European Commission

ICOS
International Cooperation
On Semiconductors

Energy Harvesting: Main technologies and actors

Gustavo Ardila, Associate Professor
CROMA
Grenoble Alpes University, France
gustavo-adolfo.ardila-rodriguez@grenoble-inp.fr

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The Faculty, Brussels

Outline

- ☐ Introduction
- ☐ Energy harvesting technologies (IEEE-IRDS)
  - Main technologies, trends, challenges, examples
  - Main actors : Universities / RTO
- ☐ Summary
- ☐ Impact for Europe (international cooperation)
- ☐ Impact for the industry

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IRDS International Roadmap for Devices and Systems™

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Energy Harvesting

INTRODUCTION

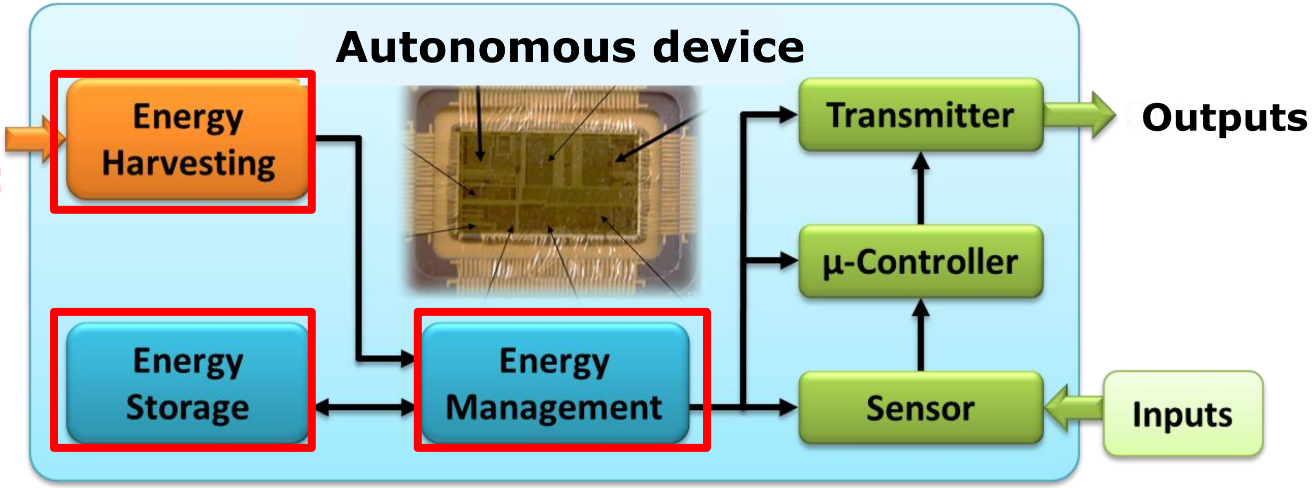
Introduction

- Market growth on connected devices : IoT (estimated 250 billion devices by 2030), healthcare, wearables, home automation…

- EH is important in applications with specific requirements : simple battery is not enough (reduce waste), cords would increase the cost / complexity, too many devices, harsh environment, implants…

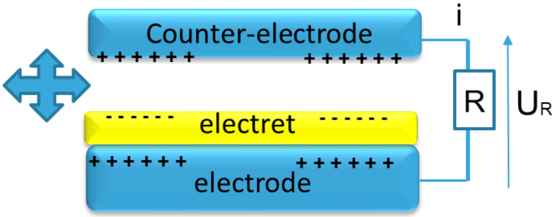
- Energy supply is essential (<mW, tens of µW) → Energy Harvesting

  - **Mechanical**
  - **Electromagnetic**
  - **Thermal…**

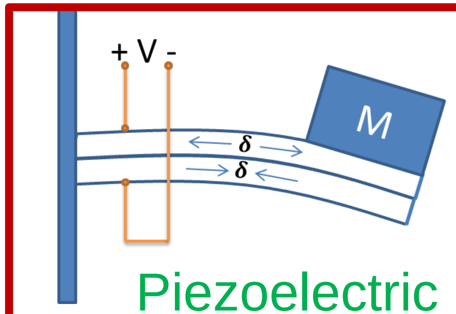


Introduction: Technologies covered so far…

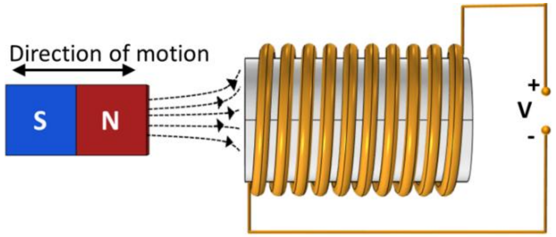
Mechanical EH



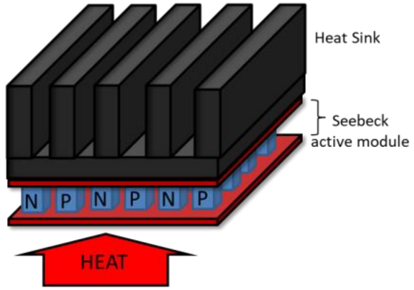
Electrostatic



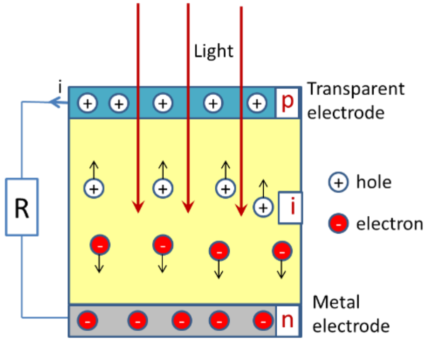
Piezoelectric



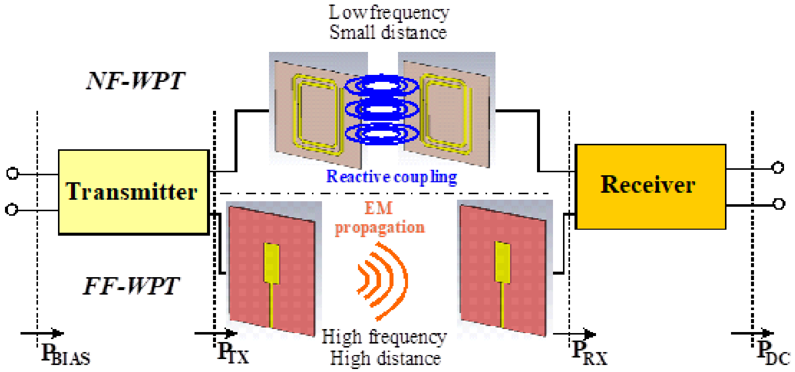
Electromagnetic



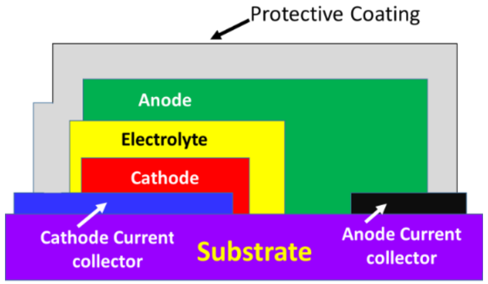
Thermal EH



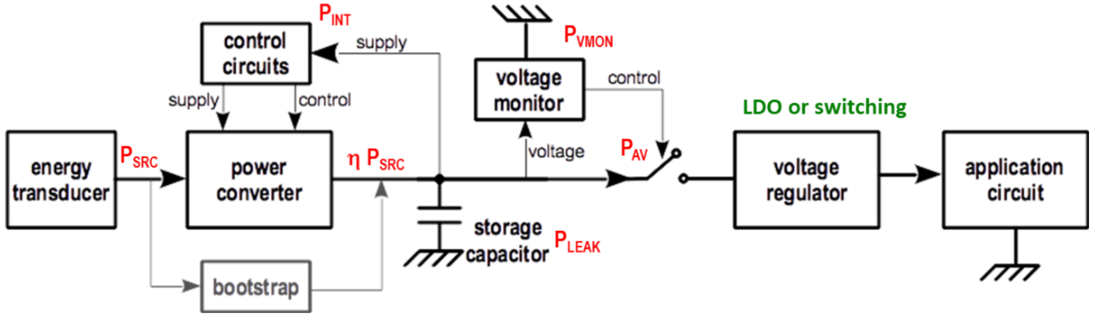
Solar EH



RF EH / wireless power transfer



Energy storage (µbatteries)

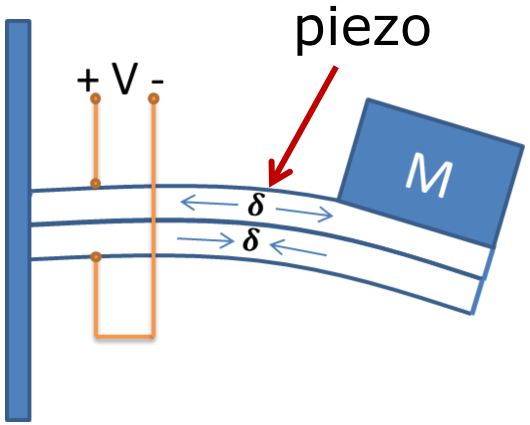


Micro power management

Energy harvesting technologies

Mechanical EH : Piezoelectric conversion

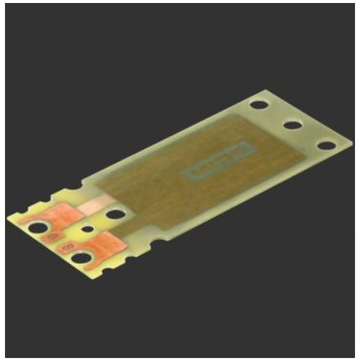
- ☐ Harvesting principle based on mechanical resonators
- ☐ Applications are linked to mechanical vibrations harvesting (movements)



- Principle

Resonant cantilever covered by a piezoelectric layer and a inertial mass attached. As the cantilever is bent, strain is transferred to the piezo layer ⟶ asymmetric charge distribution (Voltage)

MIDE (PZT)

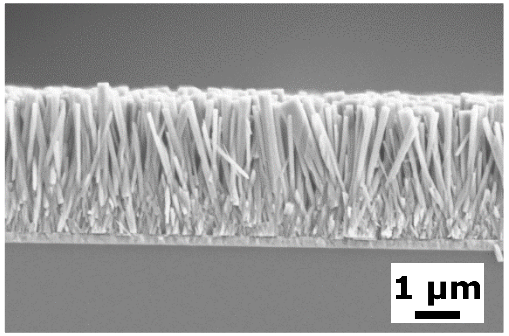


TE Connectivity (PVDF)

- ☐ Devices tuned at a specific vibration frequency
- ☐ Devices are easy to fabricate
- ☐ Macro-devices and MEMS are actually on the market
- ☐ Most used materials (commercial) : PZT (lead/toxic), PVDF

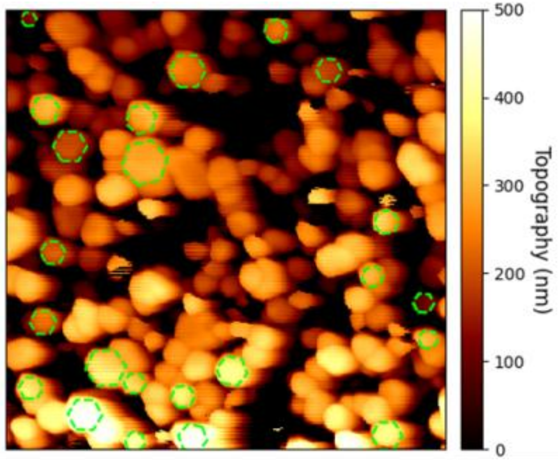
Piezoelectric conversion: current trends nanostructuring - nanowires

- ZnO NWs (biocompatible, abondant) as replacement of lead-based materials
- Characterization: Piezoelectric Force Microscopy (PFM)

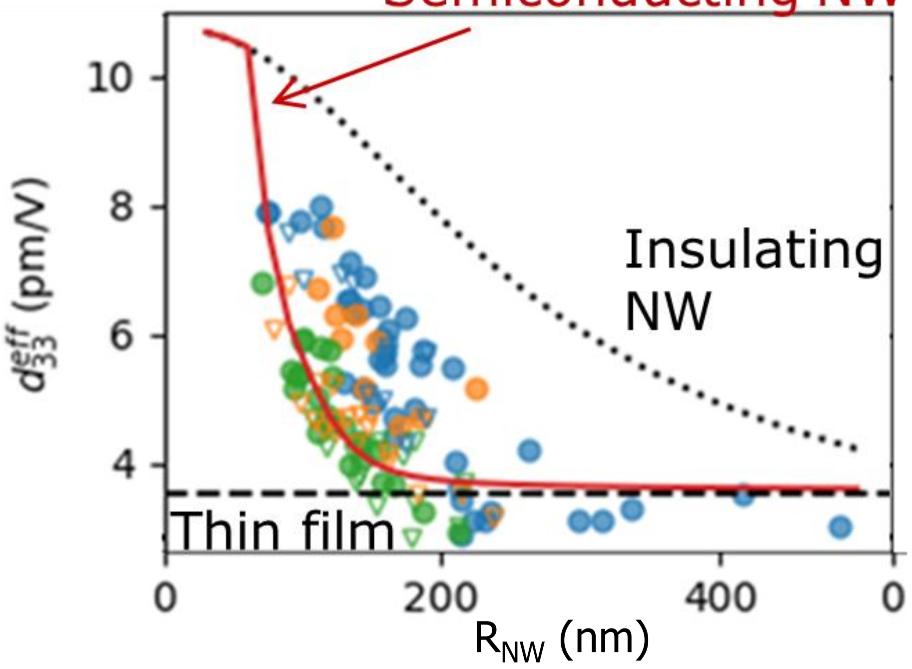


3µm long, 200nm wide

ZnO NWs (CBD)



Semiconducting NW



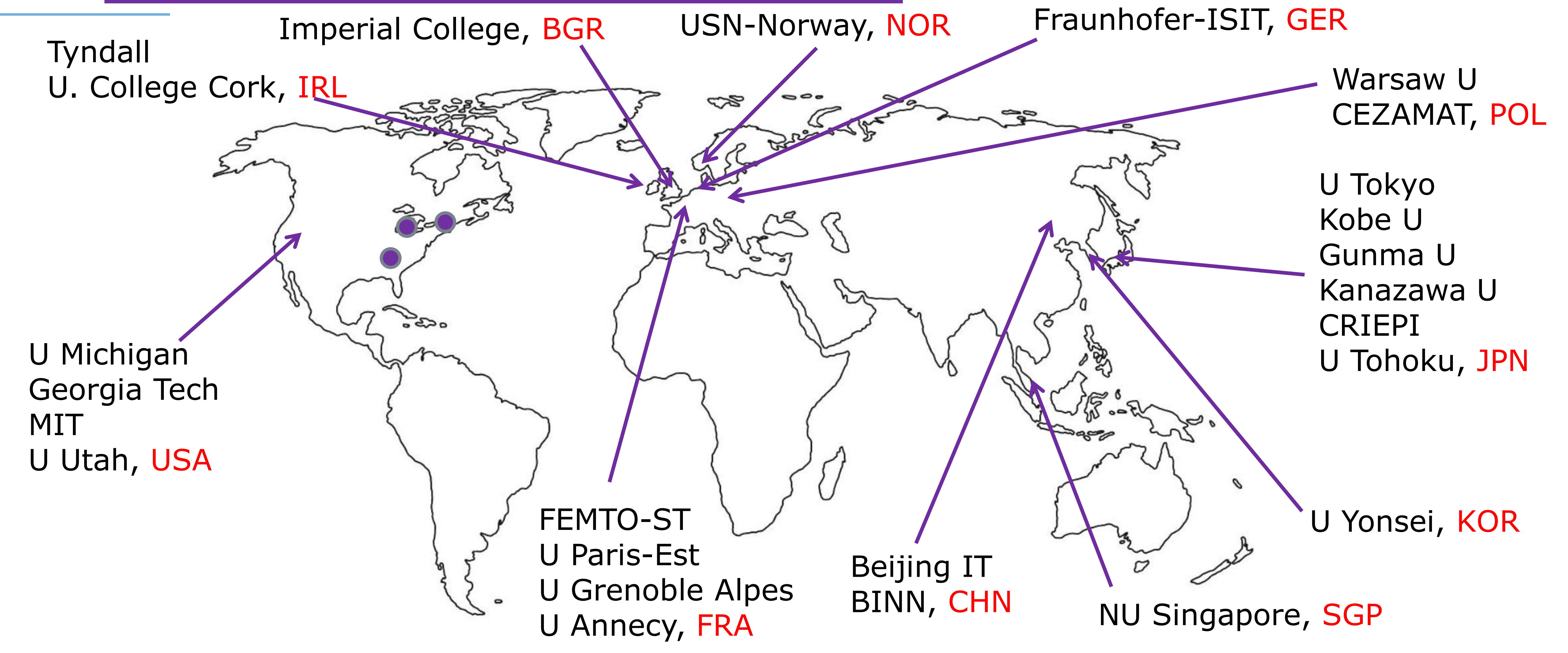
Simulation parameters (CBD):

$N_{it}=10^{13}$ $eV^{-1}.cm^{-2}$
$N_d=10^{17}$ cm^{-3}

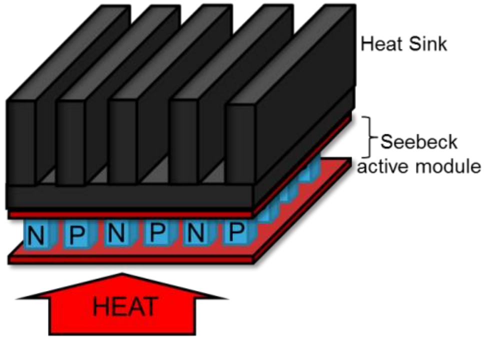
T. Jalabert et al., Nanotechnology 2023

- ➢ Piezoelectric performance increase as the NW radius is reduced
- ➢ Perspectives : Control of semiconducting properties, dimensions

Mechanical EH : Most active universities / RTO



Thermal EH

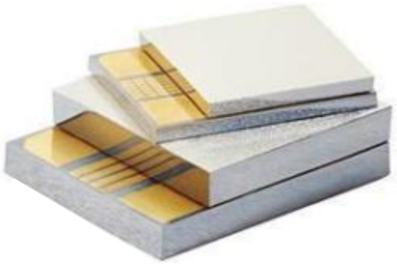


- Principle

Seebeck effect: generation of a voltage along a conductor when it is subjected to a temperature difference.

Main parameter : $zT=\sigma S^2T/\kappa$. σ : electrical conductivity (1/Ω/m), S : Seebeck coefficient (V/K), κ : thermal conductivity (W/m/K), T : temperature (K).

zT ~ 1 (now) → 3 (future)



Micropelt
~4 x 3 X 1 mm
P < 15mW
@ ΔT=30K

Nextreme
~ 11 x 10 x 1 mm
P < 130mW
@ ΔT=50K

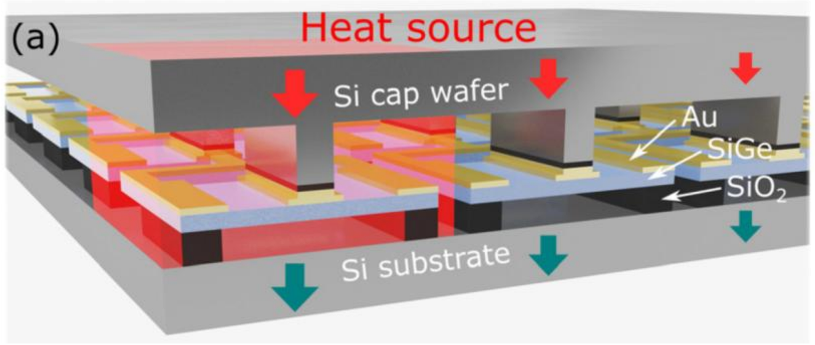
- ☐ Fast thermalization (need for a big heat sink)
- ☐ Non-flexible
- ☐ Bi_2Te_3 : Expensive/rare/toxic material/incompatible with CMOS
- ☐ Power proportional to available temperature gradient

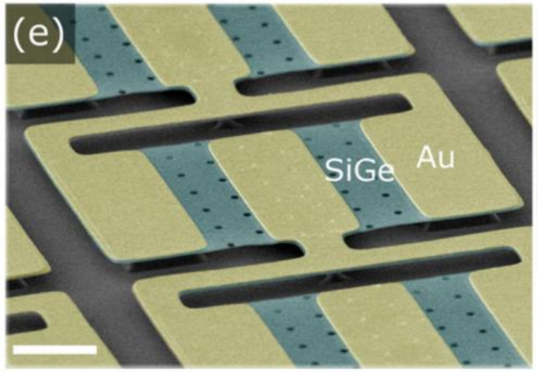
Book: H. Akinaga et al., Thermoelectric Micro/Nano Generators, Wiley 2023

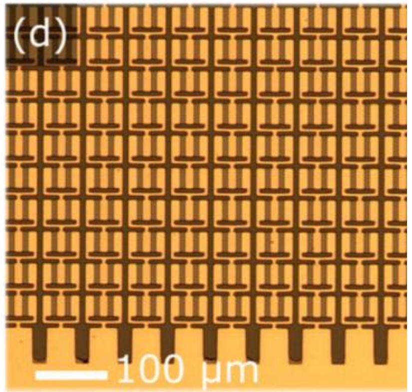
Thermal EH
Current trends : Si, SiGe and Nanostructuration

- Replacement of Bi_2Te_3 by Si thin films and nanostructures (Si, SiGe)
- CMOS compatible

$zT = \sigma S^2 T / \kappa$

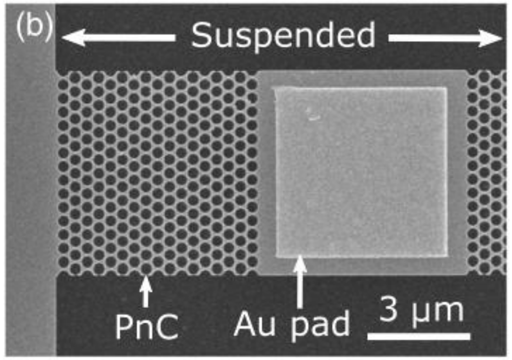


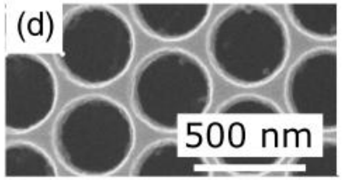




SiGe thin films (lower κ)

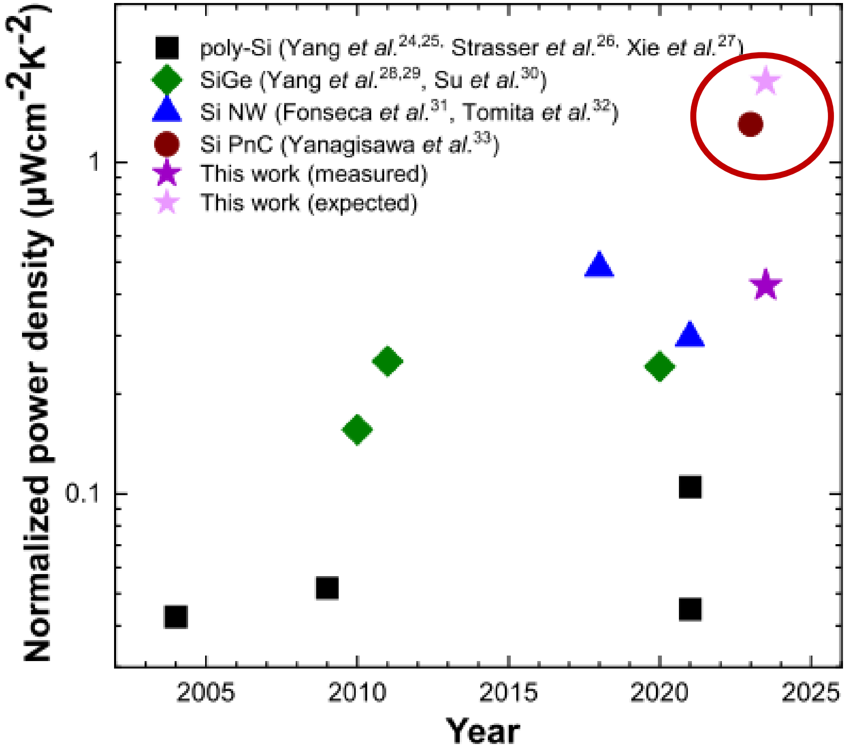
S. Koike, T. Mori et al., APL, 2024





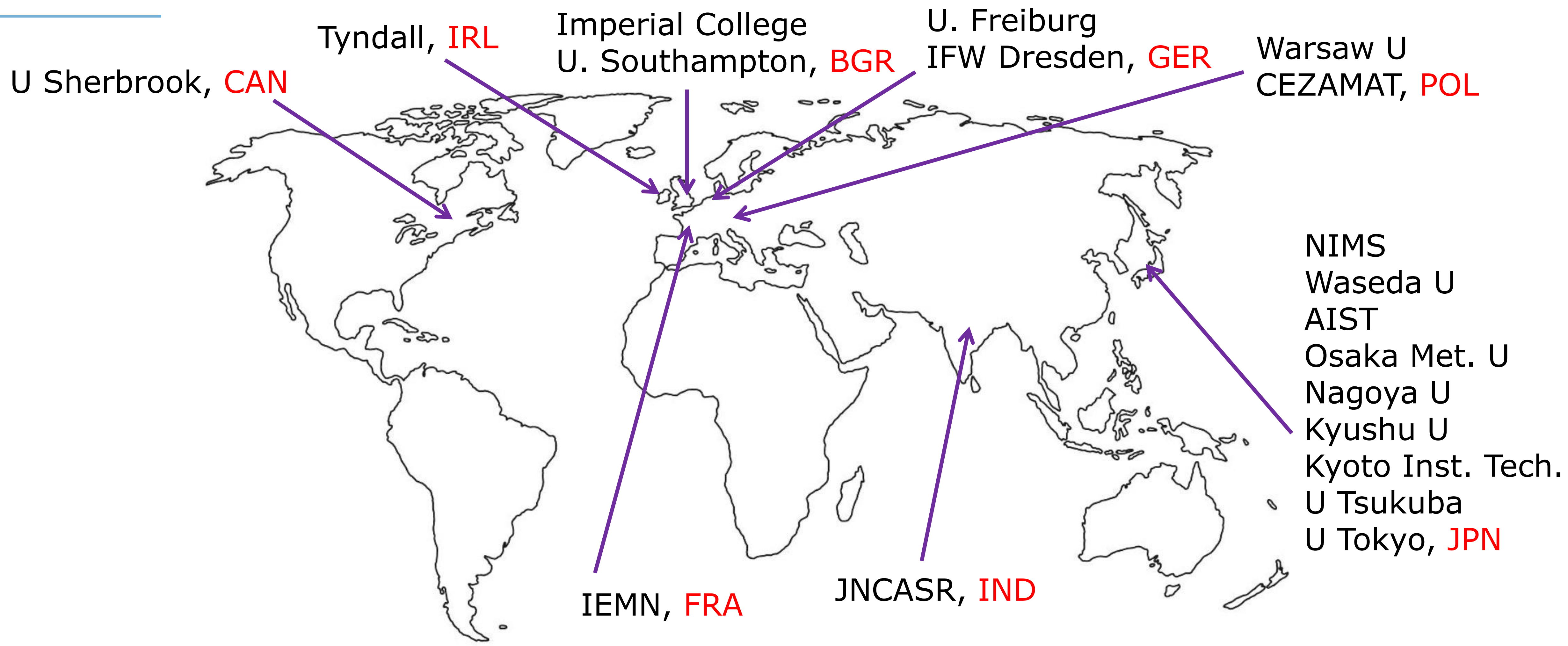
PnC (Phononic Crystals)
- Limit Phonon transport
- Reduce κ

S. Koike, T. Mori et al., J. JAP, 2023

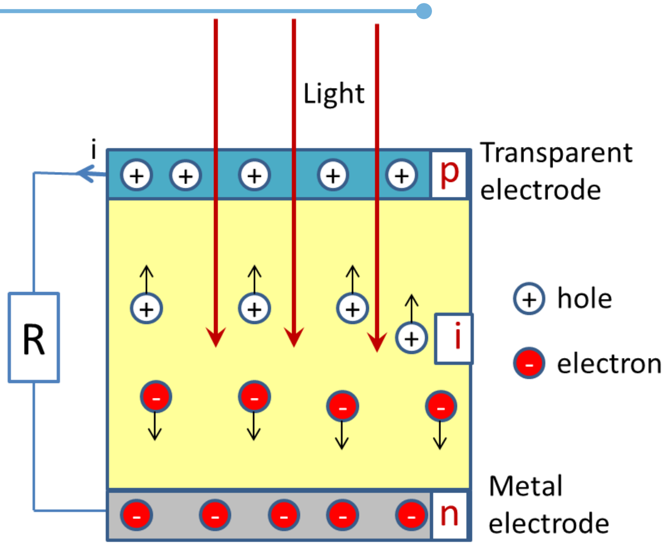


S. Koike, T. Mori et al., APL, 2024

Thermal EH: Most active universities / RTO



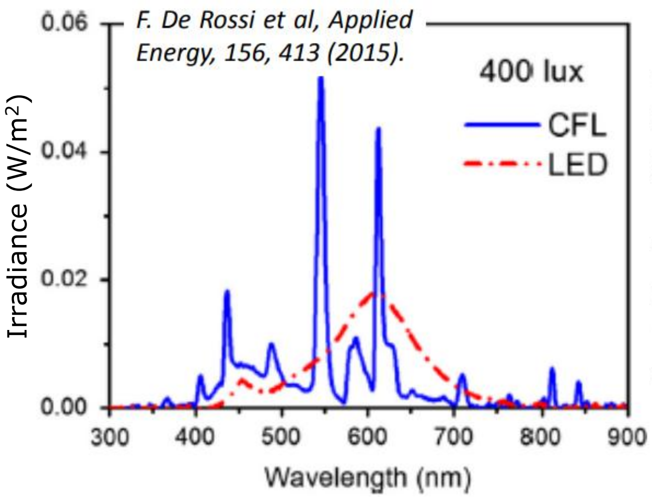
Photovoltaic EH

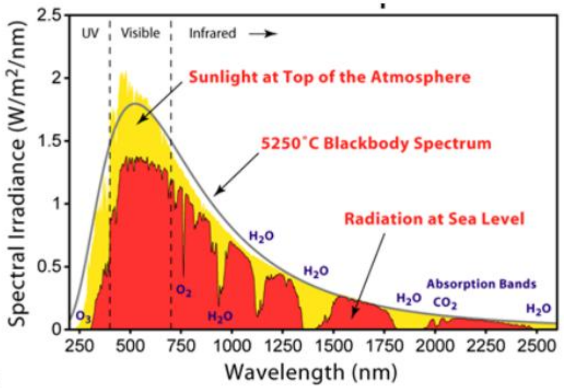


Principle : Photovoltaic effect:
- Absorption of light by the semiconductor - Electron-hole pair generation,
- separation and collection → Power delivered

- A market dominated by the Si (mature technology):
  - For outdoor applications, crystalline Si solar cells
  - For indoor applications, amorphous Si photovoltaic cells
- Solar cells spectral sensitivity and efficiency differ depending on the light spectrum which is very different for artificial and sun light

Indoor and outdoor light level





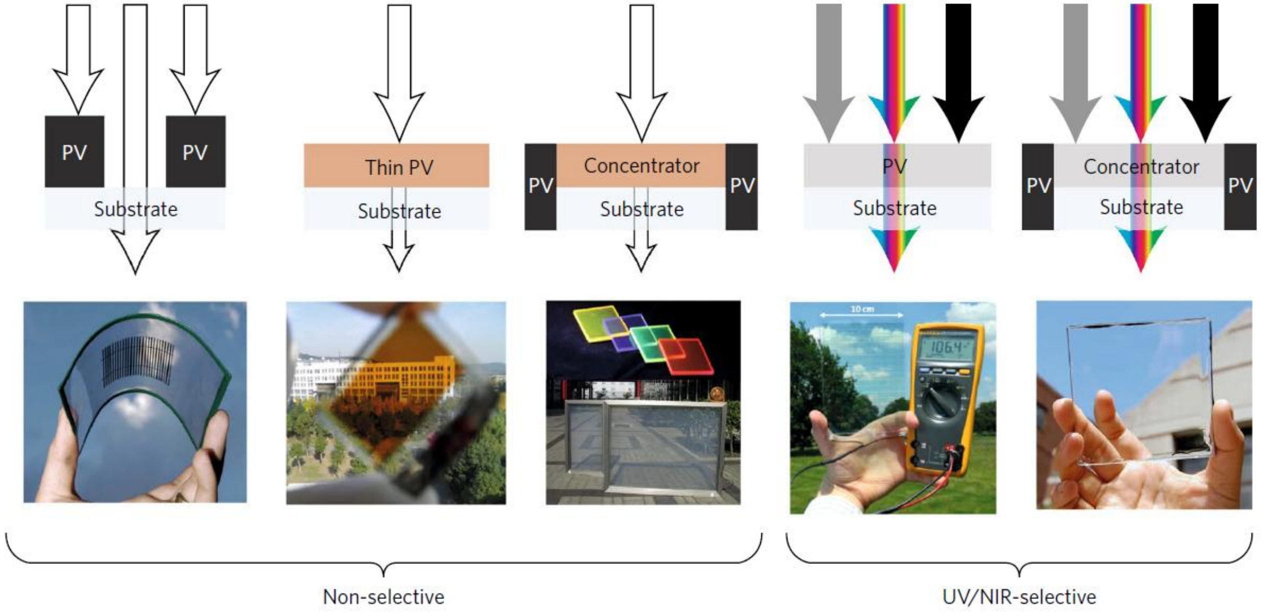
a-Si, organic, DSSC (dye sensitized solar cells), semiconductors compounds (III-V, CdTe,…), Perovskite

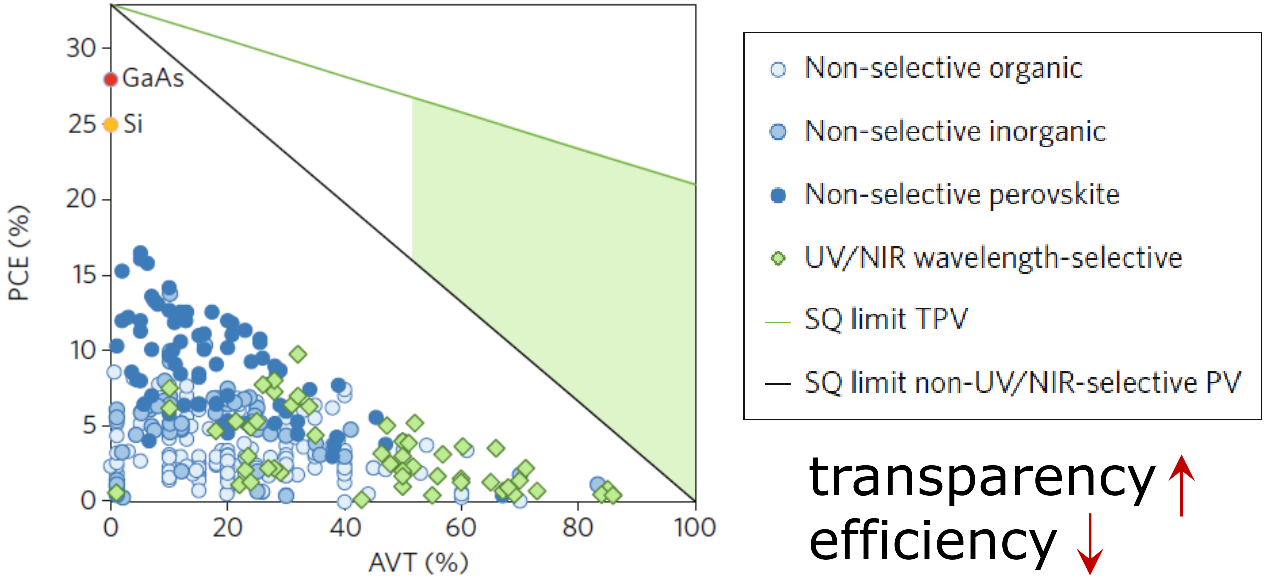
Si, tandem cells on Si, semiconductors compounds (CIGS…)

Courtesy of A. Kaminski, NEREID, 2016 .

Photovoltaic EH: current trends

- Develop high efficiency and low cost transparent PV (flexible, even better)
- PV covering other things other than roofs (e.g. windows, walls, e-devices …)
- Not all application need to be 100% transparent or highly efficient





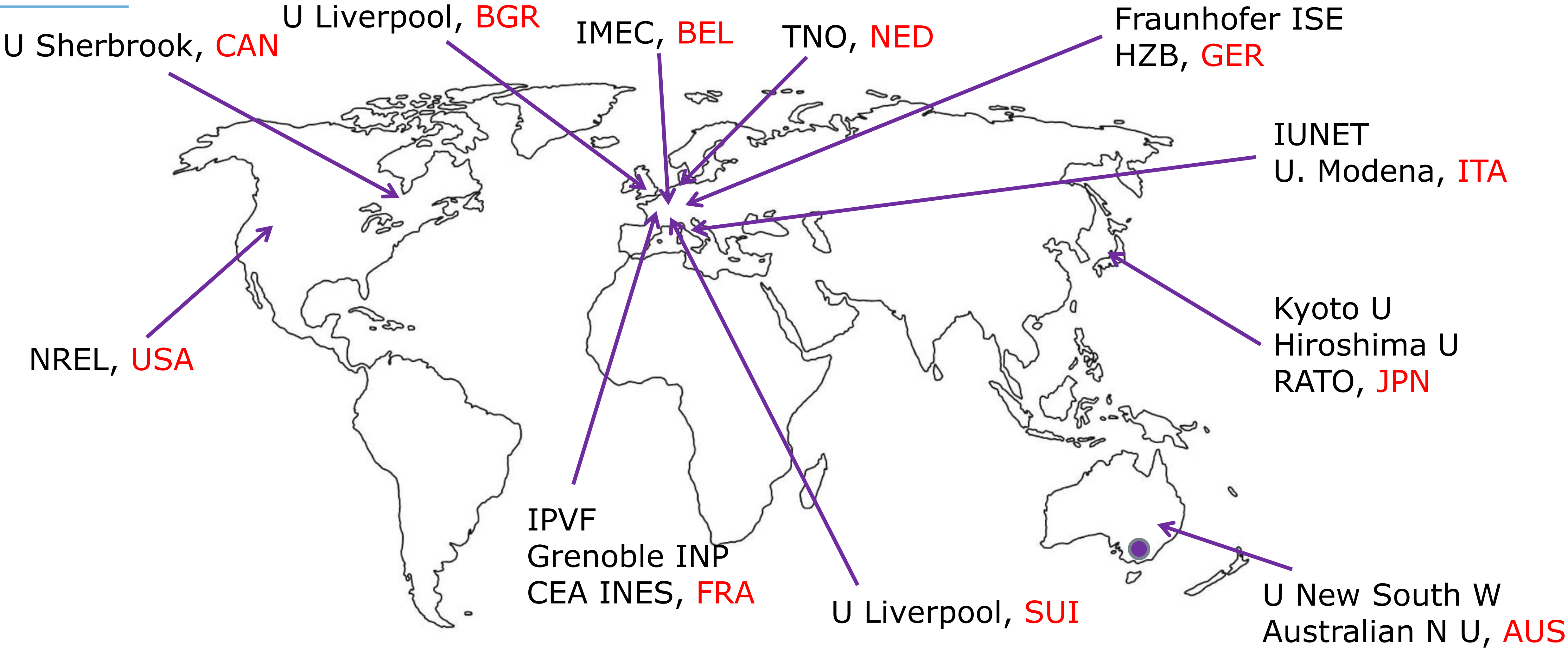
transparency ↑
efficiency ↓

- Still work to be done before reachning large scale: reduce losses, increase lifetime…
- Low resistivity transparent electrodes (Nanowires, nanotubes, thin metallic films)

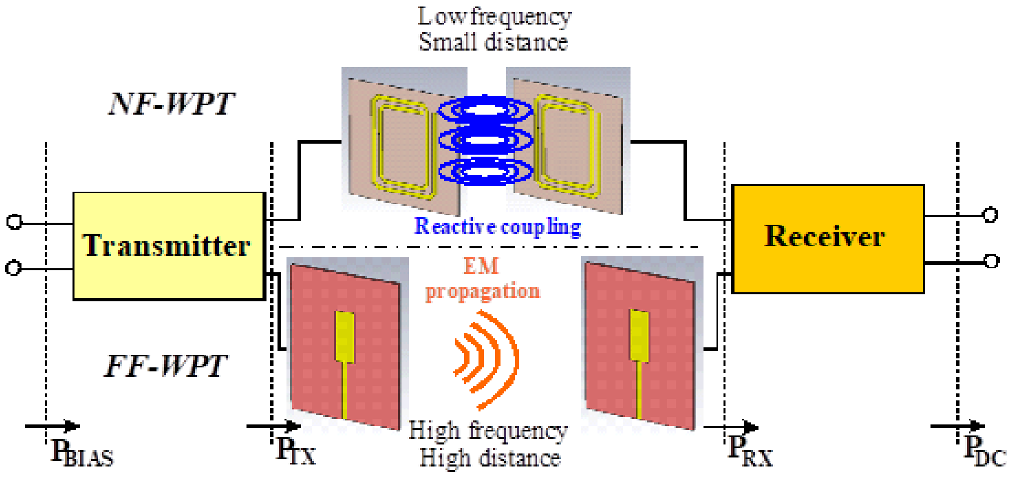
C. J. Traverse et al., Nature energy, 2017 .

S. Al-Ali et al., Energy Conv. Management, 2025 .

Photovoltaic EH: Most active universities / RTO



RF EH /Wireless power transfer



2 Principles :

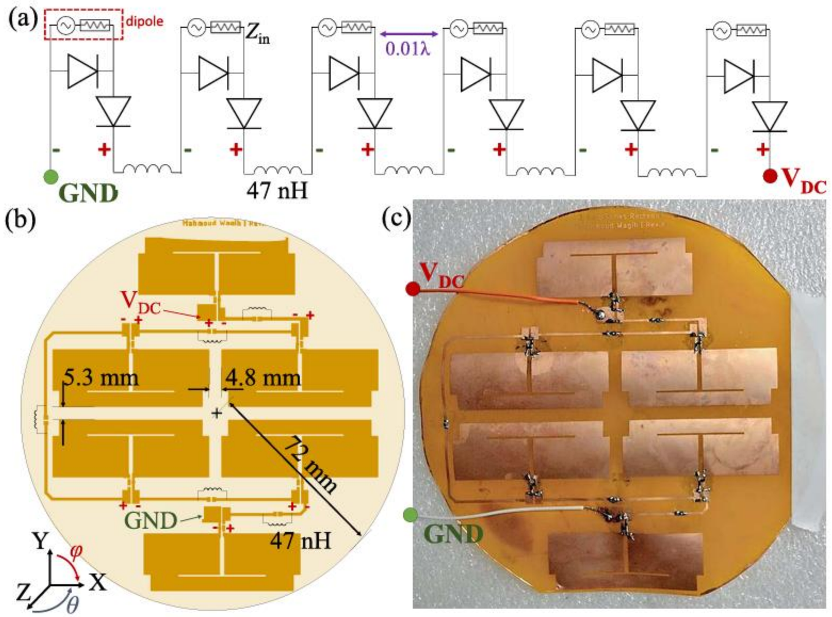
- Radiated far field RF source (High frequency 300MHz-GHz)
-> Antennas (no interaction)

Near EM field – Capacitive or inductive coupling
(low frequency 30kHz-MHz)
->coils, electrodes (strong interaction)

- Far field : Used for low/ultra low power (~µW-mW)
  - Applications (harvesting)
  - Low efficiency
  - No commercial applications
- Near Field : medium to high power app. (~mW-W-kW).
  - Medium to high efficiency
  - Commercial applications

RF EH/wireless power transfer: current trends

- Flexible inexpensive substrates (green materials) **A. Costanzo et al., IEEE Microw. Mag. 2022**
- Typically low power transmitted (regulations), low efficiency, low output voltage

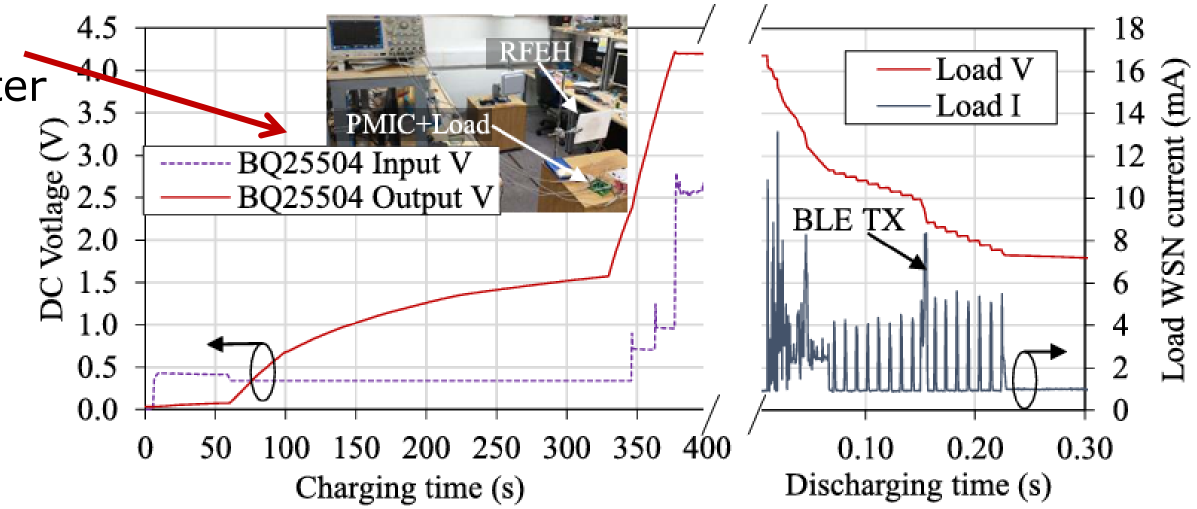


Antenna + rectifying circuits

Connection in series → Improve the output voltage

- Sub-1GHz, Sub-1μW/cm² (this is very low!)
- 36% power conversion efficiency
- From 0.2μW/cm² (a first!) → 27.5μW@1V
- 11m operation range with 1V output voltage (source 3W@915MHz)

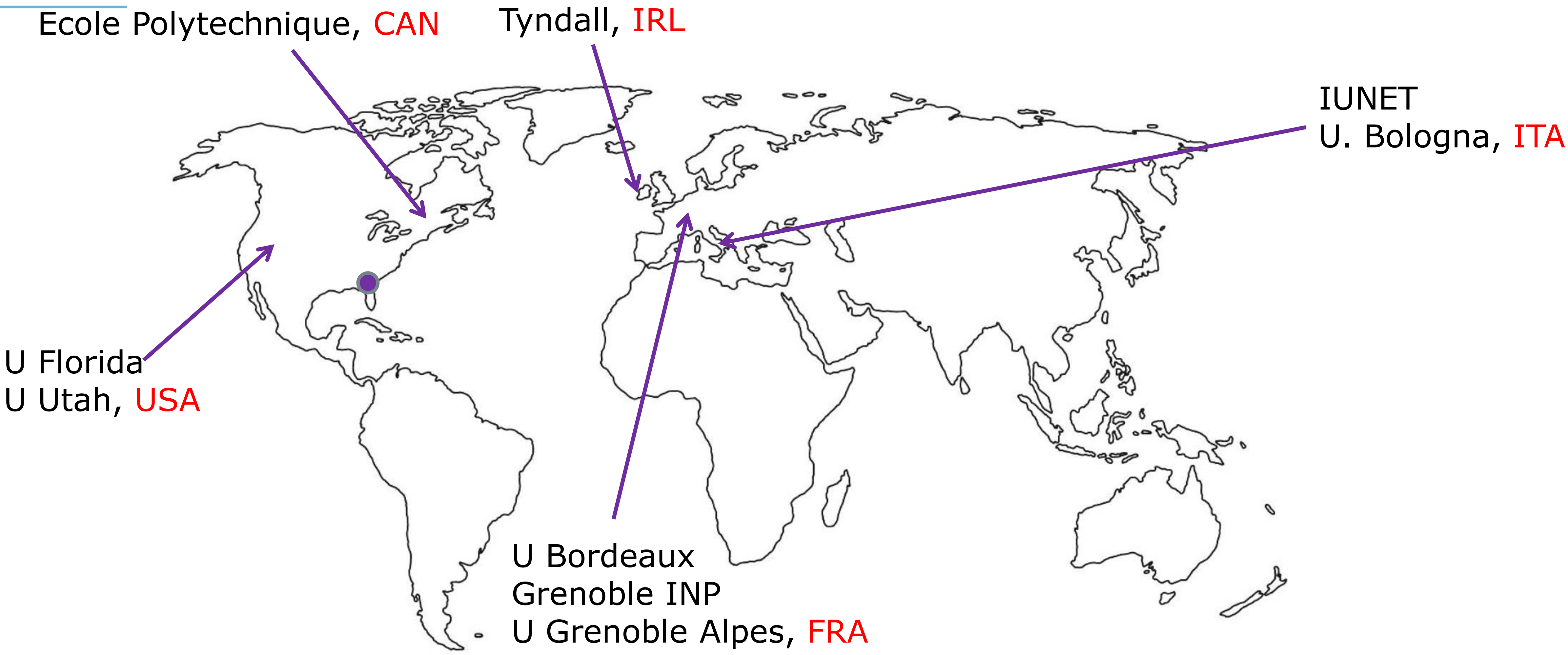
Boost converter



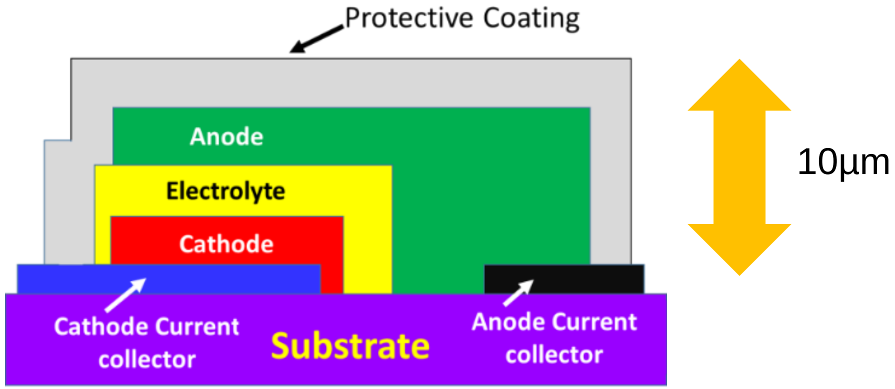
- From 0.25μW/cm² → power a low energy Bluetooth WSN

M. Wagih et al., IEEE Trans. Microw. Theory Technic., 2022

RF EH/wireless power transfer : Most active universities / RTO



Energy storage: Micro-batteries



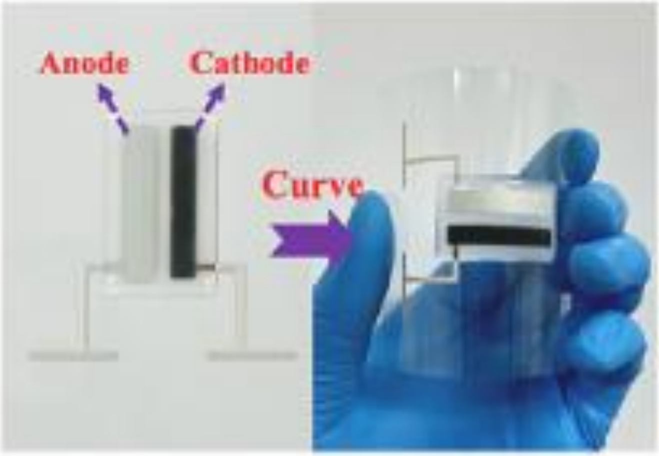
Principle :

- Electrolyte : high ion conductivity, low electronic conductivity
- Replacement of the classical liquide electrolyte → thin film
- Si integrated
- Size reduction, safer

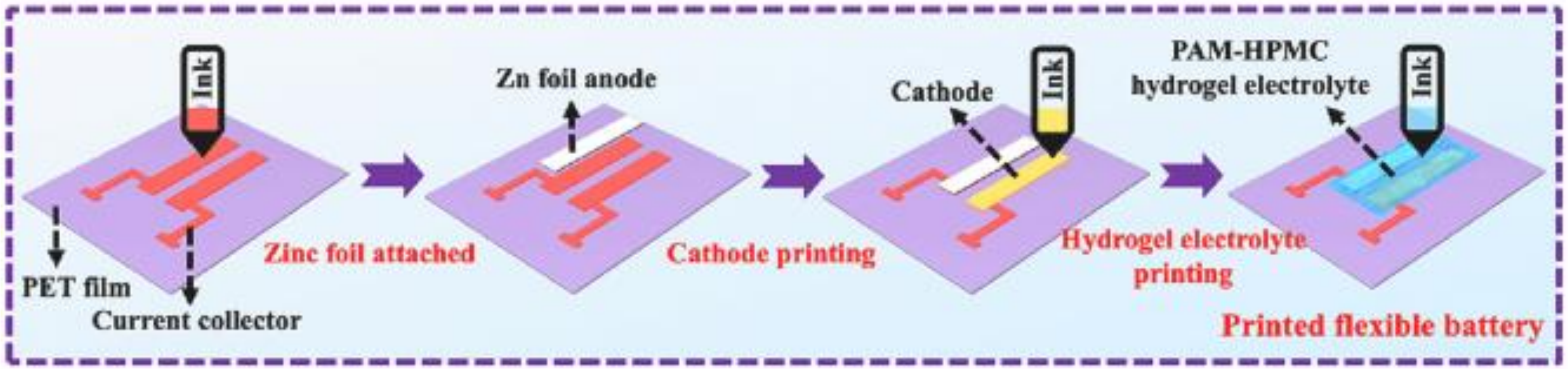
- ☐ Lithium based thin films: ~1 mWh/cm², capacity retention -> 1000 cycles
- ☐ Electrode thickness limit < ~µm
- ☐ Ionic conductivity of solid elecrolyte << liquid based (commercial)
- ☐ Thin film solid-state solutions for energy storage have existed for some years now but more energy density and higher power options at lower cost are required

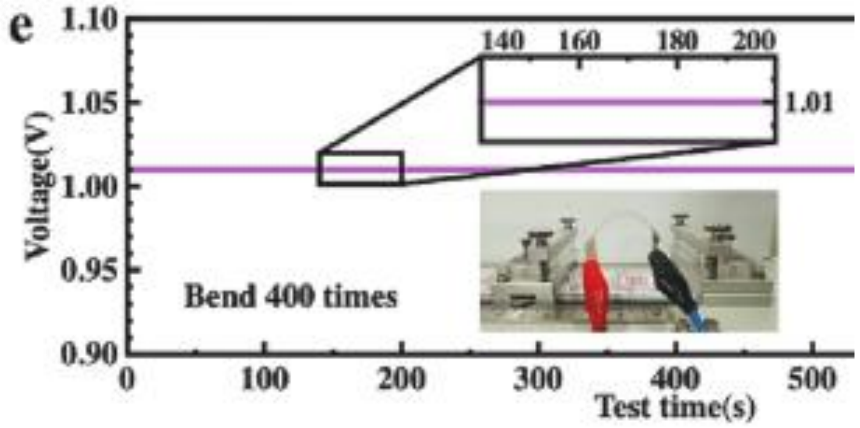
Energy storage: Micro-batteries current trends

- 3D printing : complex structures at low cost
- Fully 3D printed batteries – Chemistry work (inks)
- Hydrogel electrolyte :
  - Zinc ion (Alternatives for Li ion) : Biocompatible, abondant
  - Adjusted viscosity : Polyacrylamide- Hydroxypropyl Methylcellulose (HPMC)



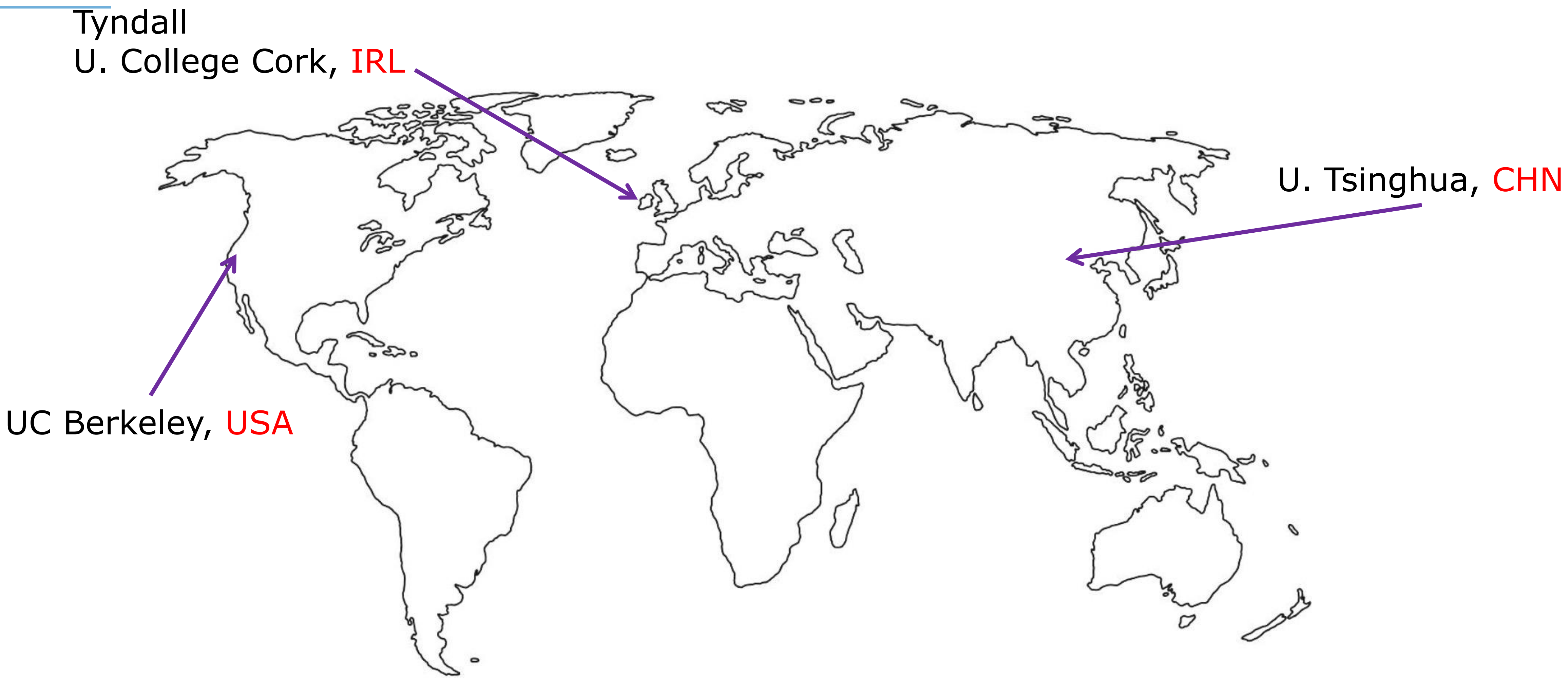
- Open circuit voltage



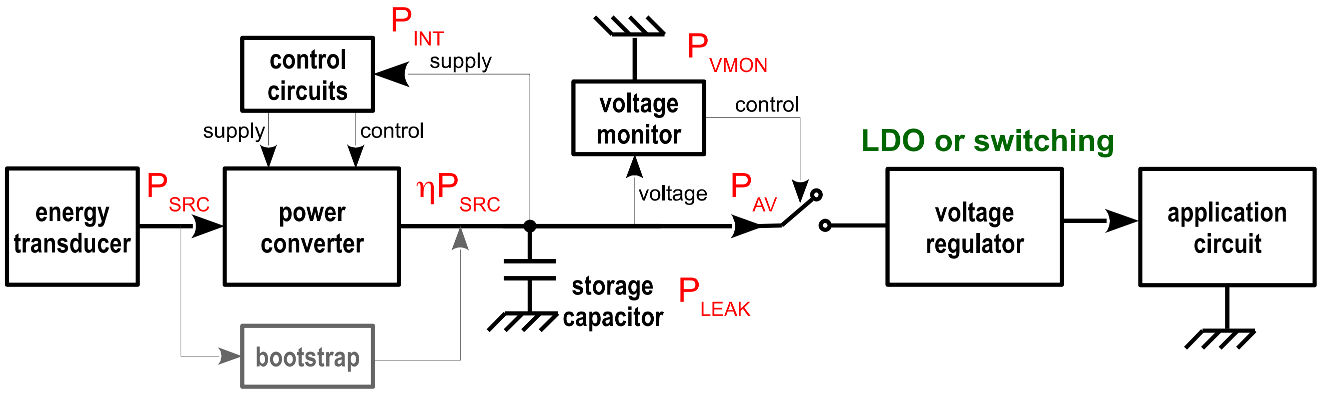


Y. Lu et al., Chem. Eng. J., 2024

Energy storage: Micro-batteries - Most active universities / RTO



Micro-power management



A. Romani et al., Computer, 2017

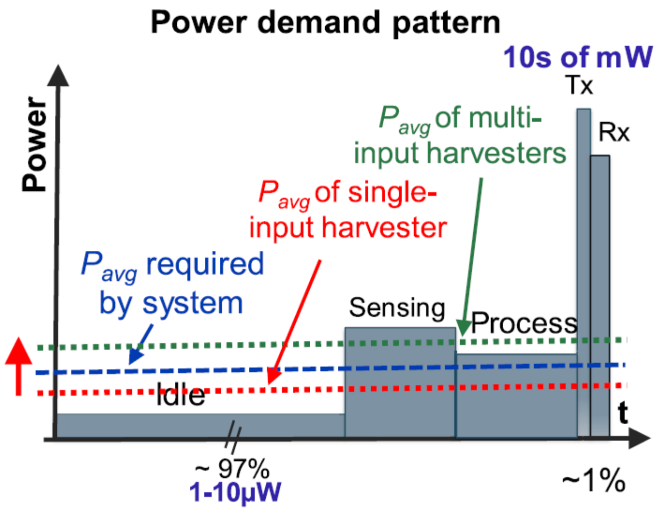
- Essential to store and deliver the harvested energy to circuits
- Must consume less than the input power
- Efficiency must be traded with self-consumption
- Should keep sources in the MPP

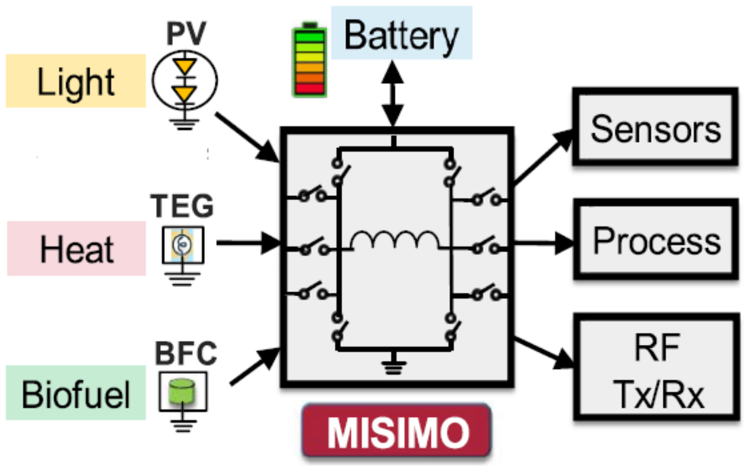
- ☐ It must be able to handle very low levels of ambient energies (1 µW).
- ☐ It must also be able to operate with near-0 voltages.

- ☐ Major silicon foundries have proposed in recent years dedicated products operating down to few µW and few hundreds mV, along with very tiny implementations requiring few components

Micro-power management: current trends

- ☐ Size reduction, increase efficiency, multiple harvesters...
- ☐ Multiple EH + Batteries, multiple out-puts
- ☐ Single inductor (DC-DC) → size reduction
- ☐ One stage → reduce losses





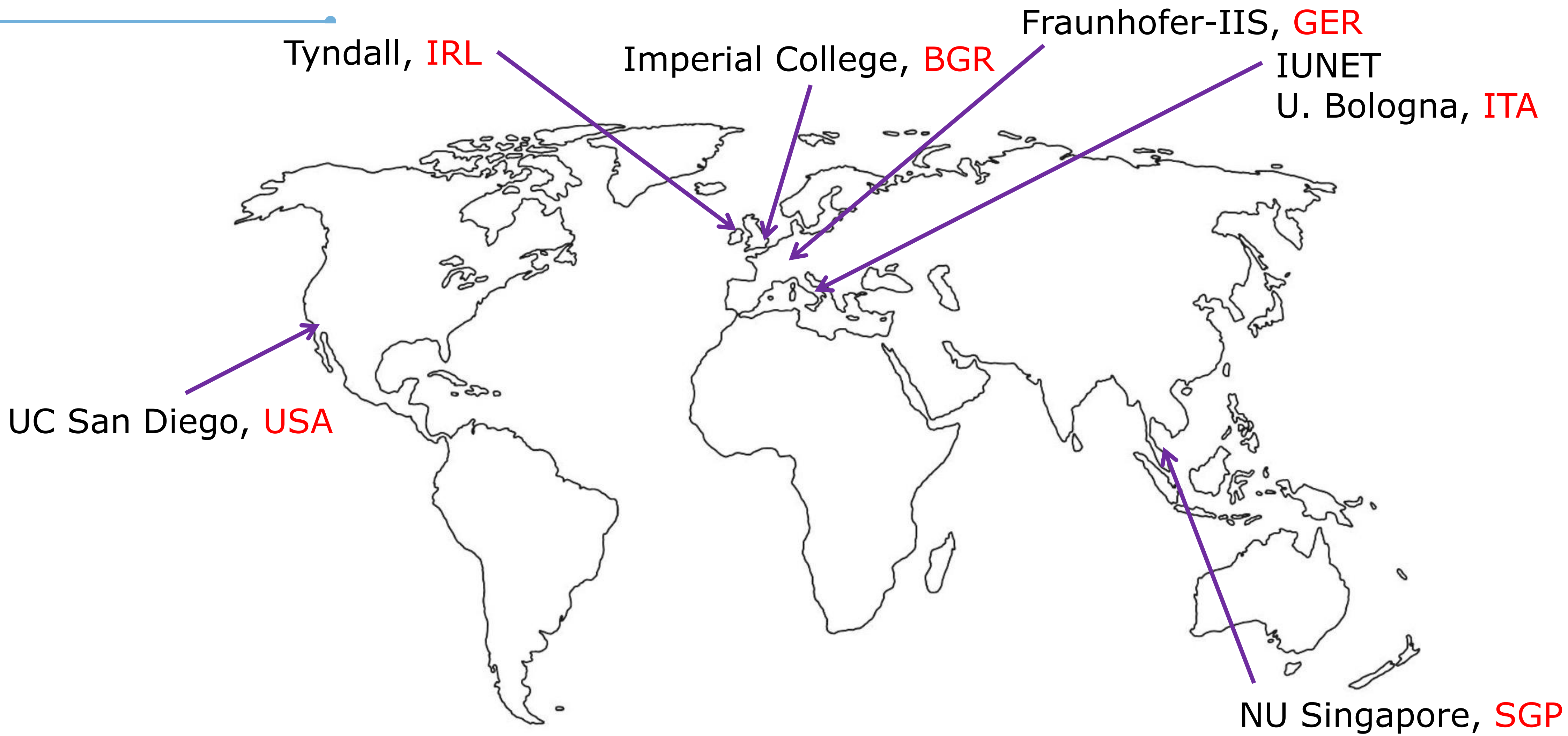
- 28-nm FDSOI
- Output power 1µW - 60mW (efficiency >69%), Vout 0.6-0.9V
- Minimum input power 262nW

S. S. Amin et al., IEEE JSSC, 2018

- 180-nm CMOS
- MMPT for piezo EH (eff.>90%)
- Output power 6µW - 60mW (efficiency >70%), Vout 0.6-1.8V

S. Chamanian et al., IEEE SSCL, 2022

Micro-power management : Most active universities / RTO



Summary

- The improvement of the EH performance/efficiency is as important as the development of “green” materials. Replacing toxic/rare materials used nowadays (lead based piezoelectrics, Bi_2Te_3 for thermoelectrics, NdFeB - neodymium, for electromagnetic conversion).
- The materials should be also from sustainable sources and their life cycle energy and carbon footprint need to be minimized.
- The use of nanotechnologies is foreseen to increase the performance of all the concepts in general.
- Flexible and low cost approaches for wearable applications (i.e. e-health) should be developed as well.
- The comprehensive system design combining all aspects of the fabrication process, harvester structure, power conversion circuits and storage will be the potential solution for increasing the power generation efficiency.

Impact for Europe : International cooperation

- To optimize system-level performance, there is need to collaborative development between all the stakeholders. Agree on common specifications and methodologies to ensure standardization and inter-operability.
- Innovation in Europe is strong in sustainability, flexible integration, micropower management among others.
- Europe have gaps in high volume manufacturing, advance packaging and system integration, high development cost, fragmented markets, lack of dedicated multi-physics tools → International cooperation:
- U.S, Japan, Taiwan : More than Moore technologies, heterogeneous integration, advanced packaging, reduced prototyping cost.
- Republic of Korea (materials) , Singapore (advance packaging) and India (design skills and workforce scaling)
- New knowledge for disruptive technologies, emerging technology for new markets
- Speed up technological innovation.

Impact for industry

- International cooperation will accelerate Europe’s technological and industrial competitiveness.
- A general limitation towards industrial adoption of Energy Harvesting is its reliance on environmental conditions. Developing a combination of Energy Harvesting combined with on-demand charging of the device could help solving this issue.
- Development of environmentally friendly (avoid critical) materials
- Develop low-cost manufacturing processes (e.g. roll to roll printing on flexibles)
- CMOS compatibility, cost reduction.
- The development of autonomous sensors will impact the industry (different applications):
  - Remote healthcare: We will require wireless and autonomous sensors (powered by body heat, mechanical movements).
  - Extensive industry automation (robotics) is inevitable in the near future. This will require hundreds and thousand of sensors
  - Avionics is expected to be one of the first industries to adopt thermal energy harvesters.

Acknowledgments

International Roadmap for Devices and Systems

MORE THAN MOORE WHITE PAPER

Energy Harvesting team

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