ESSERC 2024

SiNANO-ICOS-INPACE Workshop

"Emerging technologies in Advanced Computation, Advanced Functionalities, Ground-breaking Technologies: Impact on International Cooperation"

Energy harvesting for autonomous systems

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Outline

- Introduction
- Energy harvesting technologies (IEEE-IRDS)
  - Main technologies, trends, challenges, examples
- Conclusions and perspectives

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IRDS International Roadmap for Devices and Systems™

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Energy Harvesting

INTRODUCTION

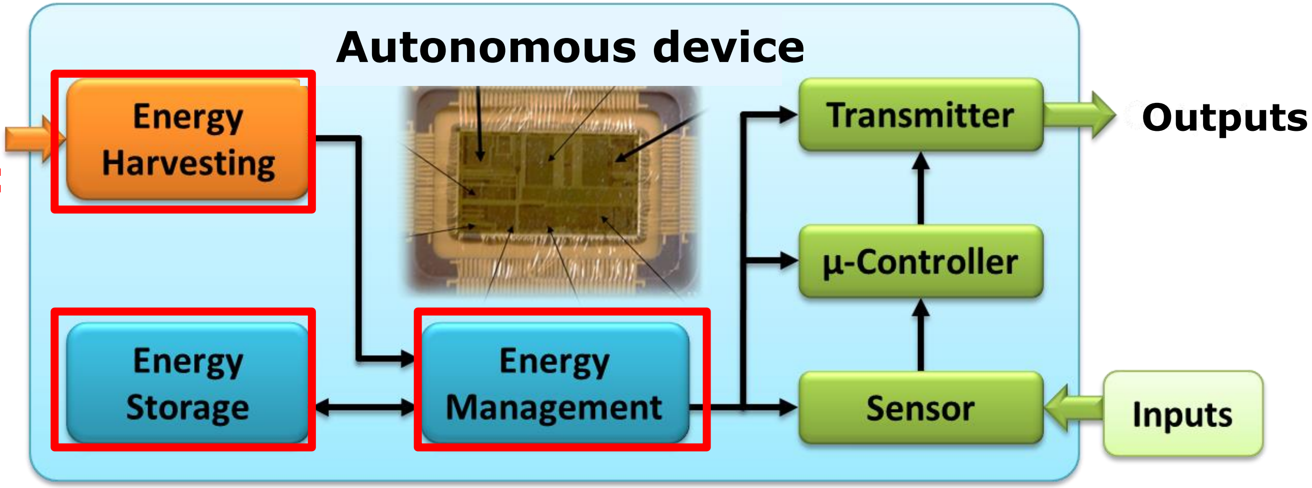
Introduction

- Market growth on connected devices : IoT (estimated 40 billion devices by 2025), healthcare, wearables, home automation…

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

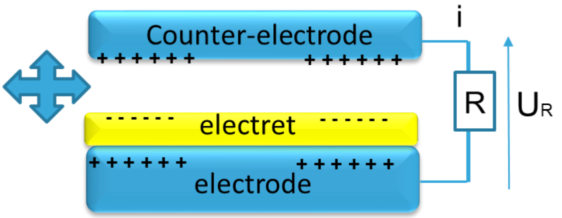
- EH is important in applications with specific requirements : simple battery is not enough, cords would increase the cost / complexity, too many devices, harsh environment, implants…

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

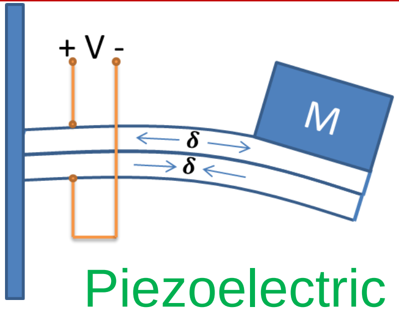


Introduction: Technologies covered so far…

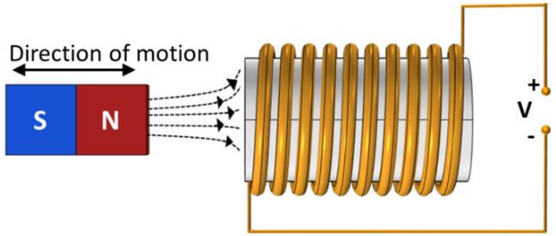
Mechanical EH



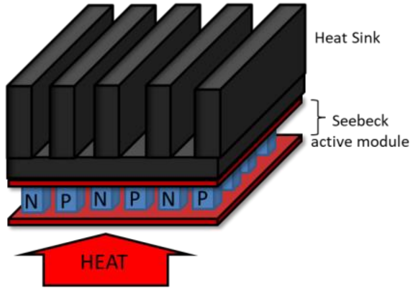
Electrostatic



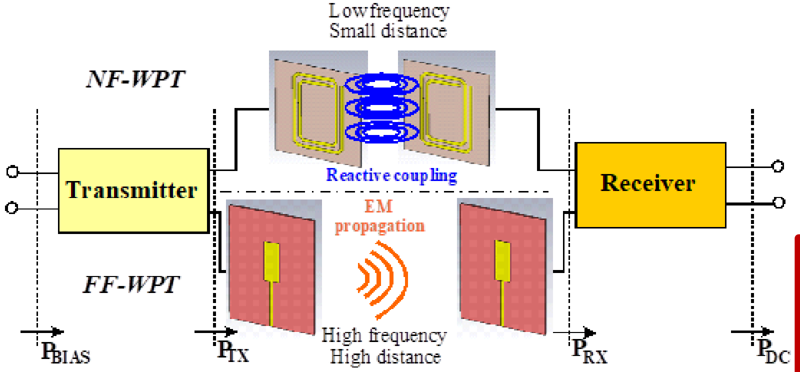
Piezoelectric



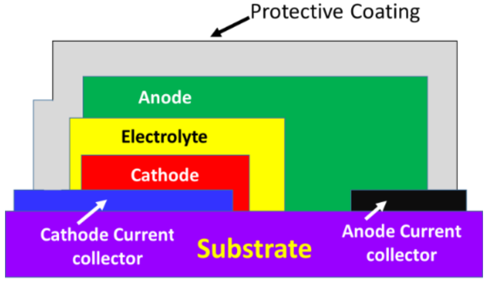
Electromagnetic



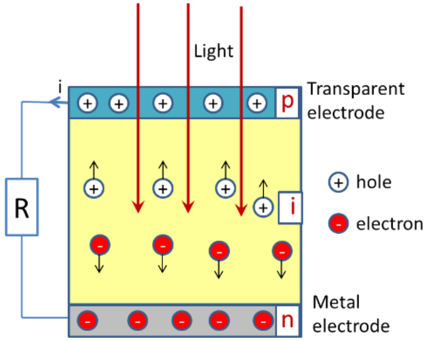
Thermal EH



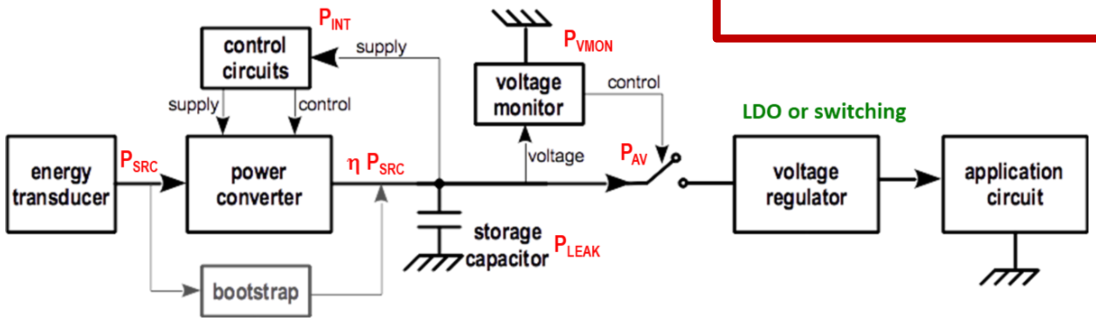
RF EH / wireless power transfer



Energy storage (µbatteries)



Solar EH

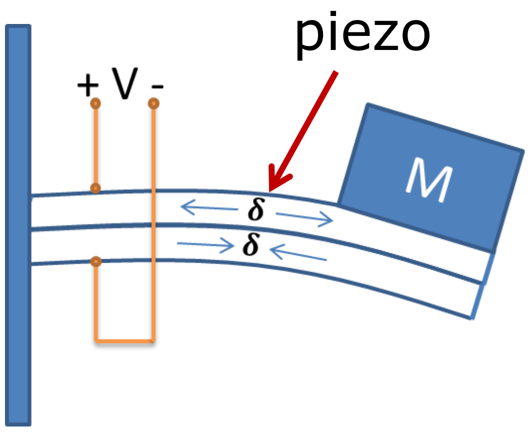


Micro power management

Energy harvesting technologies

Mechanical EH : Piezoelectric conversion

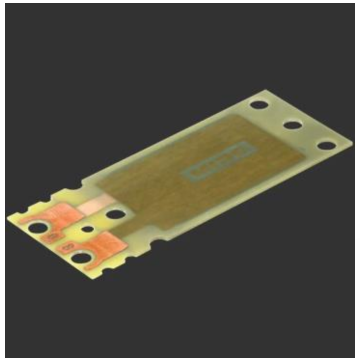
- Harvesting principle based on mechanical resonators
- Applications are linked to mechanical vibrations harvesting (movements)



- 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)

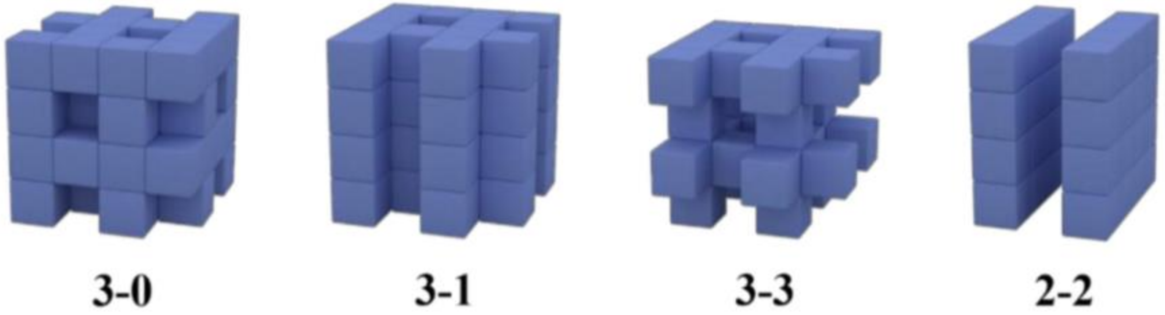


TE Connectivity (PVDF)

- 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

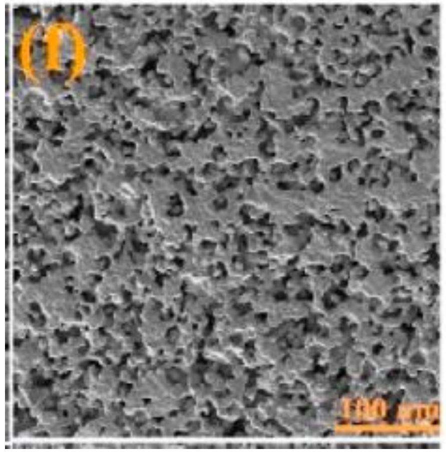
Mechanical EH : Piezoelectric conversion
Current trends : Porous materials (1/2)

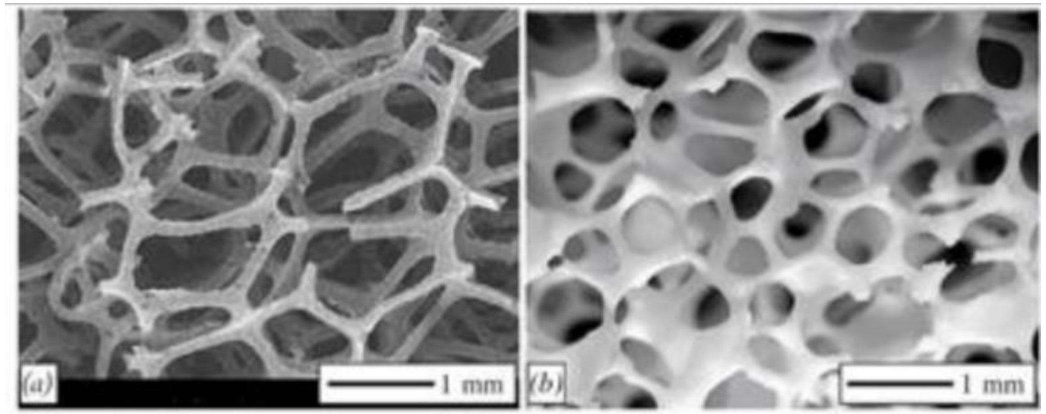
- Different types of porous materials and techniques to fabricate them…



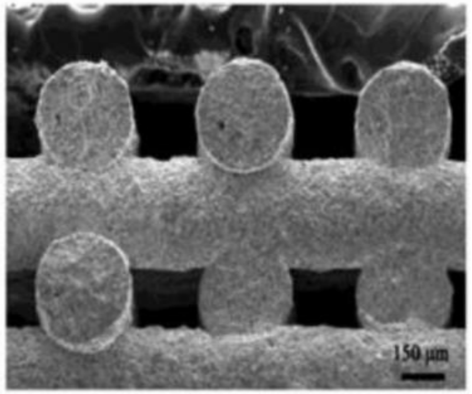
X. Zhou et al., Nanoenergy Advances 2022

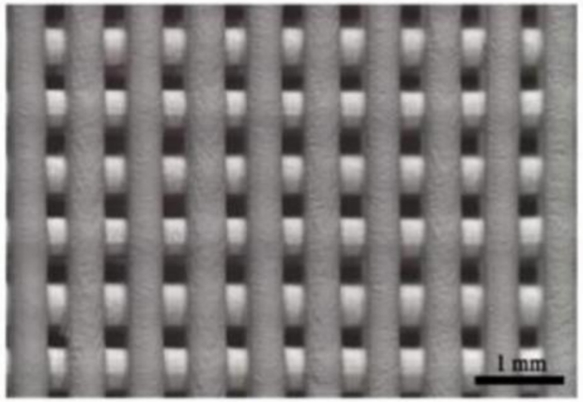
Burnt-Out Polymer Spheres (BURPS)





Replica template





Additive manufacturing (inks): innovative, most promising technology

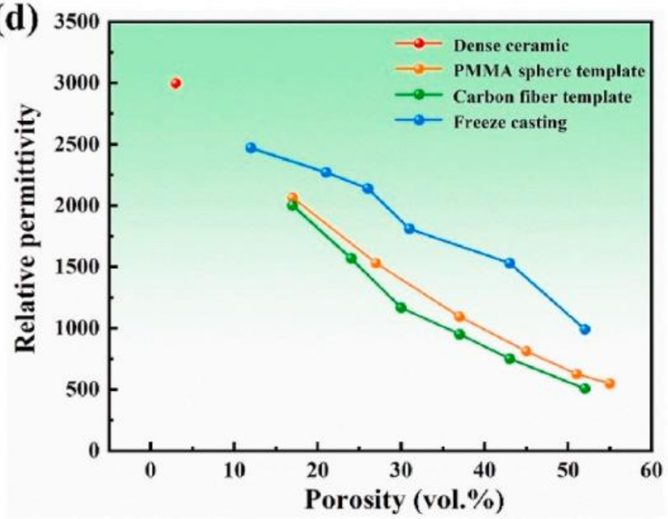
Mechanical EH : Piezoelectric conversion
Current trends : Porous materials (2/2)

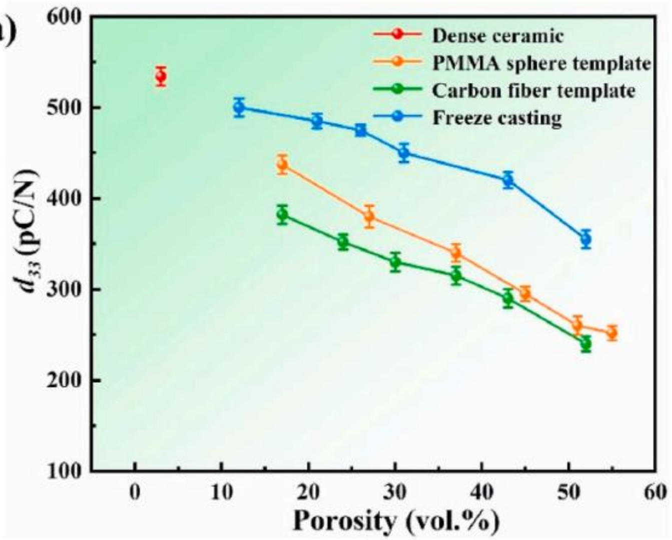
X. Zhou et al., Nanoenergy Advances 2022

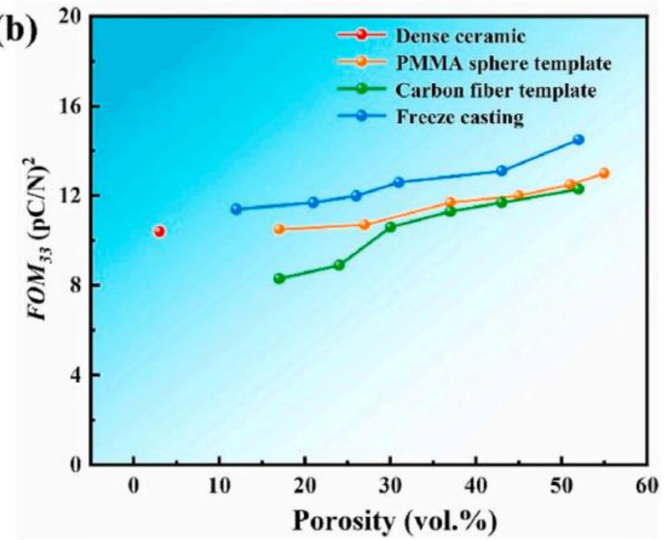
Piezoelectric coeff.

$$FOM = \frac{d_{33}^2}{\varepsilon_0 \varepsilon_{33}}$$

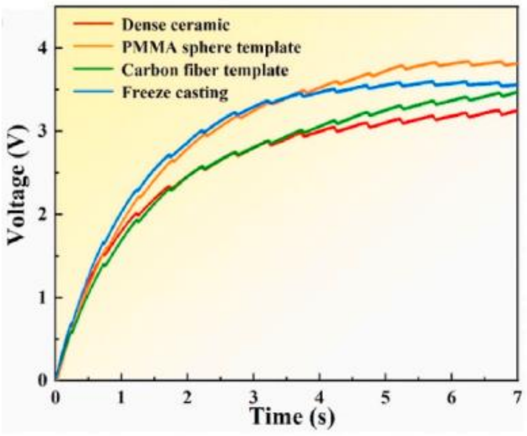
Permittivity

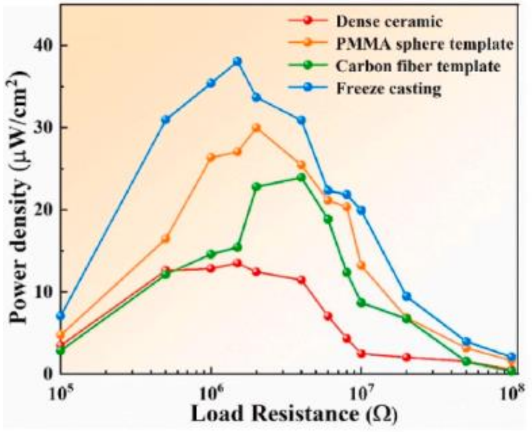






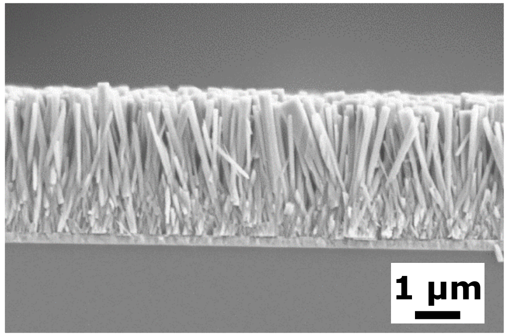
- ☐ Reduced permittivity and piezo coefficient
- ☐ Higher FOM
- ☐ Increased voltage stored in a capacitor
- ☐ Increased optimal power (for a given resistive load)
- ☐ Low cost





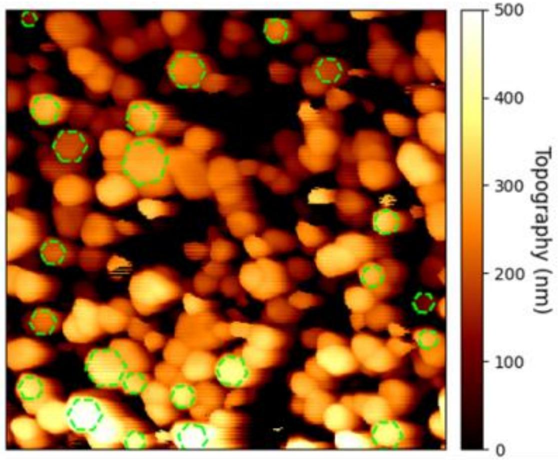
Mechanical EH : Piezoelectric conversion
Current trends : Nanostructuring - Nanowires

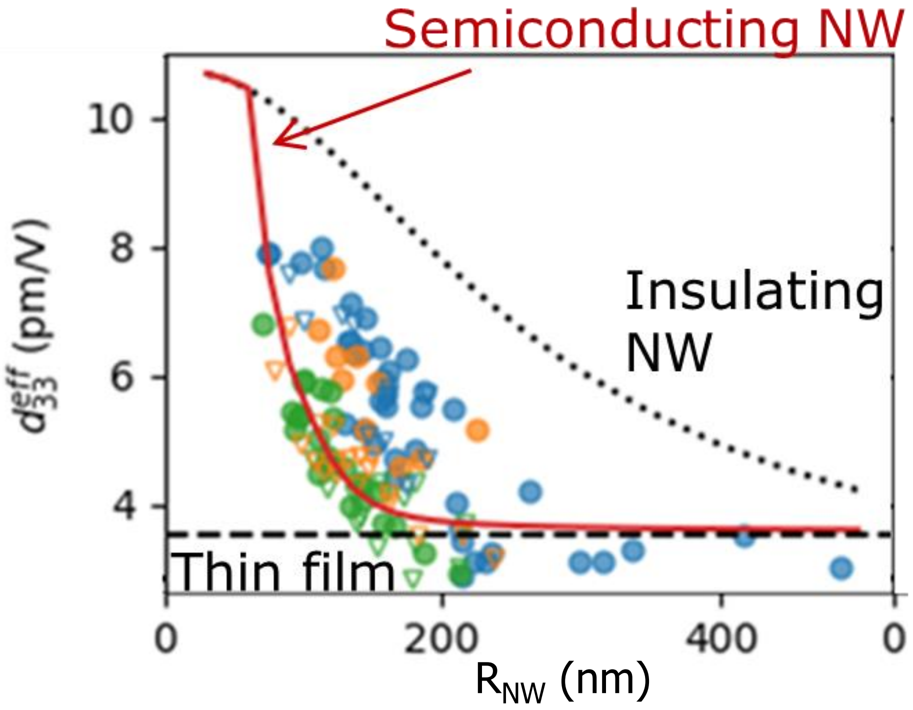
- ZnO NWs (biocompatible, abondant) as replacement of lead-based materials
- Characterization: Piezoelectric Force Microscopy (PFM)



3µm long, 200nm wide

ZnO NWs (CBD)





croma

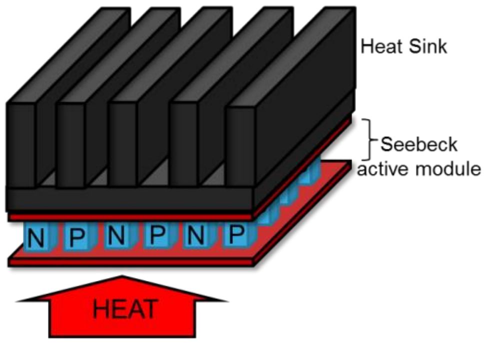
Simulation parameters (CBD):

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

T. Jalabert et al., Nanotechnology 2023

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

Thermal EH

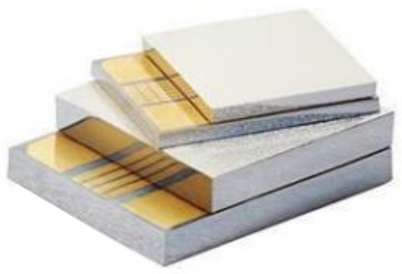


- Principle

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

Main parameter : zT=σS²T/κ. 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

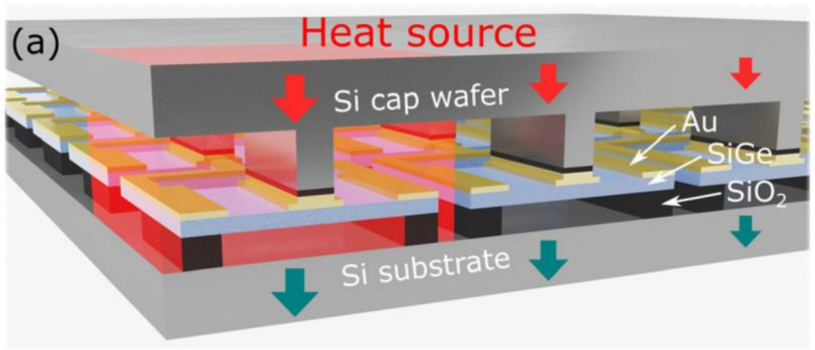
- ☐ Power proportional to available temperature gradient
- ☐ Fast thermalization (need for a big heat sink)
- ☐ Non-flexible
- ☐ Bi_2Te_3 : Expensive/rare/toxic material/incompatible with CMOS

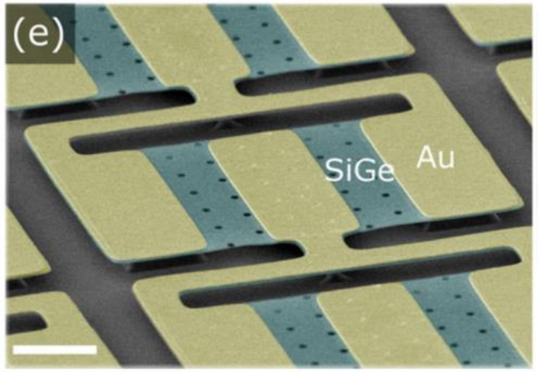
Book: H. Akinaga et al., Thermoelectric Micro/Nano Generators, Wiley 2023

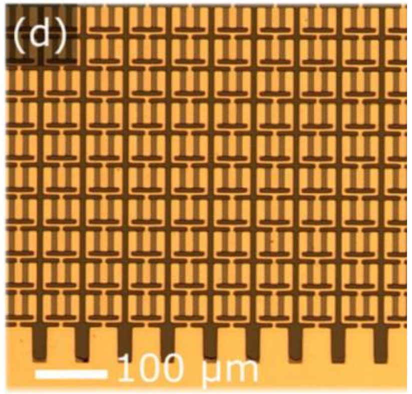
Thermal EH
Current trends : Si, SiGe and Nanostructuration

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

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

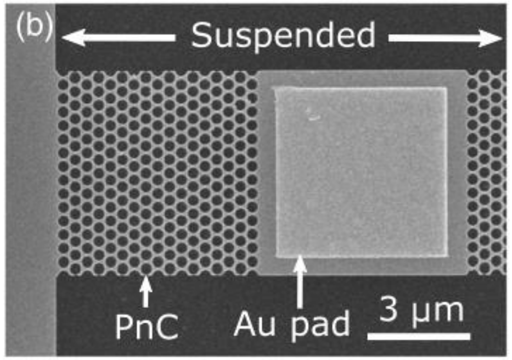


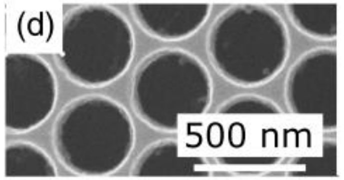




SiGe thin films (lower κ)

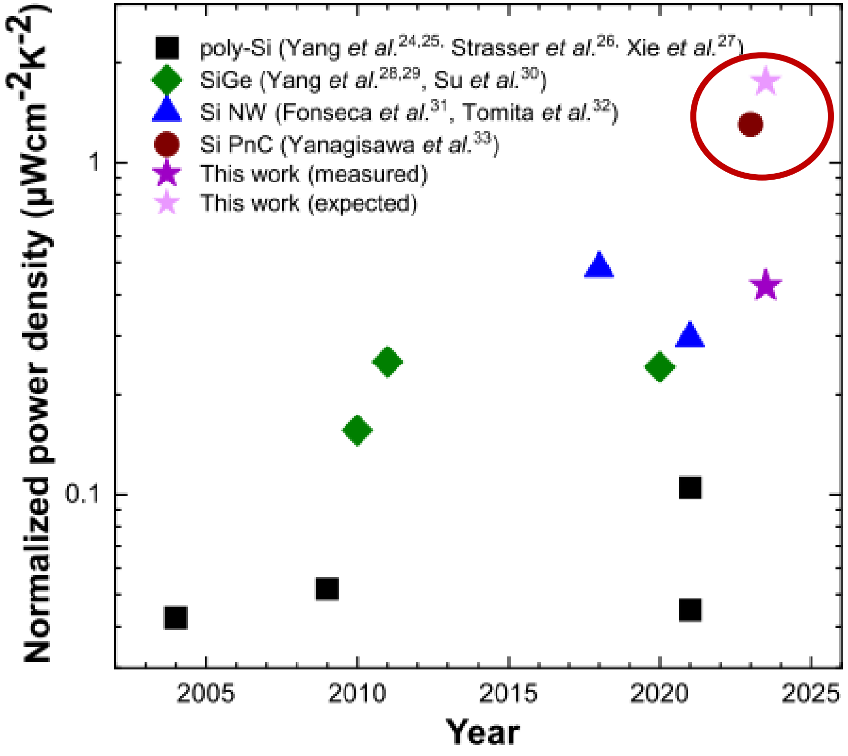
S. Koike, T. Mori et al., APL, 2024





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

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



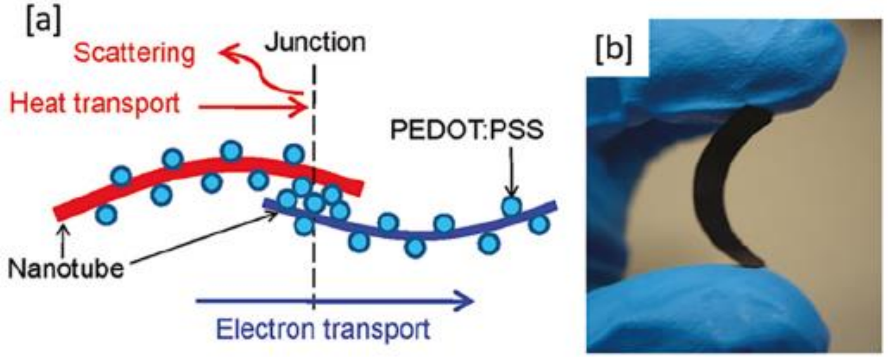
S. Koike, T. Mori et al., APL, 2024

Thermal EH

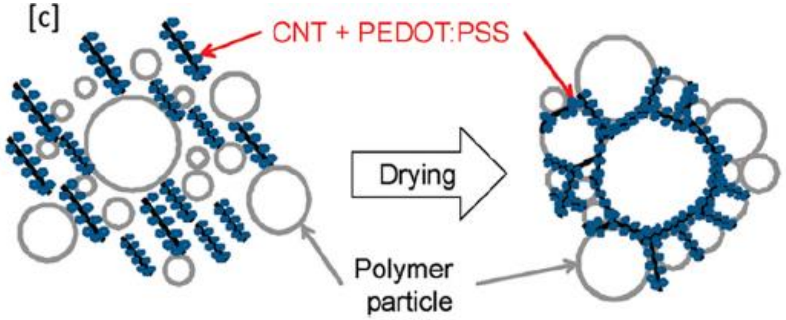
Current trends : Organic materials (Flexible)

- Advantages : Low κ, low cost, flexible, eco-friendly, roll to roll production (wearables)
- Inconvenients : Low zT, typically low σ
- Possible solution: Composites (CNT…) ⟶ adjust properties

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



C. Yu et al., ACS Nano 2011

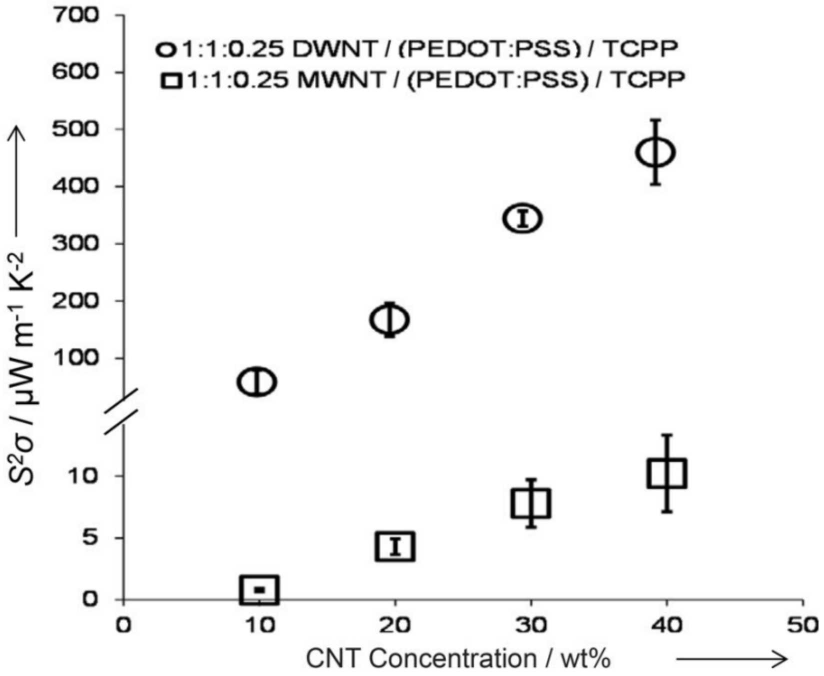


D. Kim et al., ACS Nano 2009

PEDOT:PSS : stabilize and disperse CNTs in aqueous solution, <u>Increase σ</u>

Polymer (TCPP): stabilize CNTs

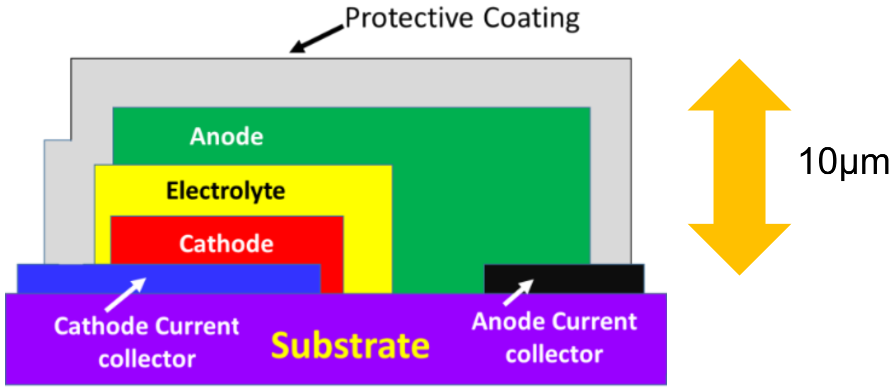
zT ~ 0.39



G. P. Moriarty et al., Energy Tech. 2013

Review: N. Nandihalli, T. Mori et al., Nano Energy, 2020

Energy storage: Micro-batteries

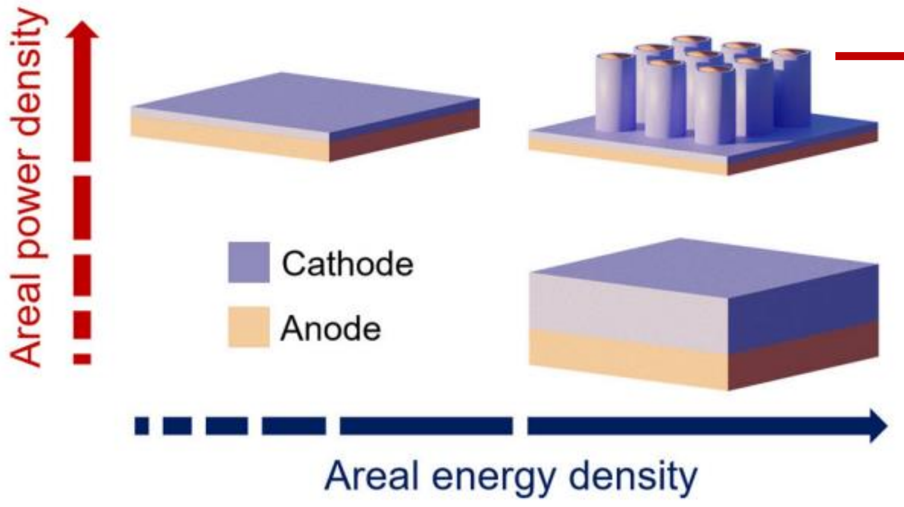


Principle :
- Electrolyte : high ion conductivity, low electronic conductivity
- Replacement of the classical liquide electrolyte ⟶ thin film
- Si integrated
- Size reduction, safer

- ☐ Lithium based thin films on Si: ~5 mWh/cm^2, 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 structuration (Si-based)

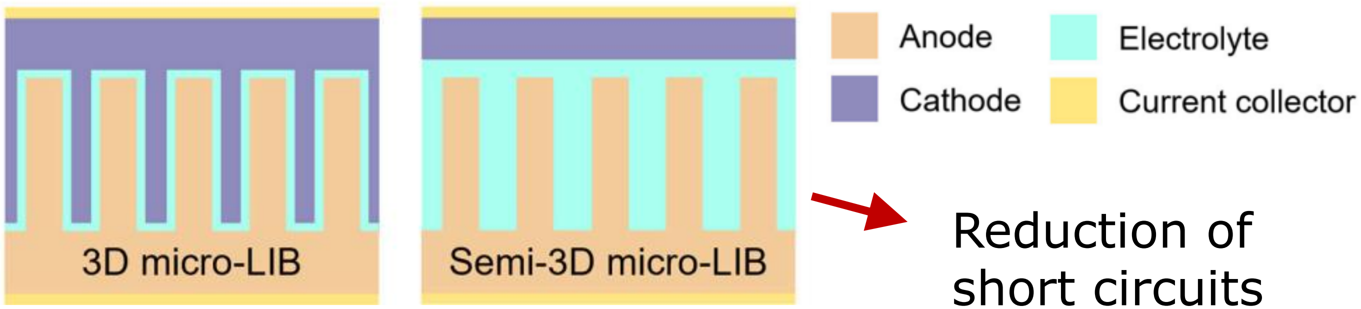
- Design of 3D Si anode – based µbatteries



- Thicker electrodes : distance of traveling of ions increases → reduction of power.
- Film delamination

Review: A. Deatama Refino et al., Comm. Mat., 2024

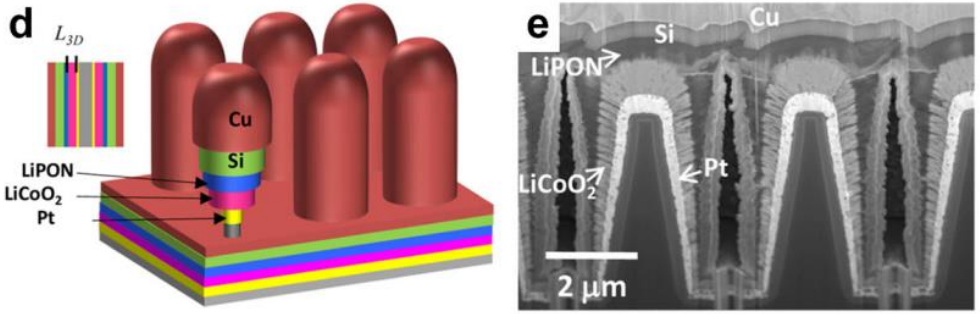
- 3D and semi-3D structures



Coaxial

→ Reduction of short circuits

Example of a co-axial structure



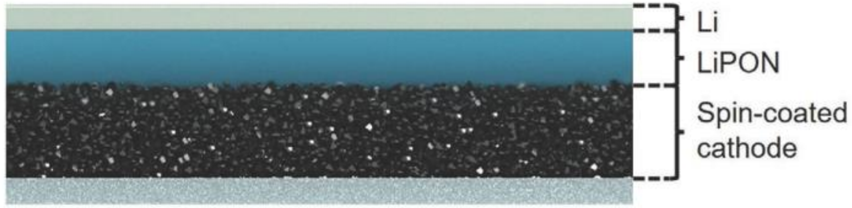
A. A. Talin et al., ACS Appl. Mater. Interfaces, 2016

Perspectives : Work on reliability and packaging.

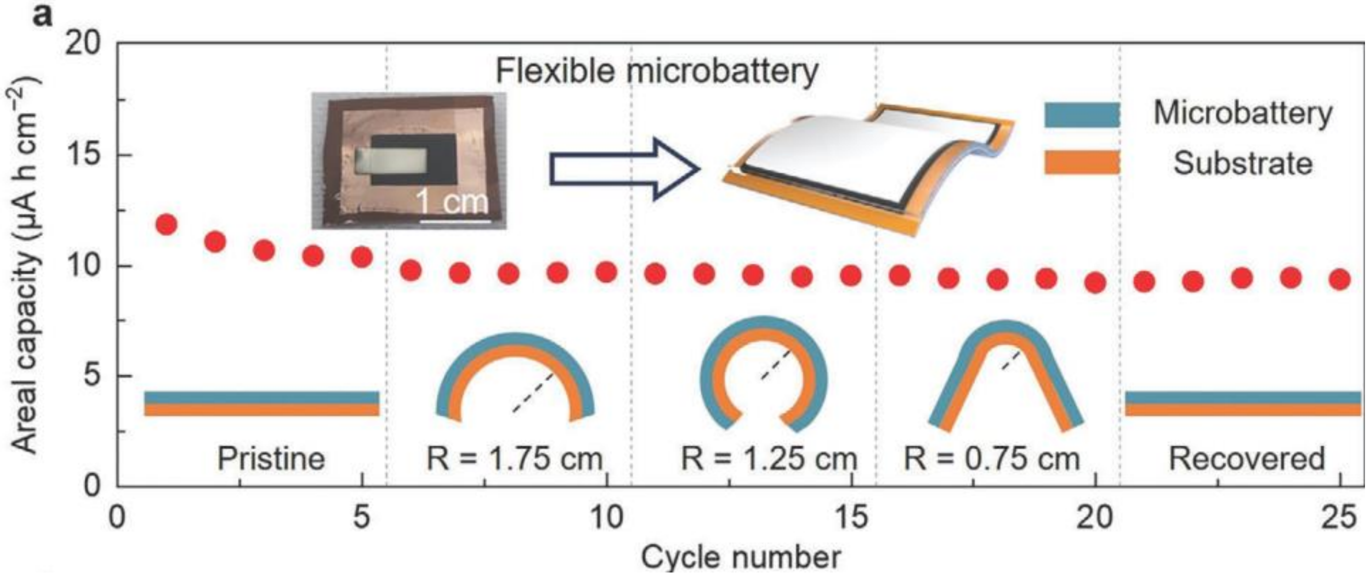
Energy storage: Micro-batteries

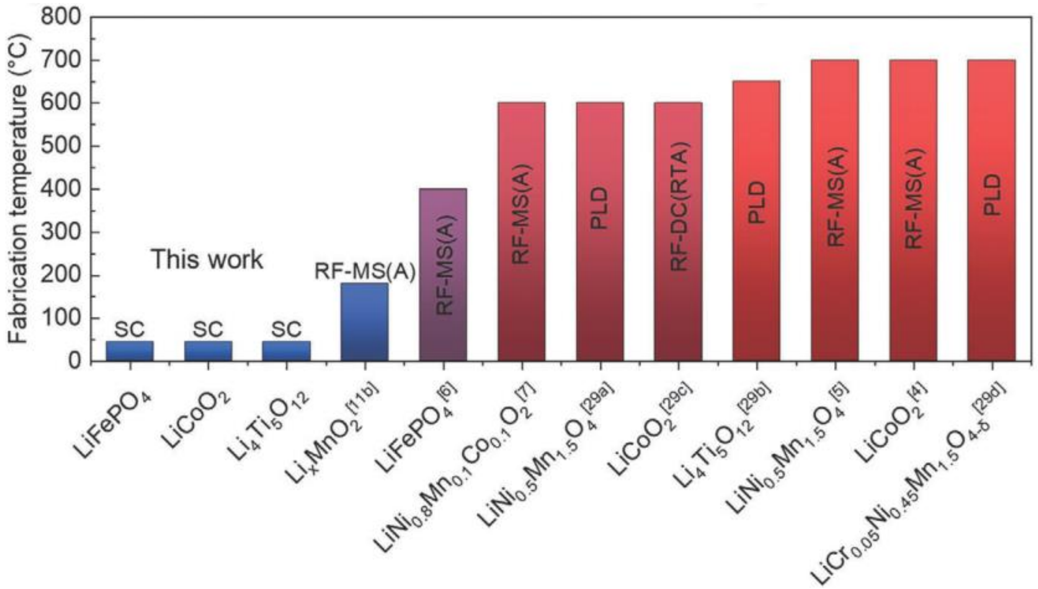
Current trends : Low temperature fabrication

- Low temperature fabrication : spin coating of Lithium Oxide electrodes (~45°C).
- Mixture of cathode powders + PVDF
- Compatible with flexible substrates (polyimide here)
- Rest of the structure by Sputtering + Evap



Cross section



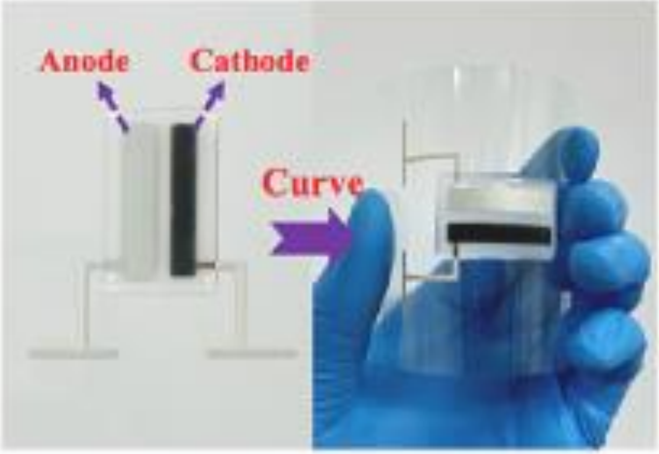


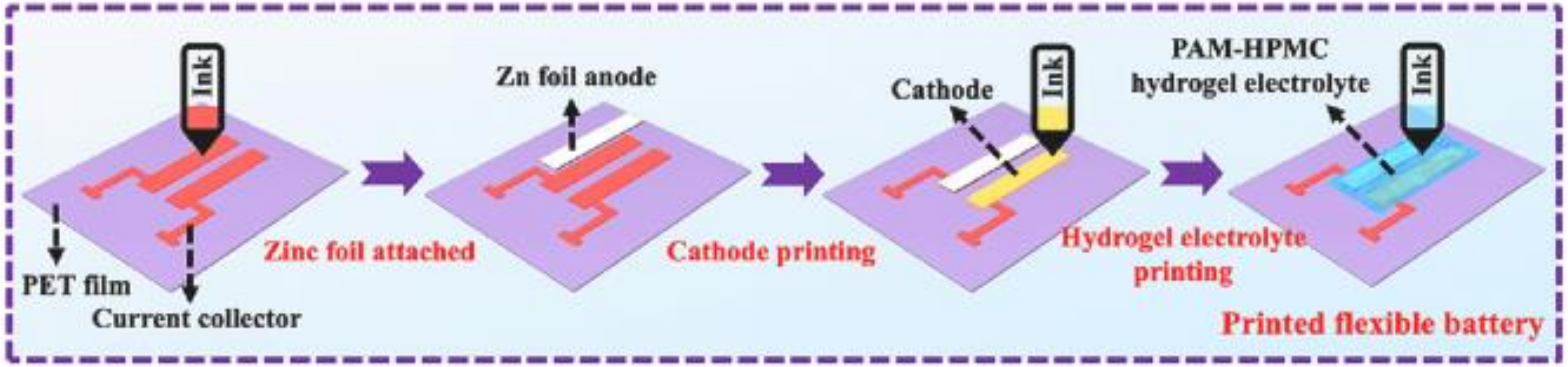
- Low capacity degradation during bending tests

B. Ke et al., Adv. Energy Mat., 2024

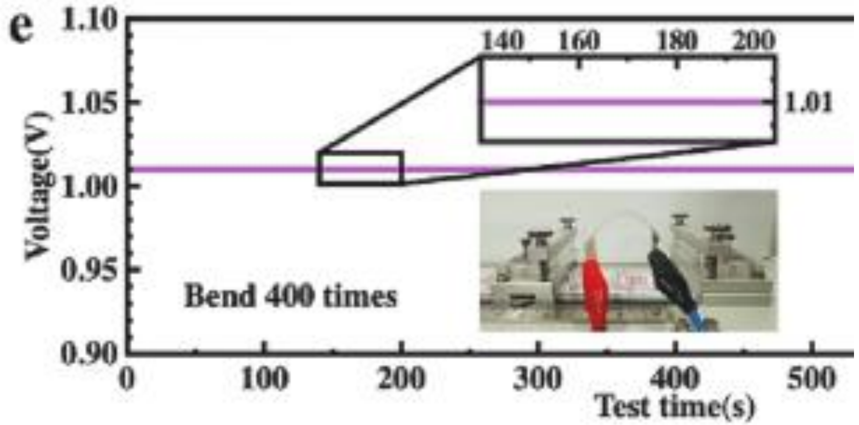
Energy storage: Micro-batteries
Current trends : 3D printing technologies

- 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

Conclusions and perspectives

- 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).
- 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.

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Acknowledgments

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https://irds.ieee.org/editions/2022

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Thank you for your attention !