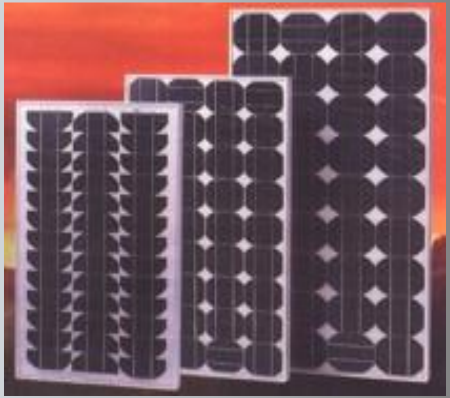
move



High Efficiency CIGS $Cu(In,Ga)Se_2$ solar cells

Generations of solar cells

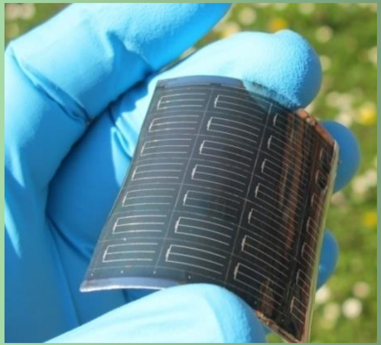
1st Generation:
Silicon wafer-based



- Wafer thickness: 200µm
- Rigid
- Heavy

- 55 years old
(95% market share)

2nd Generation:
Thin-films: CdTe, CIGS,..



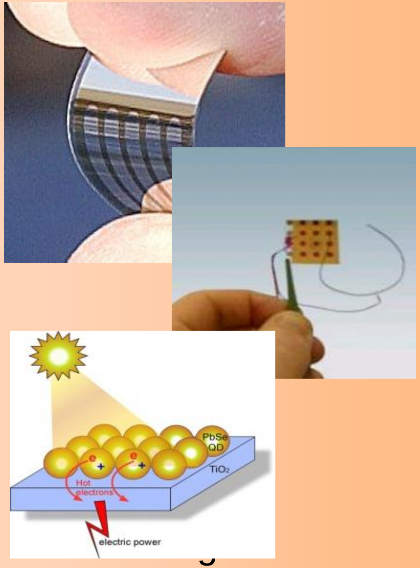
Rigid substrate
- Absorber thickness: <3µm but still heavy
- Large area deposition
- Monolithic integration

Flexible
Light-weight

R-2-R

- 20 years old (5% market share)

3rd Generation:
new concepts such as
Bifacial, tandem,



High-EFFICIENCY flexible solar cells @ Empa

Approach: absorber alloying

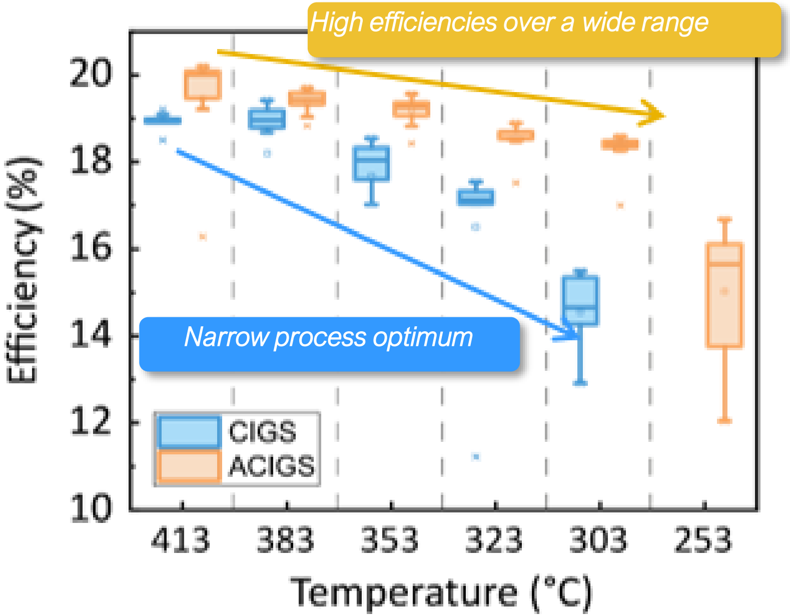
- Tiny amounts of silver in CIGS

→Improved PV performance:
Power conversion efficiency >22%

→Improved Process tolerance

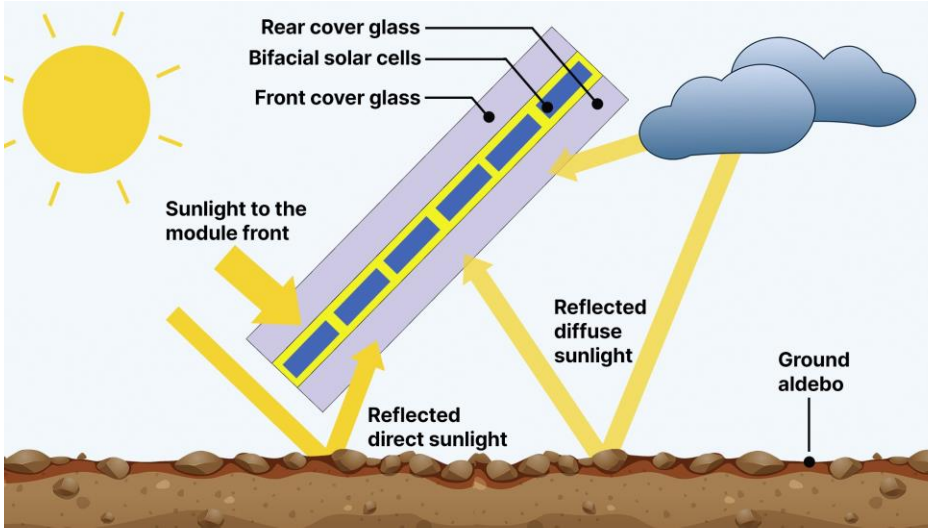
→Low temperature process enabling polymer or other delicate substrates

Can we bring up efficiency even further?

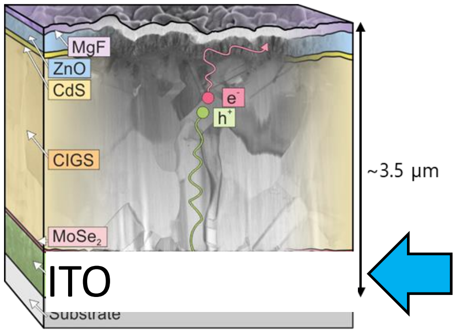


Yang et al, 2021, *Solar RRL*, *5*(5), 2100108
https://doi.org/10.1002/solr.202100108

Idea: Bifacial CIGS solar cells



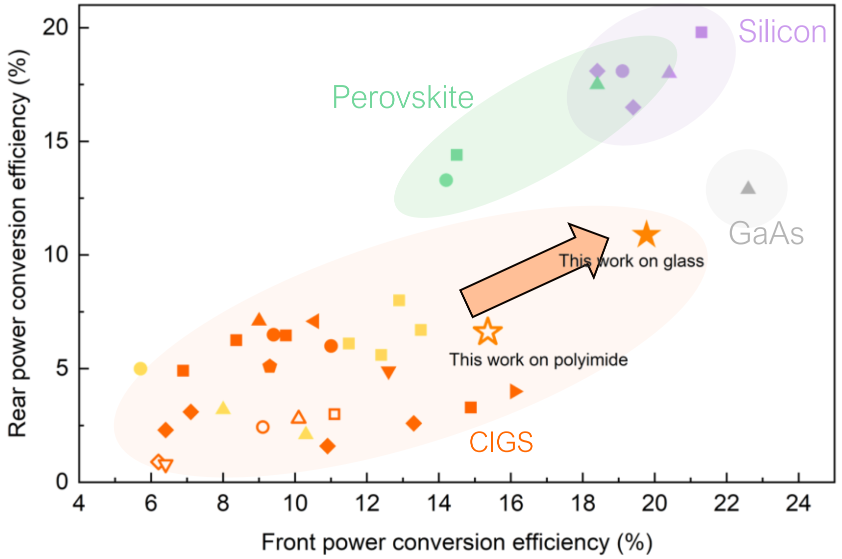
What about bifacial CIGS ?



Our approach

- Replace metal Mo with transparent ITO

(possible due to low process temperature of Ag alloyed material!)

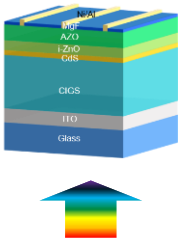


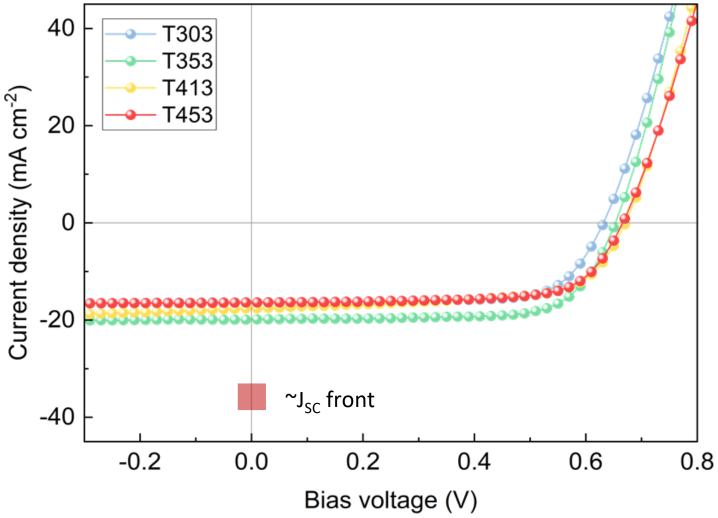
- **Breakthrough**: devices work well!
- Romain Carron ¬ Yaroslav Romanyuk

Can we bring up efficiency even further?

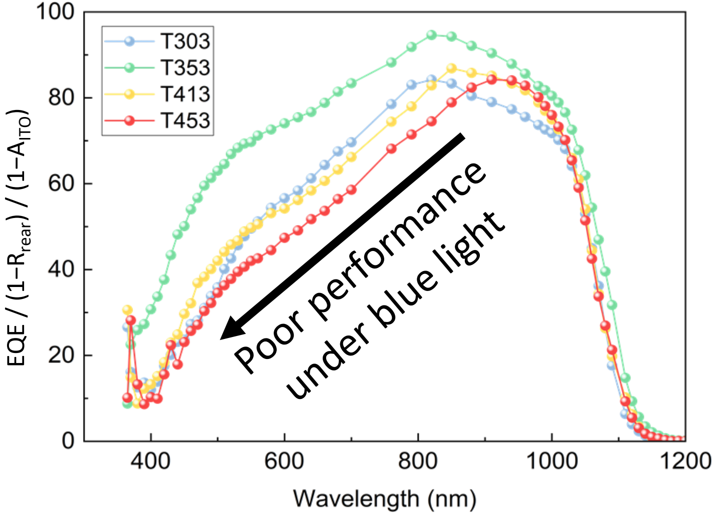
Yang et al., 2023, *Nature Energy*, *8*, 40-51.
https://doi.org/10.1038/s41560-022-01157-9

Phycisal limits: low photocurrent under rear illumination





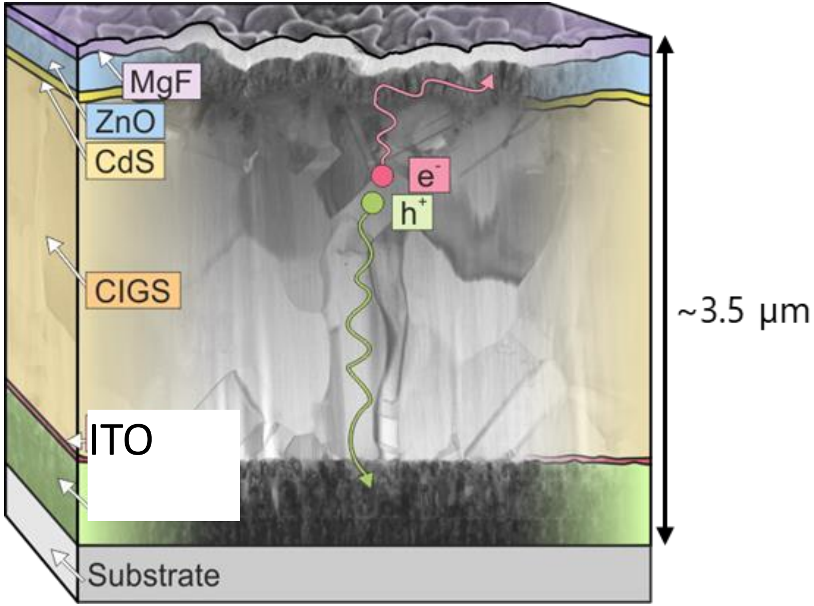
Rear illumination: missing about half photocurrent

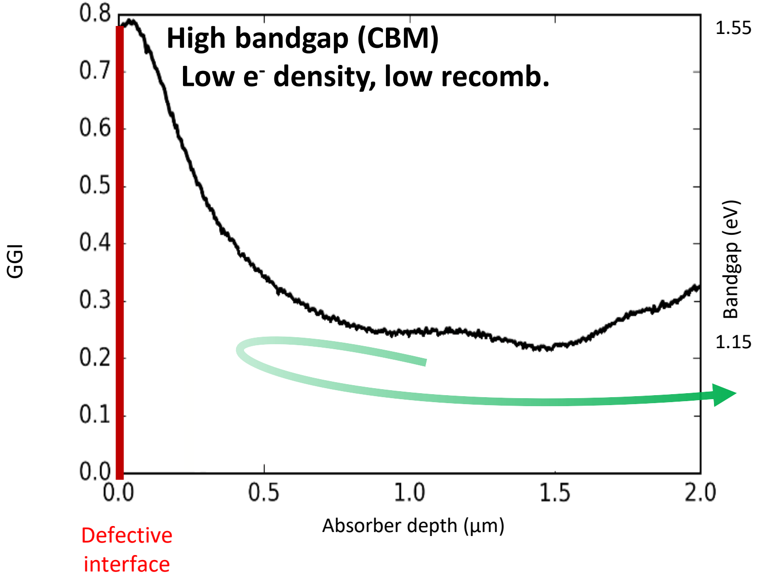


External quantum efficiency corrected for absorption and reflection

Yang et al., 2023, *Nature Energy*, *8*, 40-51.
https://doi.org/10.1038/s41560-022-01157-9

Bandgap gradient



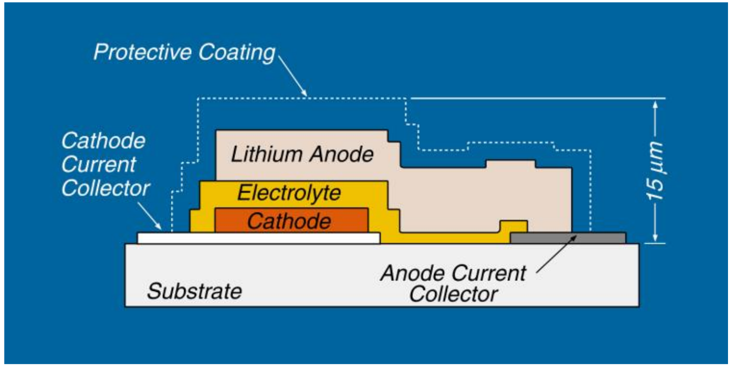


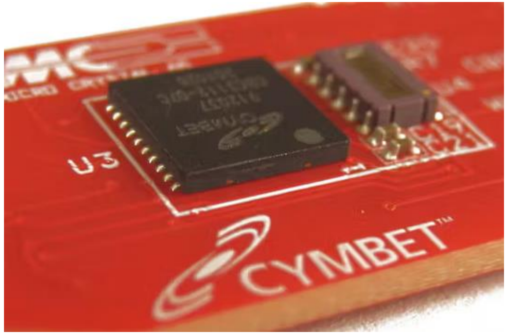
Issue: big bandgap at rear interface

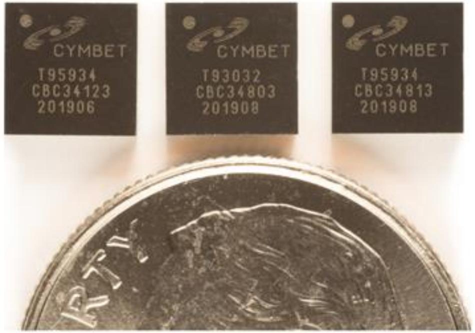
- Low electron density, low recomb.
- Bad efficiency to create backside e-h pairs

Outlook: absorber without gradient/ charge selective contacts

Thin-film batteries (TFB)







TFB is a miniature solid-state battery

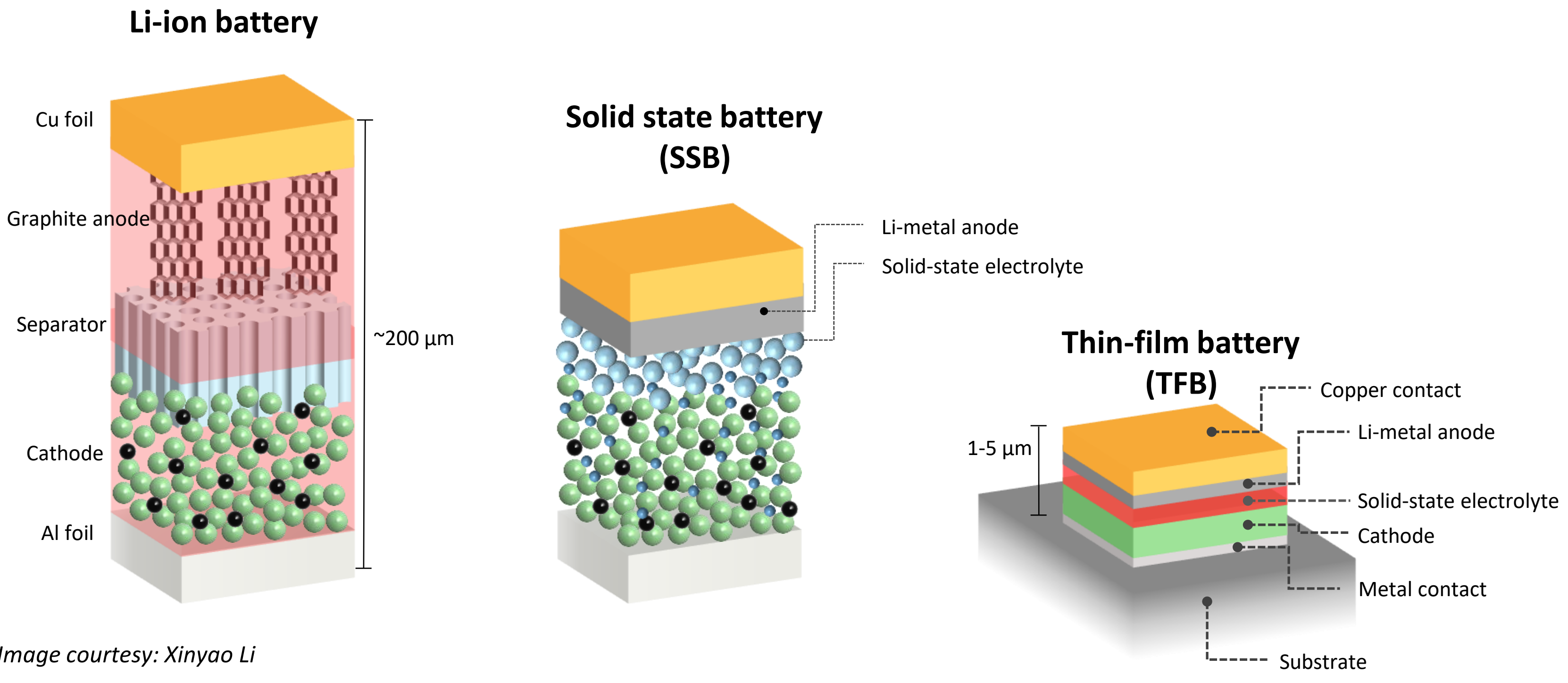
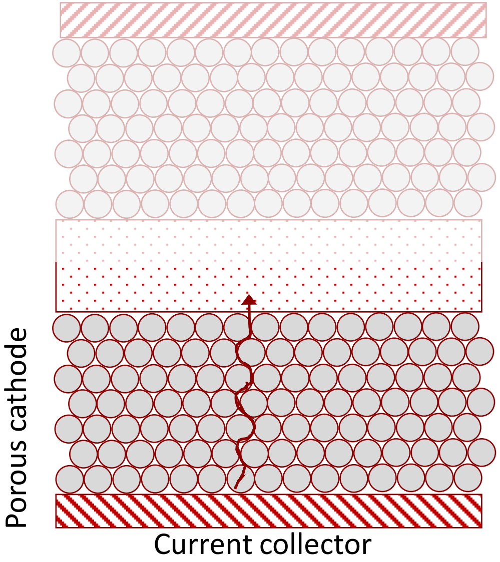


Image courtesy: Xinyao Li

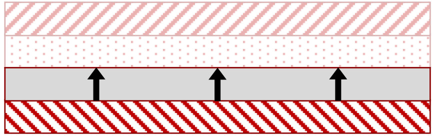
Ion diffusion path determines charging rate

Li-ion battery



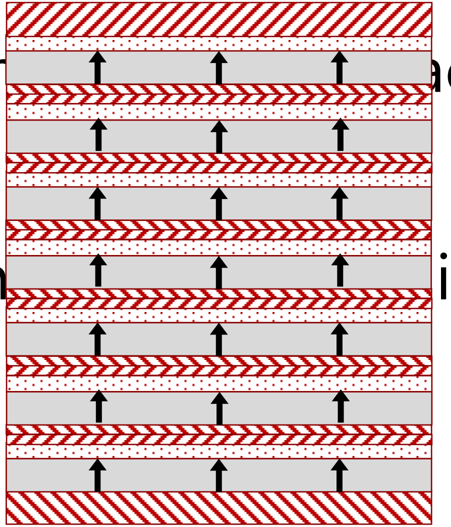
high energy
low rate

Thin-film battery



very low energy
high rate

Monolithic multi-cell
thin-film battery!?



Car … acity
wh … ing

high energy
high rate

Thin-film battery fabrication line at Empa

ALD

FLA

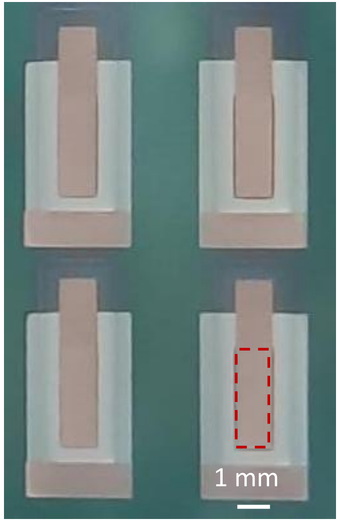
Magnetron sputtering

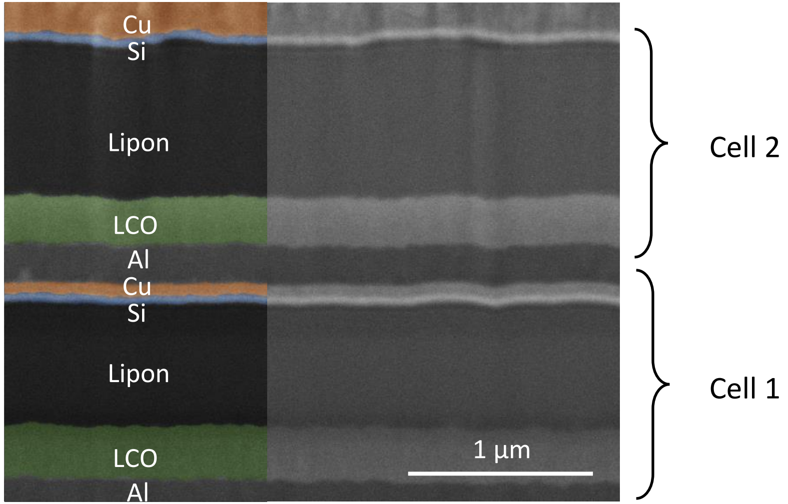
Wet glovebox

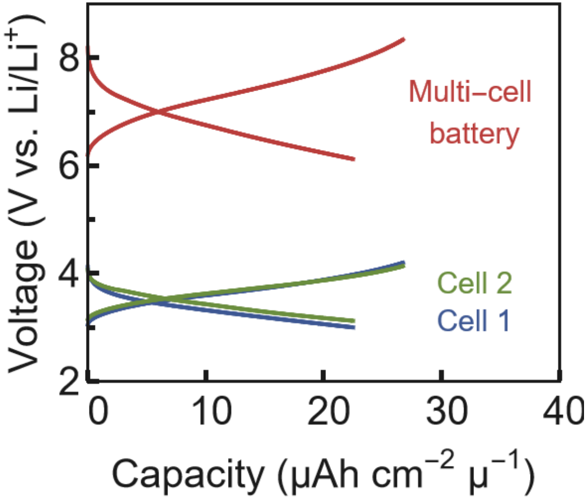
Dry glovebox

Thermal evaporator

Experimental proof of concept:
the first tandem stacked thin-film battery

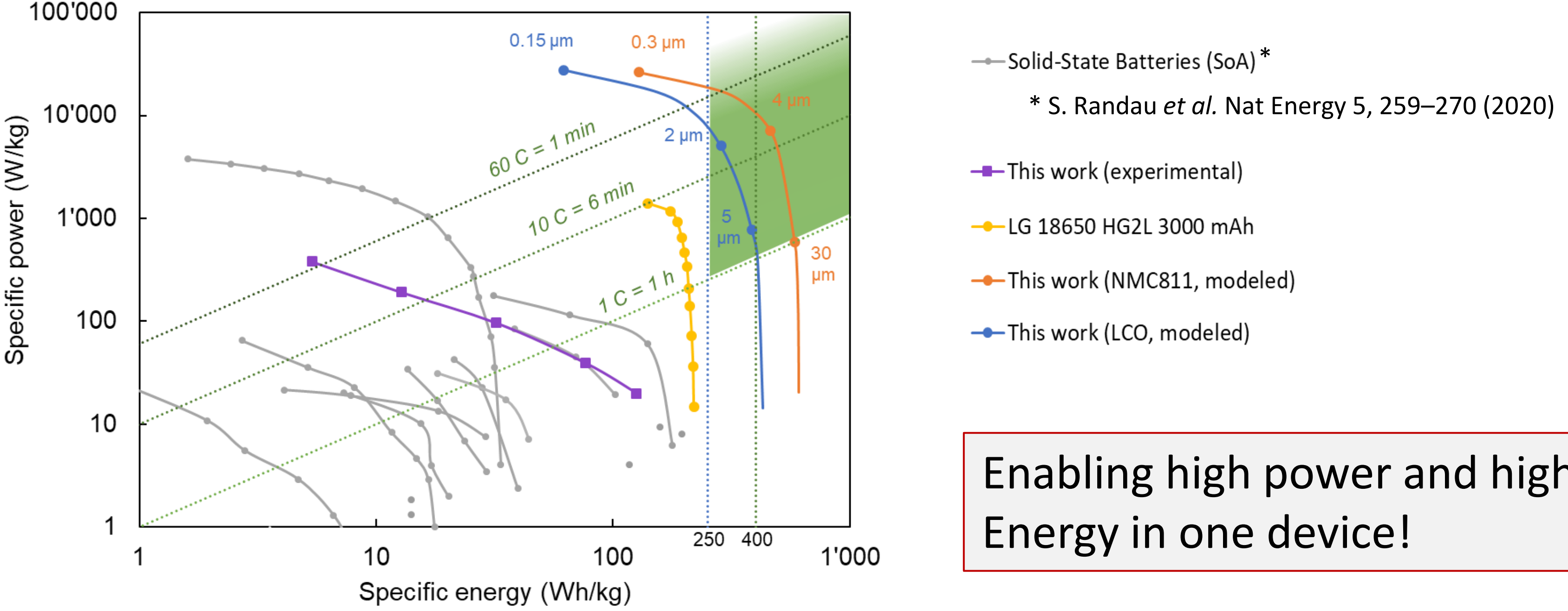






Futscher et al., *Comm Chem.* 6 **(2023)** 110

Benchmarking with solid-state batteries



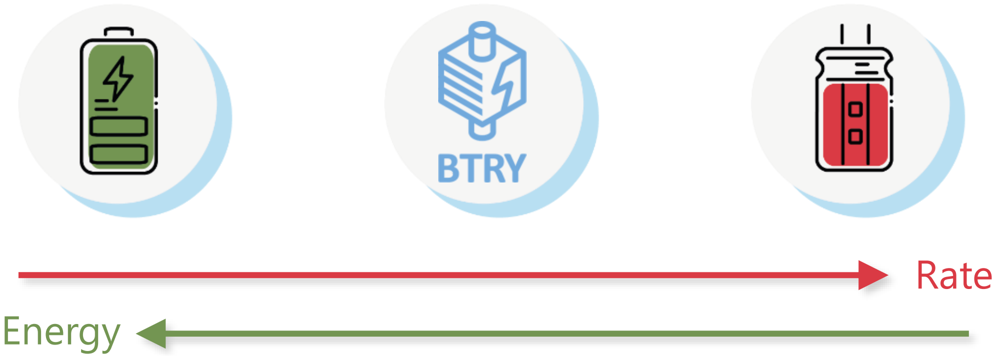
Enabling high power and high Energy in one device!

Futscher et al., *Comm Chem.* 6 **(2023)** 110

Empa spin-off BTRY AG

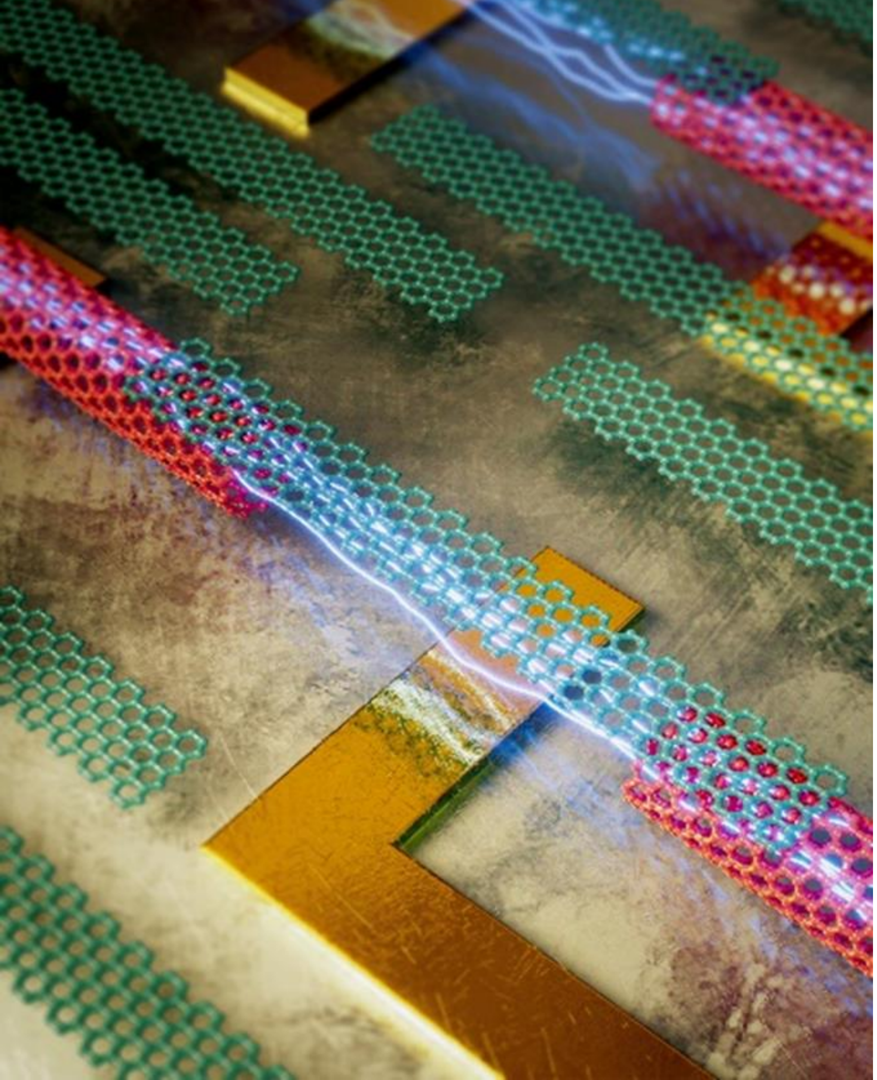
“A sustainable, reliable solid-state Li-ion battery that can be charged in one minute.”

Li-ion battery | BTRY | Supercapacitor



M. Futscher & A. Aribia

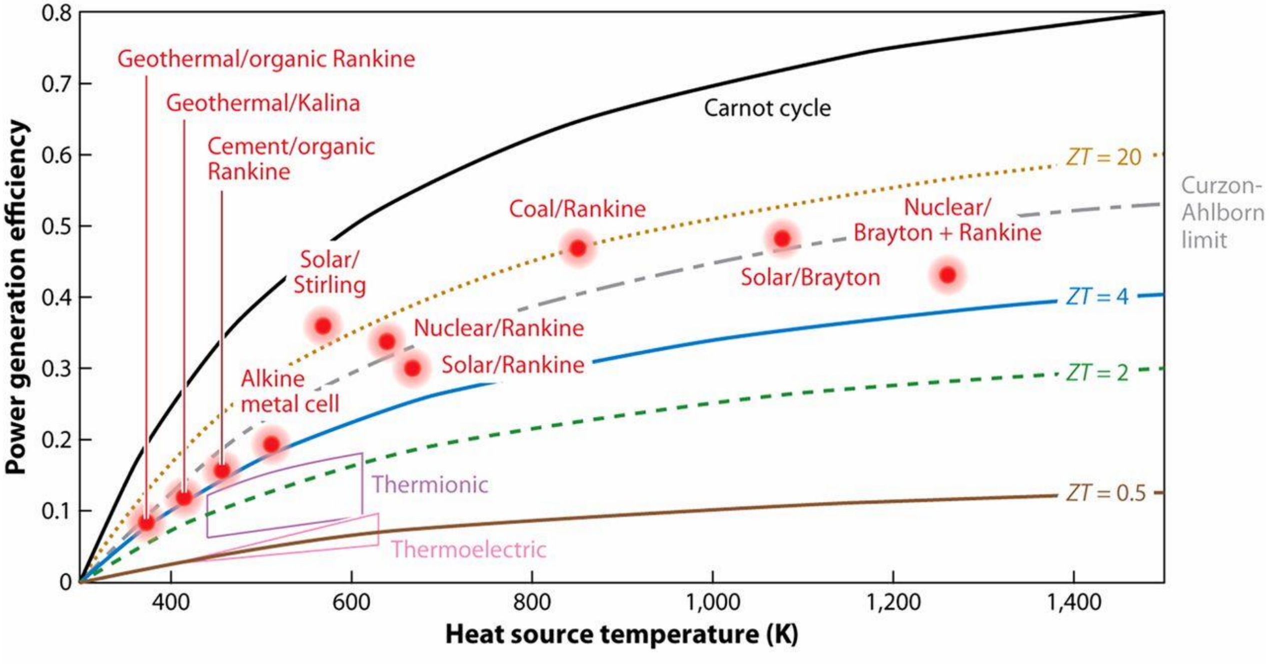
spin-off | Empa
High-Tech Gründerfonds
iBAT
WISSENSCHAFT. BEWEGEN GEBERT RÜF STIFTUNG
BÜROZÜRI by Zürcher Kantonalbank
Spin-off | ETH zürich
esa business incubation centre
BRIDGE
Zürcher Kantonalbank
VENTURE KICK
Innosuisse



Quantum heat engines as thermoelectric generators

Generating electricity from (waste) heat?

He et al. Science 2017



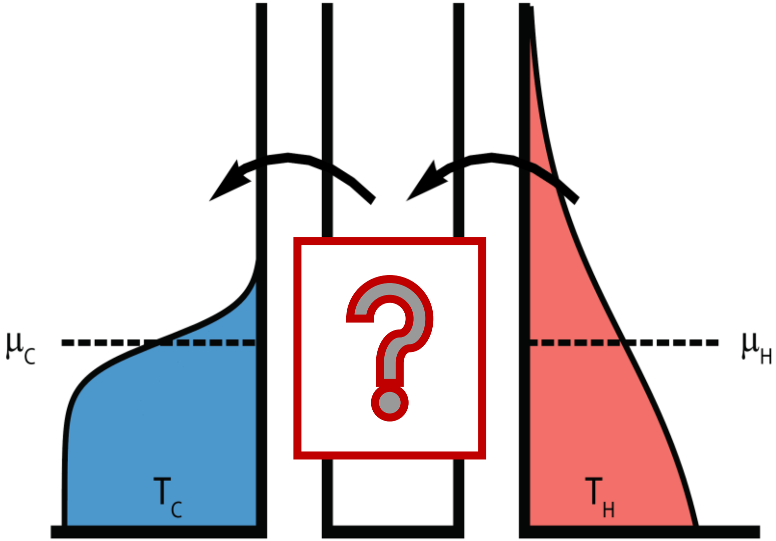
Carnot cycle is upper thermodynamic limit of all heat engines, but no power output is produced

Classical (cyclic) heat engines reach the Curzon-Ahlborn limit of maximum efficiency at maximum power output

Thermoelectrics do not reach Curzon Ahlborn limit so far!

Can we make thermoelectrics more efficient by using quantum heat engines?

PHE (Particle exchange Heat Engine) Design with electrons



«Quantum dot»

$$\eta = \left(\frac{T_{hot} - T_{cold}}{T_{hot}}\right)\left[\frac{\sqrt{1+ZT_m}-1}{\sqrt{1+ZT_m}+\left(\frac{T_{cold}}{T_{hot}}\right)}\right]$$

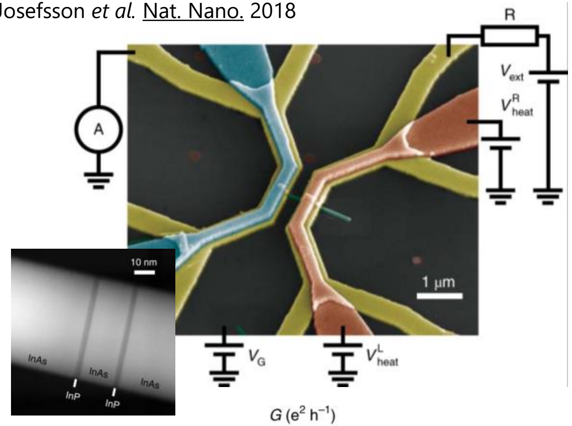
For ZT → ∞ $\eta = \left(\frac{T_{hot} - T_{cold}}{T_{hot}}\right)$ **Carnot efficiency**

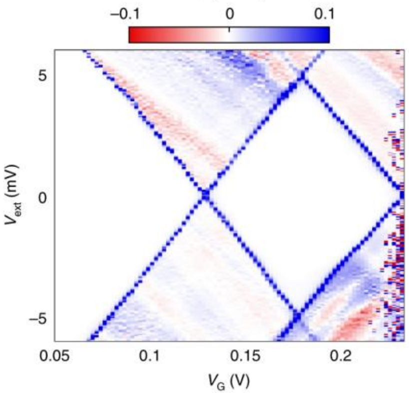
Question: Where is the Curzon-Ahlborn limit for maximum power output?

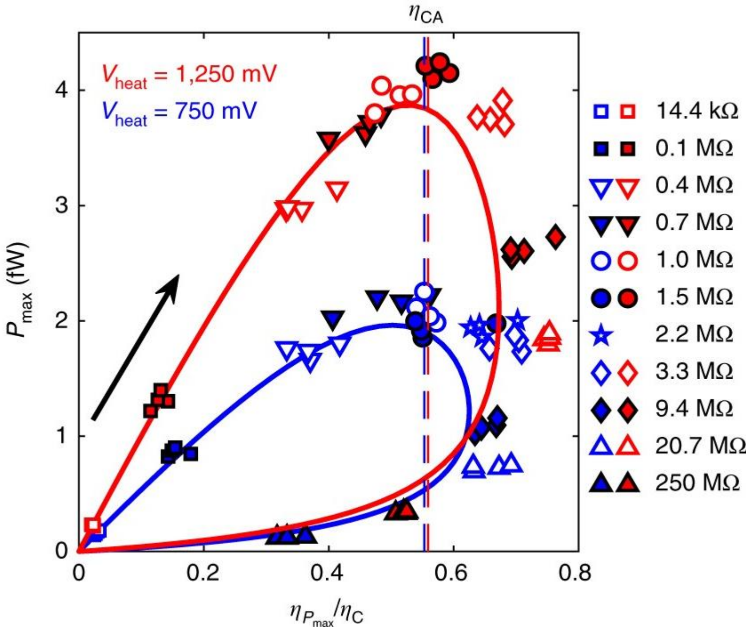
Experimental quantum heat engine

Curzon-Ahlborn limit

Josefsson *et al.* Nat. Nano. 2018





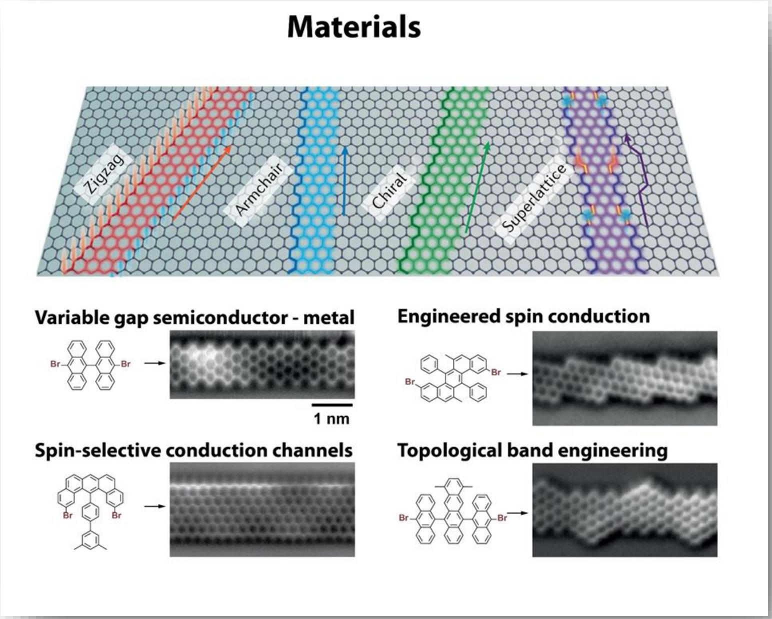


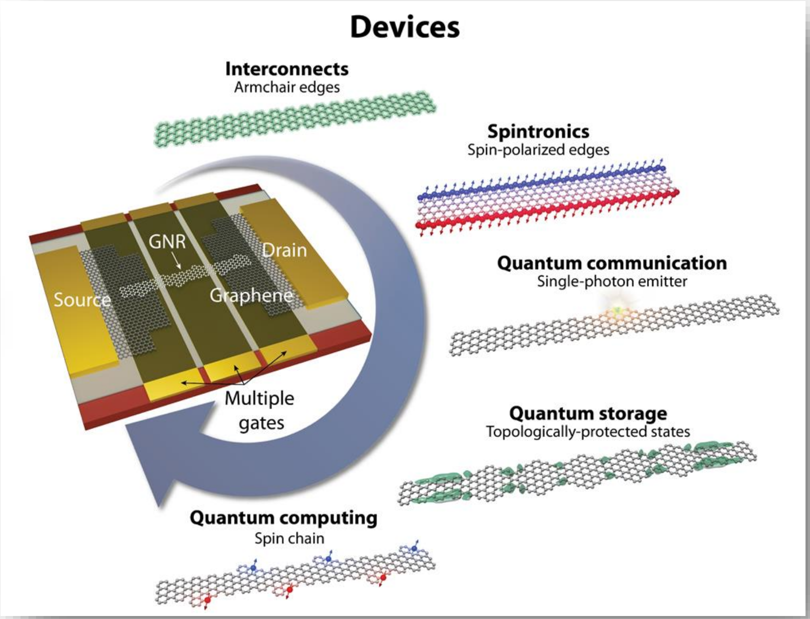
However: This device only operates at temperatures below 1K, level splitting in semiconducting quantum dots is small.

Question: Can we bring up the Quantum Engines to room temperature?

Graphene nanoribbons

A versatile material platform for quantum technologies



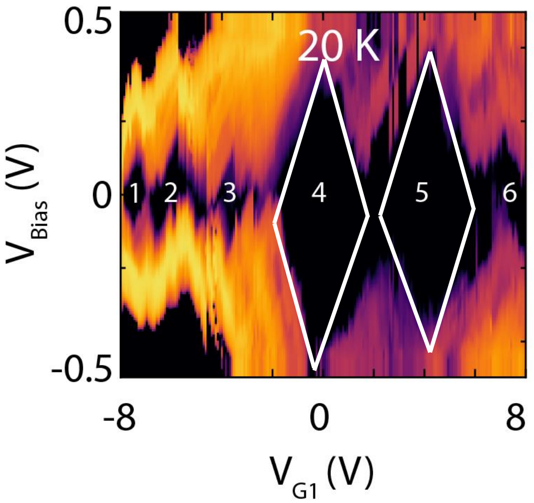


Paradigm shift: *"one for all"*

Gabriela Borin-Barin
Roman Fasel

Mickael Perrin
Michel Calame

Toward room temperature quantum devices



Coulomb diamonds visible up to 250K

Mickal Perrin, ETHZ, Empa, ERC starting grant

Zhang *et al.* Nano Letter 2023

Summary

Empa
Materials Science and Technology

- Physics and chemistry are the base of interdisciplinary, energy-related material science
- Bifacial Solar Cells as way to increase efficieny
- Thin-film batteries strive for high power & energy density at same time
- Exploratory new methods like quantum heat engines are at the horizon as a new generation of thermoelectric generators.

Empa – The Place where Innovation Starts

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