Program

	Monday 4 Ocrobre		Tuesday 05 October
8:15-8:30			Welcome
8:30-9:45		S3	**Christophe COUTANCEAU**
8:45-9:00			"Clean hydrogen production from electron-reforming of oxygenated organic compounds"
9:00-9:15			
9:15-9:30			**Perspectives Atelier #3**
9:30-9:45			~45min Energy Conversion
9:45-10:00			#
10:00-10:15			~30 min Round Table #3
10:15-10:30			#
10:30-10:45			Coffee break/posters
10:45-11:00			
11:00-11:15		S4	Prix These 2020
11:15-11:30			**Claudia de Melo SANCHEZ**
11:30-11:45			Prix These2021
11:45-12:00			**Zhelu HU**
12:00-12:15			Prix These 2021
12:15-12:30			**Giulia LOMBARDI**

Invited talk
Pr. Christophe Coutanceau

IC2MP Université de Poitiers

Clean hydrogen production from electron-reforming of oxygenated organic compunds

GDR NAME – Workshop Group 3 “energy conversion”

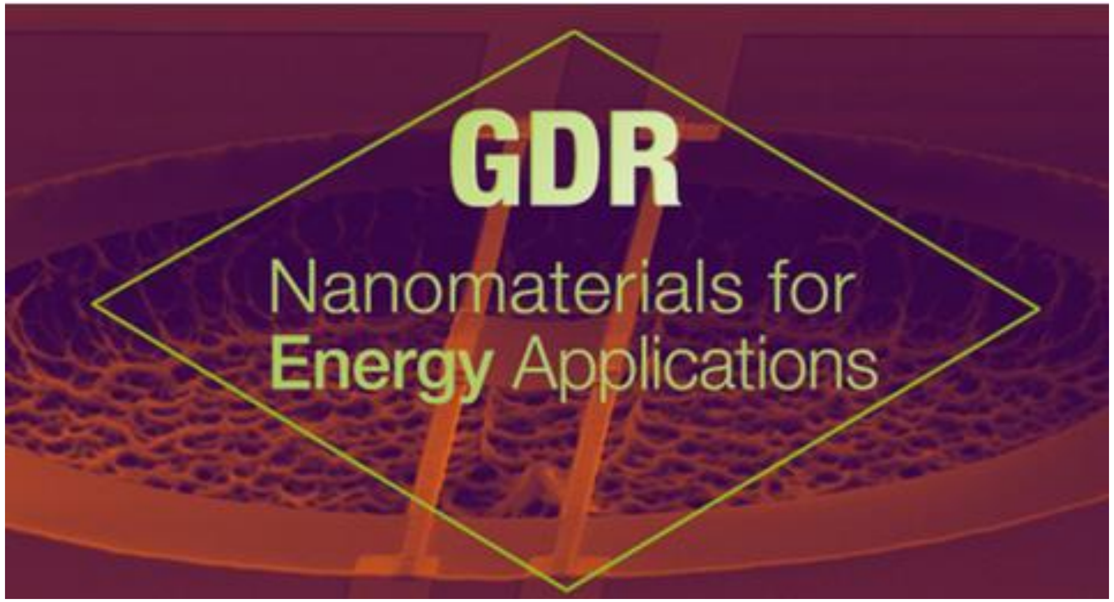
Co-chairs:

<u>Guylaine Poulin-Vittrant</u>, **<u>Nicolas Stein</u>**, Paolo Bondavalli, Romain Bachelet

Participants:

Rodolphe Vaillon, Andrea Cattoni, Philippe Basset, Bruno Fabre, Jérôme Saint-Martin, Guillaume Savelli, Sylvie Hébert, Sawako Nakamae, Christophe Coutanceau, Marian Chatenet, Maria Tchernycheva, Noëlle Gogneau, Gustavo Ardila, Vincent Consonni, Mohamed Amara, Guillaume Nataf, Michel Devel

Focus on Perspectives



N A M e

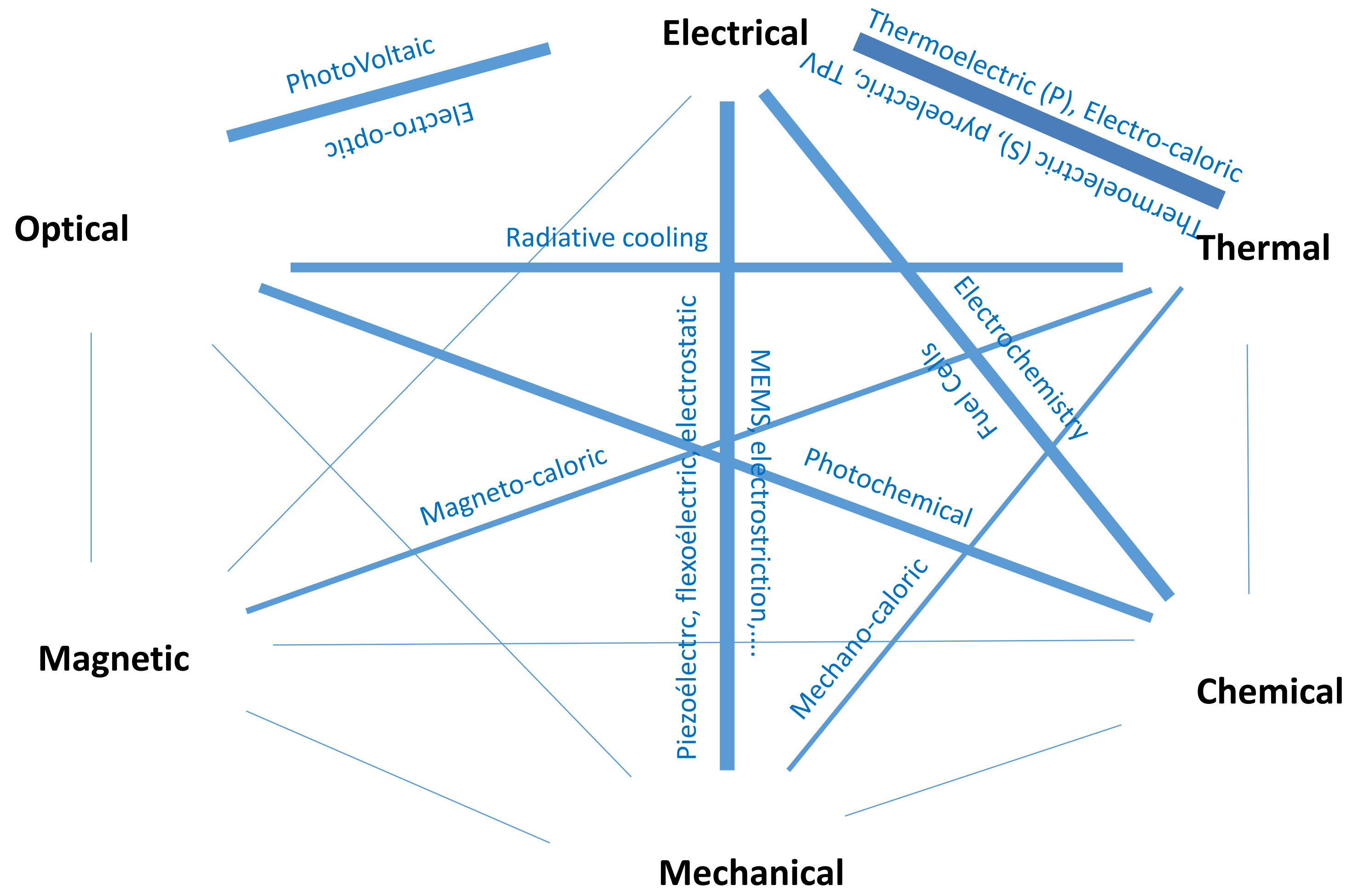
GDR Nanomaterials for Energy Applications

GDR2086

Plenaries October 4-6, 2021 – ESIEE Paris

- **Perspectives** (our definition!)
  - Emerging tendency / potential in each sub-thematic of conversion energy
  - Challenges and how to overcome them
  - Identification of the lacks/strengths of the community

Energy conversion overview!



>15 possible conversions or couplings!

Conversions

1. Thermal ⬄ Electric

1.1. Pyroelectricity et (electro)caloric effect (*Romain Bachelet* & ***Guillaume Nataf***)
1.2. Thermoelectricity (***Nicolas Stein***)
1.3. Radiative thermoelectric & Thermo-photovoltaic (***Rodolphe Vaillon***)
1.4. Thermionic (***Mohamed Amara***)

2. Optical ⬄ Electric

2.1. Photovoltaic **(*Andrea Cattoni*)**
2.2. Light Emitting Diodes (*Maria Tchernycheva*) not present

3. Chemical ⬄ Electric

3.1. Photo-electrochemical (*Bruno Fabre*) not present
3.2. Fuel cells (*Christophe Coutanceau*) done !

4. Mechanical ⬄ Electric

4.1. Piezo/flexo-electric **(*Guylaine Poulin-Vittrant*)**
4.2. Electrostatic (*Philippe Basset*)

5. Hybrides/multiples

5.1. Thermionic - TPV (*Rodolphe Vaillon*)
5.2. Piezo-pyro-tribo-photo-electric (Guylaine Poulin-Vittrant **,***Romain Bachelet*)

1. Thermal ⇔ Electric

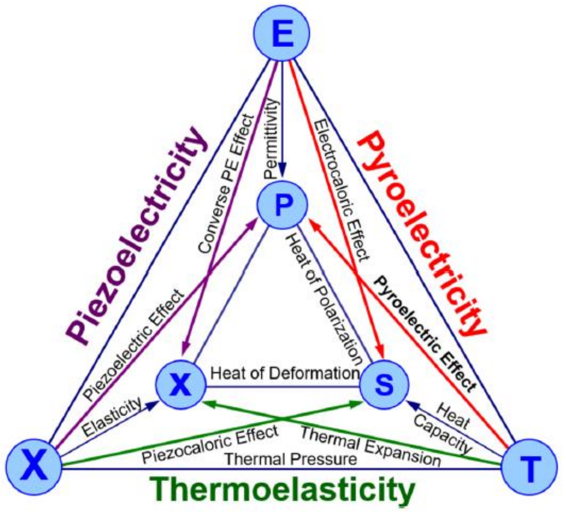
Romain Bachelet	INL, EC Lyon, CNRS
Paolo Bondavalli	ThalesGroup
Sylvie Hébert	CRISMAT, ENSICAEN, CNRS
Sawako Nakamae	SPEC/IRAMIS/CEA, CNRS
Jérôme Saint Martin	C2N, université Paris Saclay, CNRS
Guillaume Savelli	LITEN, CEA
Nicolas Stein	IJL, université de Lorraine, CNRS
Rodolphe Vaillon	IES, université de Montpellier, CNRS
Mohamed Amara	INSA de Lyon, CNRS
Guillaume Nataf	GREMAN, université de Tours, CNRS

Pyroelectrics

APL Materials RESEARCH UPDATE scitation.org/journal/apm

Pyroelectric thin films—Past, present, and future

G. Velarde *et al.*, APL Mater. **9**, 010702 (2021)



New high FoM lead-free materials

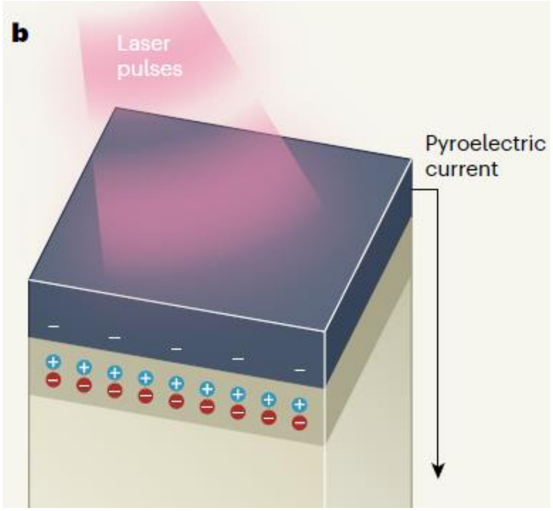
<u>See reviews</u>:
[Alpay, MRS Bulletin (2014)]
[Bowen, En. Env. Sci. (2015)]

Non-Linear Materials Employed in Ericsson Cycle

Material[b]	Type[c]	Q_{ECE}	E_1	c'	T	W_{cycle}[a]	η_{Carnot}	$\eta_{Eric}/\eta_{Carnot}$	Ref.
		MJ m^{-3}	MV m^{-1}	MJ m^{-3}K^{-1}	°C	kJ m^{-3}			
0.95PST-0.05PSS	C	4.2	2.5	2.5	−5	154	3.7%	14%	30
0.90PMN-0.1PT	C	1.4	3.5	2.5	30	45	3.2%	5%	23
0.75PMN-0.25PT	X (111)	3.2	2.5	2.5	75	91	2.8%	11%	31
0.75PMN-0.25PT	F	15	90	2.5	100	397	2.6%	38%	32
PZT95/05	F	31	78	2.5	220	631	2.0%	56%	33
PVDF-TrFE 55-45	P	38	200	2.3	37	1206	3.2%	62%	34,35
PVDF-TrFE-CFE	P	61	350	2.3	77	1718	2.8%	73%	35,36

On dielectric/polar surfaces. On dielectric/polar nanostructures/intefaces ?

[Meirzadeh *et al*., Adv. Mater. (2019); G. Catalan & B. Noheda, Nature (2019); Yang *et al*., Nature (2020)]



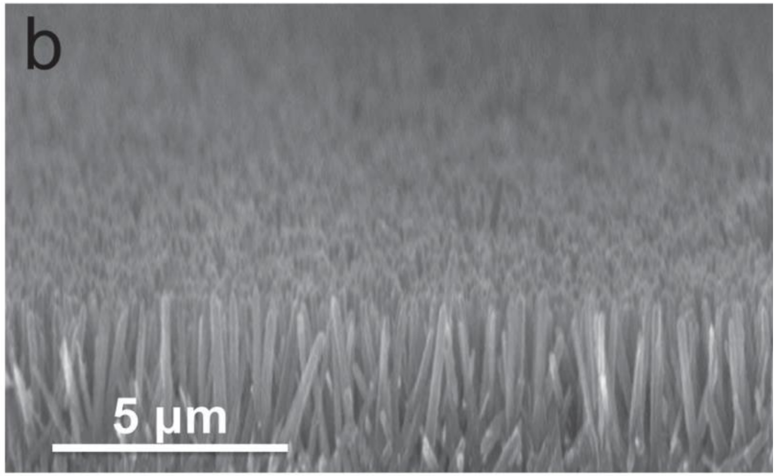
Artificially faster T cycles for density conversion enhancement (Link to WG #6)

Interest within the GDR NAME community?...
➔ Contact R. Bachelet/G. Nataf

Electrocalorics (*Romain Bachelet & Guillaume Nataf*)

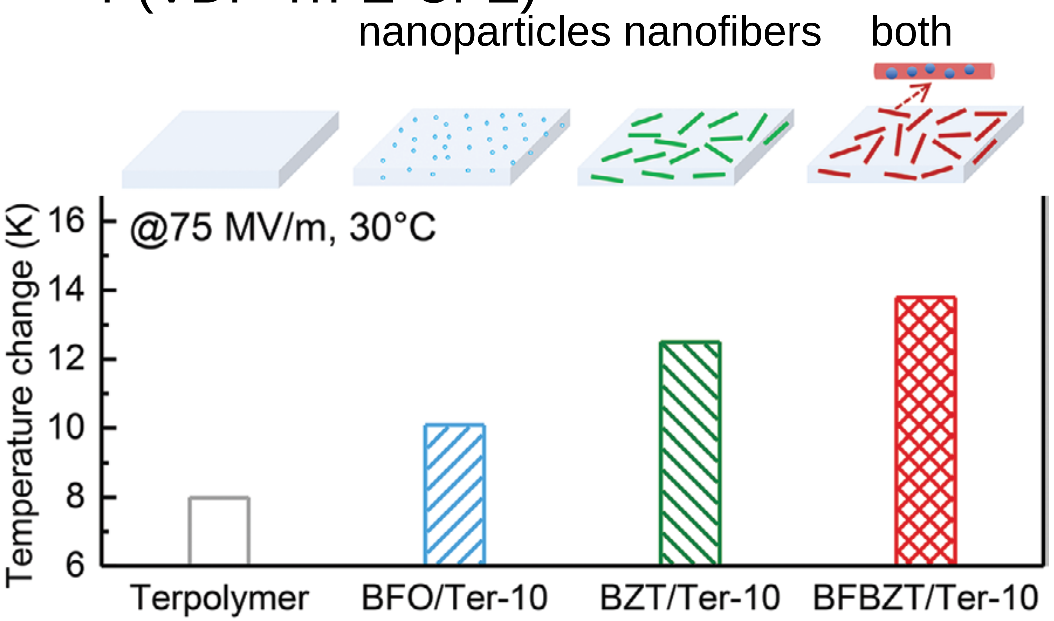
$Ba_{0.67}Sr_{0.33}TiO_3$ nanowire arrays

ΔT = 10 K ; ΔS = 16 J kg^{-1} K^{-1}



Zhang *et al.* Adv. Mater. **28**, 4811–4816 (2016)

P(VDF-TrFE-CFE) +

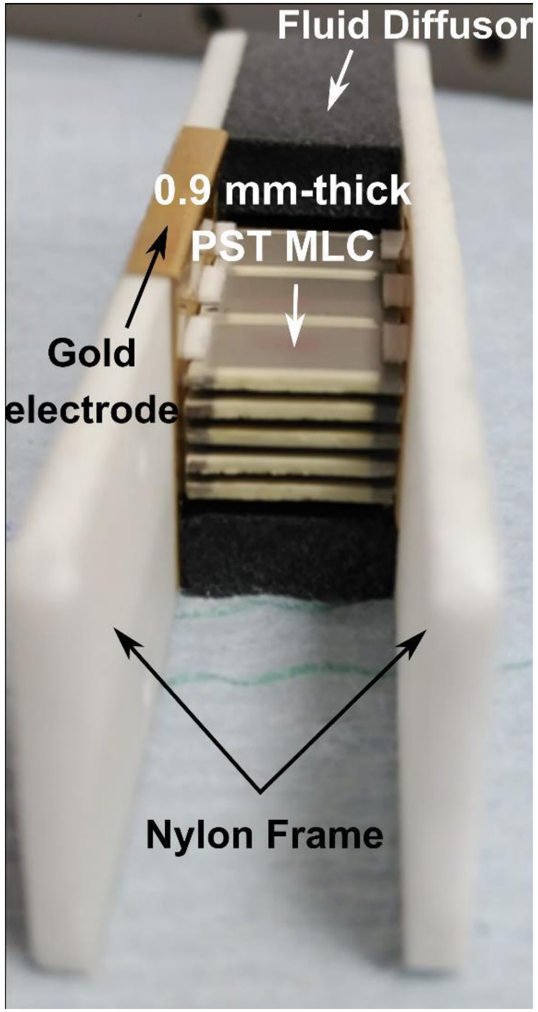


Jiang *et al.*, RSC Adv. **5**, 61946–61954 (2015)

Perspectives

- Lead-free materials
- Direct measurements
- Theoretical support
- Integration in devices

Cooling device based on multilayer capacitors of $Pb(Sc,Ta)O_3$



Torelló *et al.* Science **370**, 125–129 (2020)

Other caloric materials

- **MagnetoCalorics**

- **MechanoCalorics** (BaroCaloric, ElastoCaloric),…

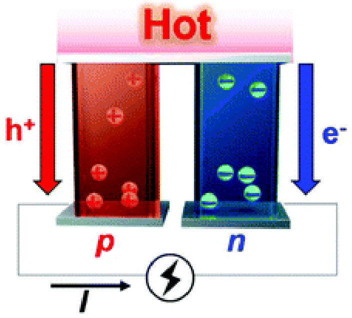
➔ **Interests/advantages of nanomaterials/nanocompoistes**:
Grain boundaries in alloys mitigating fatigue [see REVIEW X. Moya & N.D. Mathur, Science (2020)]

Interest in GDR NAME community?...
GDR members working on that ?...

➔ Contact R. Bachelet/G. Nataf if interested

1.2. Thermoelectric

REMINDER



Nanoscale, 2019,11, 19684

Principle
Direct conversion of thermal flux into electrical power

Figure of merit: $ZT = \frac{T\sigma S^2}{k_{ph}+\kappa_e}$

Nanostructuring

- k_{th} lowering by reducing phonon mean free path
- S improvement by energy filtering (quantum confinement)

MATERIALS : SOME TRENDS

thin-film **Heusler alloy** $Fe_2V_{0.8}W_{0.2}Al$ (Hinterleitner, B. alloy. *Nature* **576,** 85–90 (2019))

a metastable bcc W-type structure = a large slope of the electronic DOS at nearly the Fermi energy as well as Weyl-like fermions => large S and very large charge carrier mobilities.

Hybrid systems with conducting polymer and inorganic nanostructures / « *Polymer-Based Low-Temperature Thermoelectric Composite »* K. Yusupov et al. , Adv Functional Mat., 2020, 2002015.

energy filtering mechanism (Soret Effect) => enhancement of transport properties

2D perovskites / « *Sn-based perovskite for thermoelectric energy conversion by incorporating bulky conjugated ligands"*
S. Hsu et al., Nano Lett. 2021, 21, 18, 7839–7844

hybrid organic–inorganic superlattice-like structure => reduces the thermal conductivity

1.2. Thermoelectric

CALCULATIONS : DEVELOPMENT AREAS

- high throughput methods for prediction

- ab-initio approaches

which are becoming quantitative and more precisely to tackle the highest energies and couplings: phonon/phonon and phonon/electron

- the coupling of transport equations to ab-initio methods with molecular dynamics, Monte Carlo, NEGF...

And more generally coupling multi-scale approaches (in time and space)

- hardware

to take maximum advantage of parallel computing CPU and/or GPU, artificial intelligence (AI) and of course quantum computers to do quantum simulations

1.2. Thermoelectric

MESUREMENTS : TRENDS FOR THIN FILMS

Figure of merit: $ZT = \frac{T\sigma S^2}{k_{ph}+\kappa_e}$

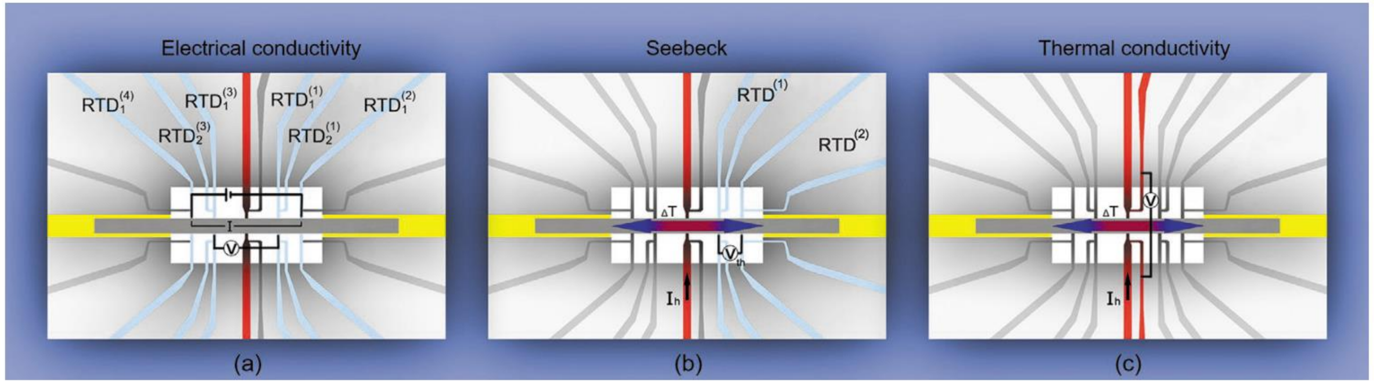


Figure 4. a) A schematic view of the σ measurement setup, b) a schematic view of the α measurement setup, and c) a schematic view of the λ measurement setup.

V. Barati, et al. , Adv. Electronic Mat., 2020, 1901288.

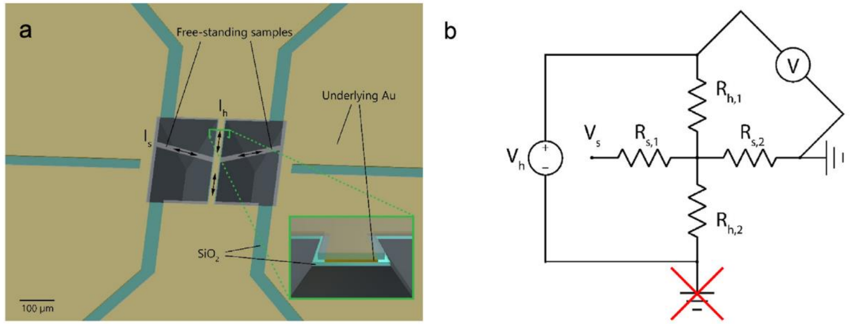


Fig. 1 – Schematic of the device for the in-plane measurement of thermoelectric properties (a). The inset is a close-up of a cross-section view of the supported central electrode. (b) Equivalent circuit of the device modelling the electrical properties including the voltage sources. The heating current source is assumed to be isolated from ground.

D. Osenberg, et al., J. of Mat. Res. and Tech., 2021

- All-in-one solutions through pure electrical characterizations.
- Design of microdevices in clean rooms
- Need to directly deposit thin films on the chips.

1.2. Thermoelectric

SWOT analysis

STRENGTHS

- Decoupling TE parameters with low dimensions
- Energy filtering
- Reducing lattice thermal conductivity

WEAKNESSES

- Measurement challenges for nanostructures, especially for thermal conductivity of 1D nanowires and hybrid systems **(link with WG 1)**
- Small community in France

OPPORTUNITIES

- Integration in TE modules **(link with WG 6)**

Design, Thermal dissipation (maintaining ΔT in nano/micro), interconnexions, interface resistivity, electronic management (weak electrical signals)

RISKS

- need of reliable devices including nanostructures
- increasing difficulties to get funding without breakthrough concepts or higher TRL level

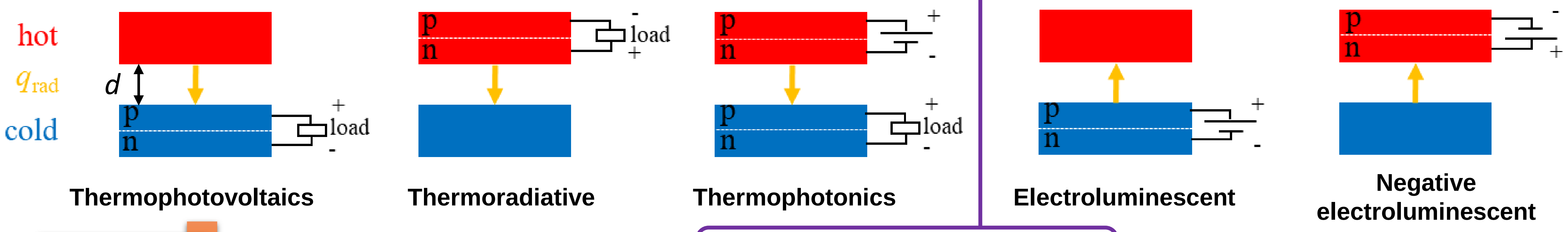
1.3. Radiative thermoelectric & Thermo-photovoltaic converters (*Rodolphe Vaillon*)

Reminder

Thermal radiation → Electrical

+ Electroluminescence

Electroluminescence → Refrigeration



$d < \lambda_{\text{Wien}}$ → near-field effects

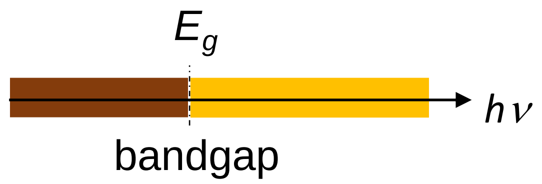
Focus

- **Challenges:** finding materials and (nano-)structures for optimum performance

- **Trends:**

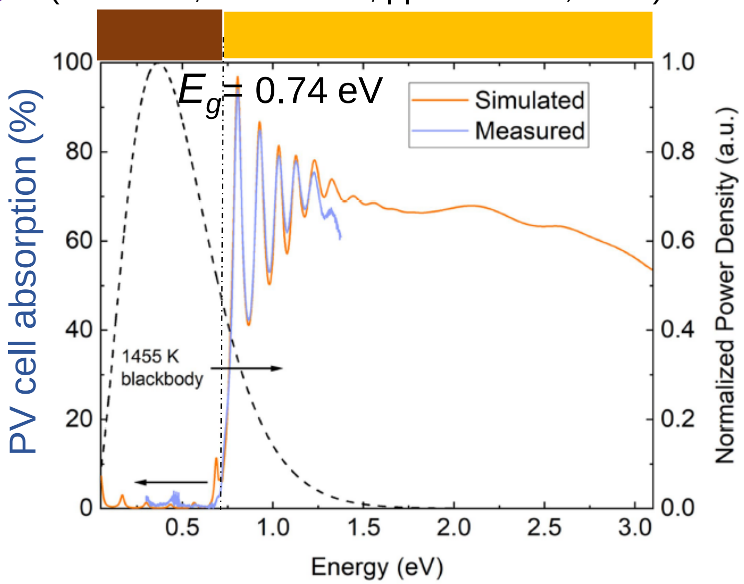
spectral selectivity →

In-band photons: nanophotonic engineering of the emitters



Out-of-band photons:
quasi-perfect back-surface reflectors on the PV cells

(Fan et al., Nature 586, pp. 237–241, 2020)



1.3. Radiative thermoelectric & Thermo-photovoltaic converters (*Rodolphe Vaillon*)

- **Challenges:**

better collection of thermal radiation

- **Trends:**

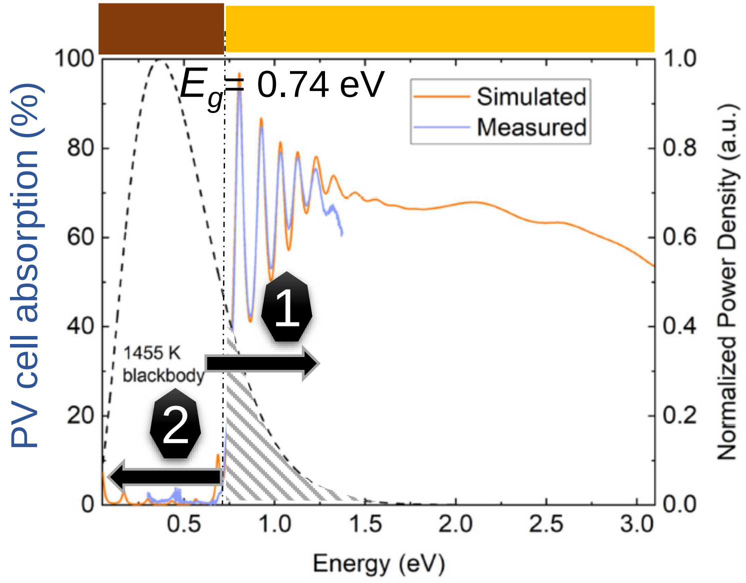
1 High-temperature emitters

degradation & thermal control

2 (Very) low-bandgap PV cells

low performance at room temp.

(Fan et al., Nature 586, pp. 237–241, 2020)



+ series resistance losses (high current; PV cell contact grid)
+ nanoscale *d* (< 500 nm) with high temperature difference
+ fabrication issues and up-scaling **(WG 6)**
+ exp. demonstrators of the other concepts (thermophotonics,…) +

- **Lacking in our community:**

Labs. working in this field…
…in particular for (nano-)fabrication of emitters and PV cells

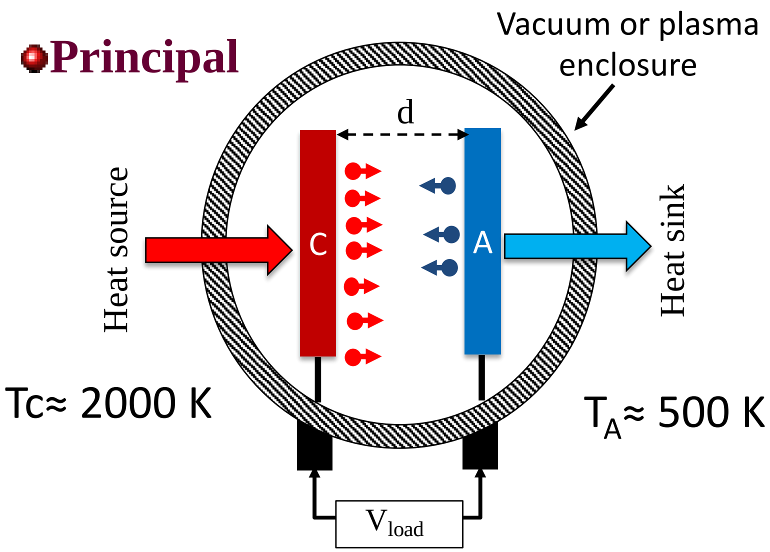
- **Strengthening our community:**

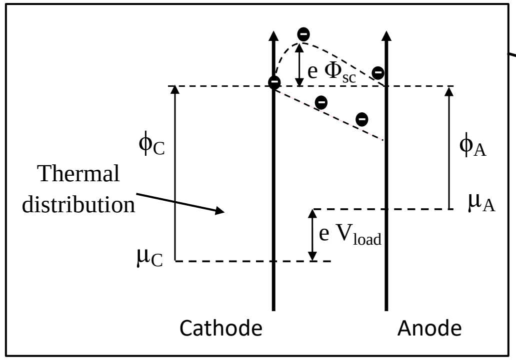
Inter-lab team
Thermal Radiation to Electrical Energy conversion (TREE)
CETHIL – ESYCOM – IES – Institut Pprime – L2C + …?

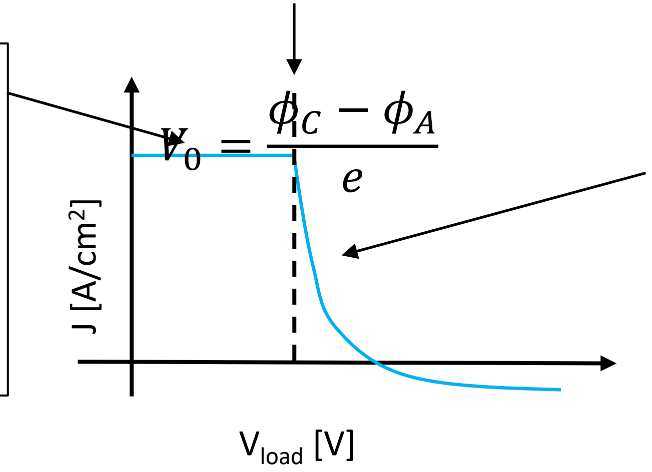
International collaborations (iTPV network)

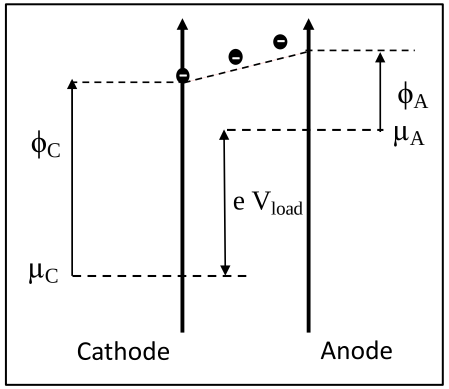
1.4. Thermionic (*Mohamed Amara*)

Principal





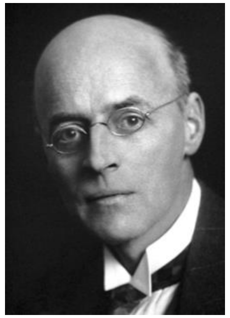




$$J = A \times T_C^2 \times e^{\frac{-\phi_C}{kT_C}}$$

- 1902 O. Richardson develops thermionic emission model
- 1904 Sir J.A Fleming invents the first thermoionic lamp
- Direct conversion of heat into electricity.
- Require very high temperatures (>2000 K)
- Low output voltages
- First application : TOPAZ thermoionic reactor developed (10 kW, η= 5%)

O. Richardson



J.A Fleming

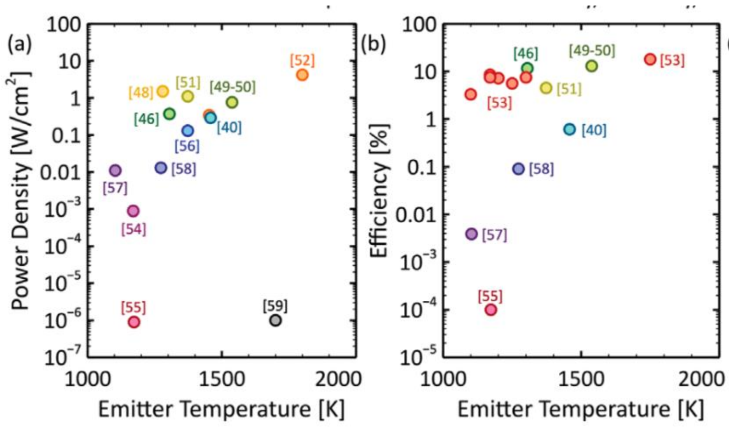
1.4. Thermionic (*Mohamed Amara*)

➢ Scientific barriers

✓ High temperature of the cathode

✓ Space charge effect

✓ Low work fuction materials



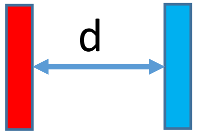
.https://doi.org/10.1002/ADVS.202003812

➢ Plsama-based TEC

- Positively charged plasma at the inter-electrodes. The most used material is cesium (Cs+) vapor.
- $P \approx 2.5 - 5$ W/cm^{-2}
- Very complex design with 30-50 % reduction of efficiency due to the plasma

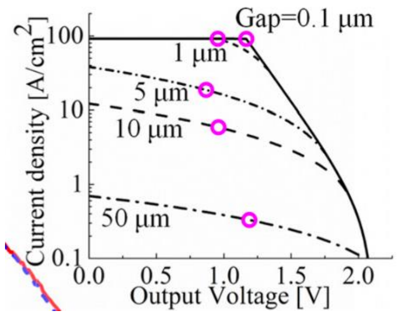
➢ Materials challenges

- Developing coating with low work function to enhance extraction of electrons : Cesium, alkaline earth oxides (BaO, MgO) and alkali halide (LiF)

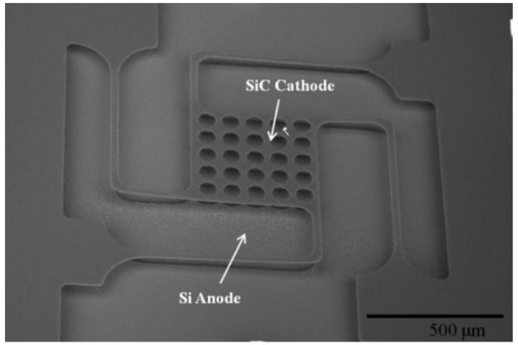


➢ µ-TEC

▪ 0.5 µm < d < 10 µm



Vacuum-encapsulated die of TECs.



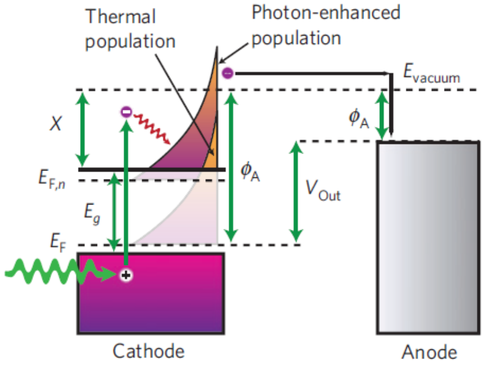
https://doi.org/10.1109/JMEMS.2014.2307882

➢ Photon-enhanced thermionic emission (PETE)

✓ Semiconductor cathode with light heat source

✓ Photo-excite carriers into conduction band

✓ Collected at low work-function anode



✓ No demonstration of a complete system

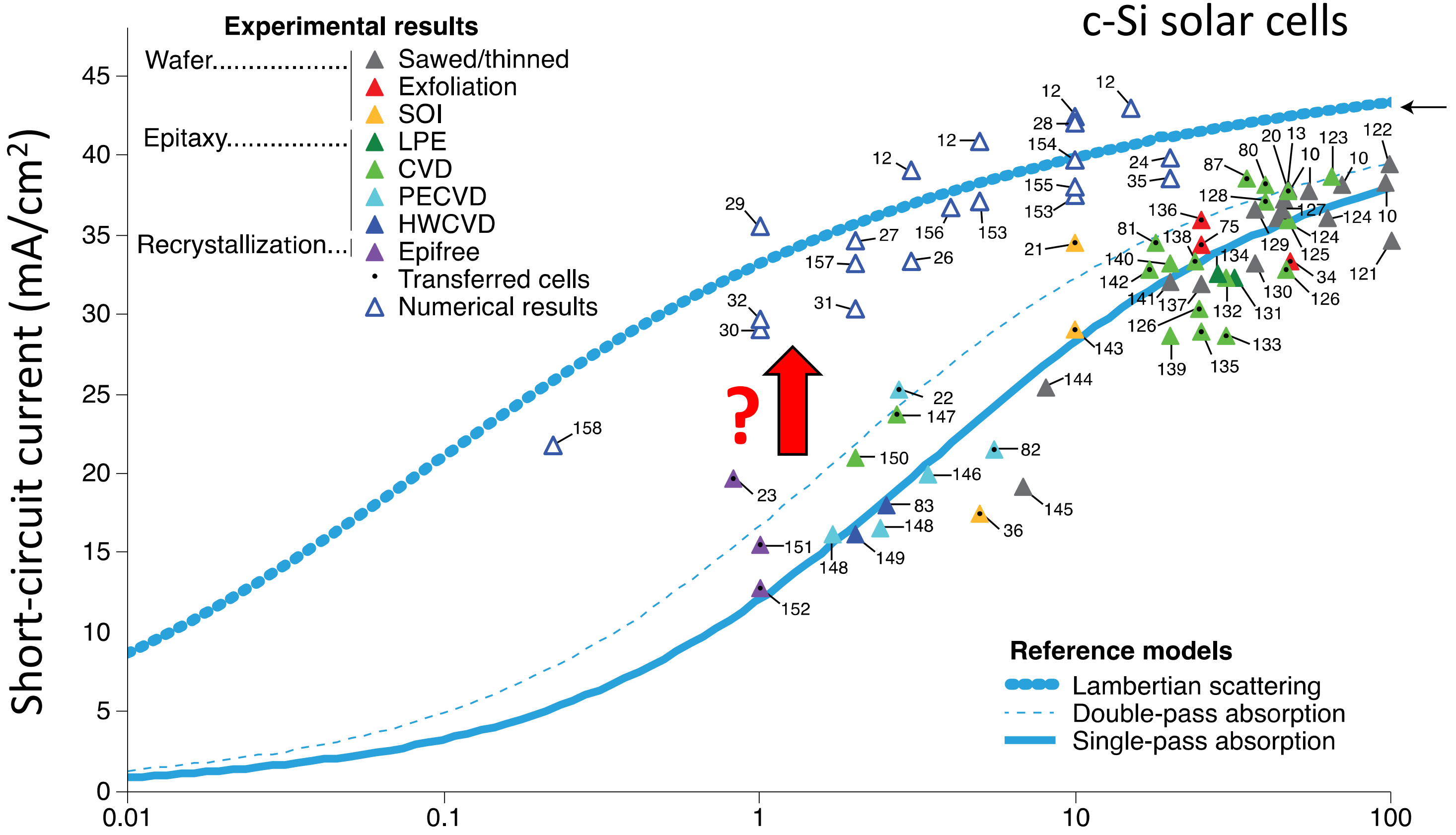
Schwede et al, Nature Materials, 9 ,762–767, 2010

2. Optical ⇔ Electric (PV)

Photovoltaic **Andrea Cattoni** C2N, université Paris-Saclay, CNRS

Light Emitting Diodes (Maria Tchernycheva C2N, université Paris-Saclay, CNRS)
not present

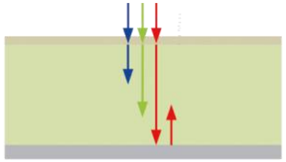
▲ Experimental results   △ Numerical results



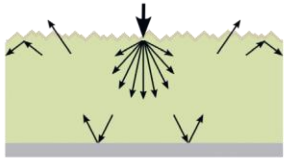
Solar cell absorber thickness

Single-pass absorption (F=1)

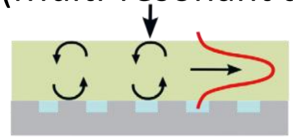
Double-pass absorption (F=2)



Lambertian scattering ($F=4n^2$)



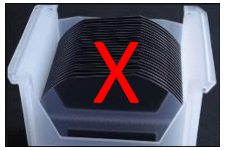
(Multi-resonant absorption)



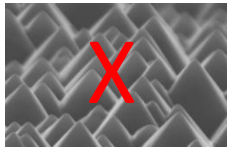
Nature Energy 5, 959 (2020)

2.1. Photovoltaic: « Light trapping in solar cells »

Andrea Cattoni, C2N-CNRS

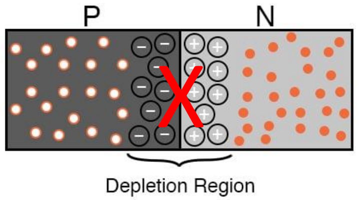


Low-cost
Ultrathin Absorbers

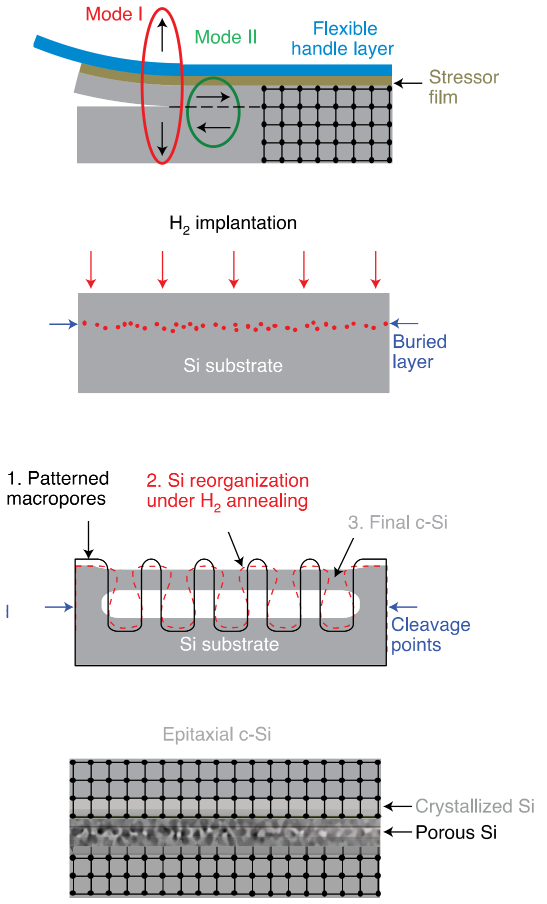


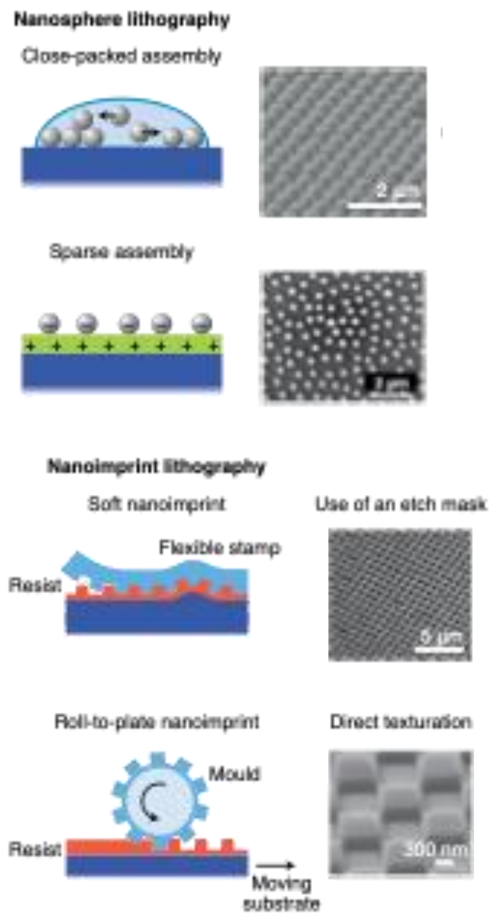
Low-cost
Nanostructuration

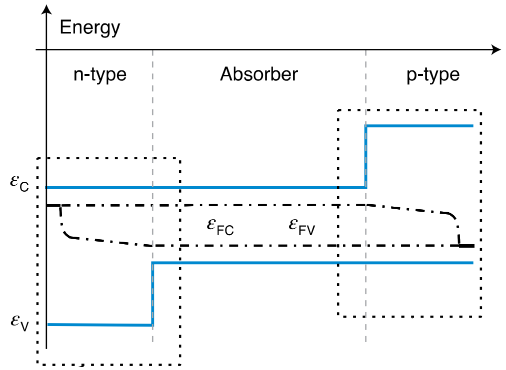
Adapted
Selective Contacts



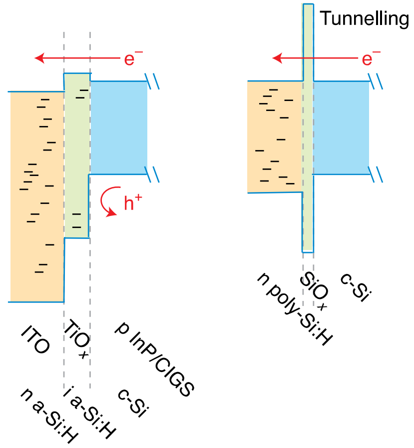
Adapted
Solar Cell **Design**

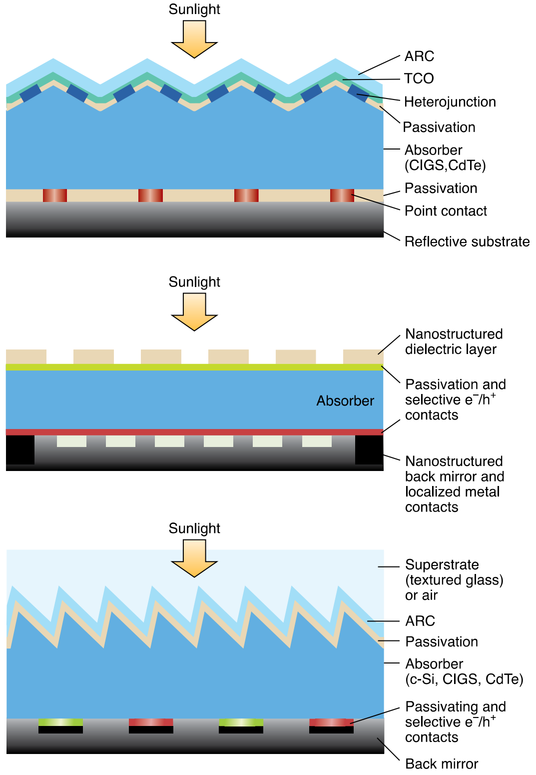






Electron selective contacts



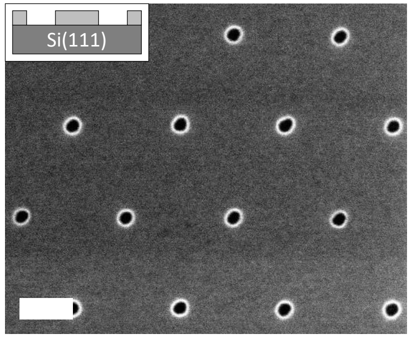


Nature Energy 5, 959 (2020)

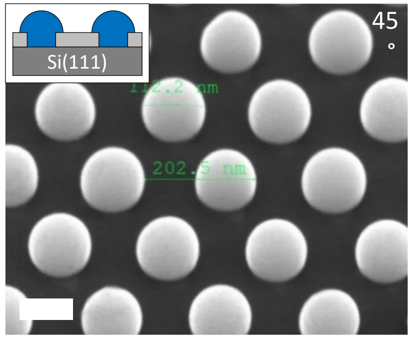
2.1. Photovoltaic: « III-V Nanowire-based solar cells »

Andrea Cattoni, C2N-CNRS

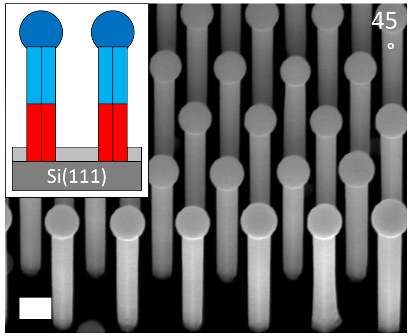
Dielectric mask patterning



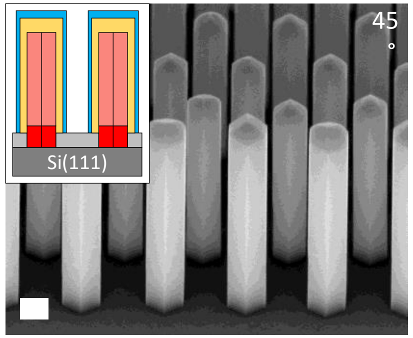
In situ Ga droplet catalyst deposition



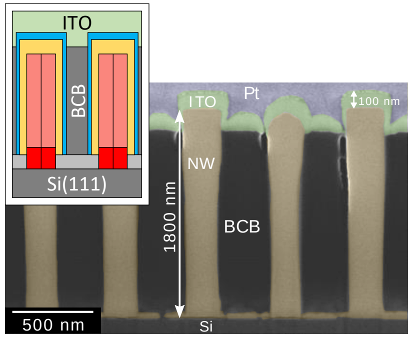
Axial junction by VLS growth



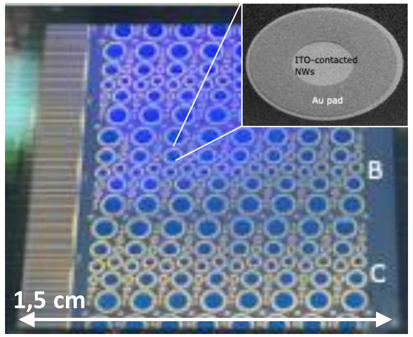
Core by VLS, droplet consumption, radial junction by Vapor-Solid growth



GaAs NWs radial p-i-n junctions planarized with BCB, ITO contact



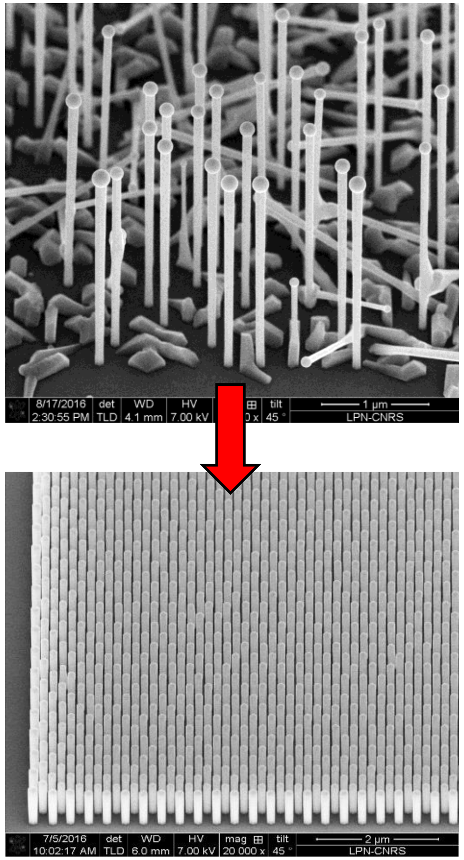
Picture, SEM view of NW-based diodes defined by photolithography



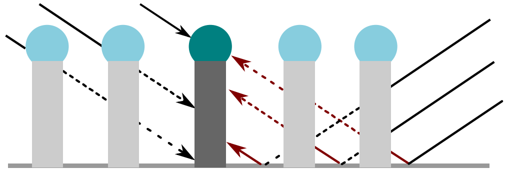
Reference	Material	Junction	Substrate	Growth Method	Surface passivation	PCE	V_{OC}	J_{SC}	FF
DAM2016	InP	Axial	p-InP	Etching	SiO_X	(17.8)	0.765	29.3	79.4
ABERG2016	GaAs	Axial	p-GaAs	Au-catalyzed	AlGaAs	**15.3**	0.906	21.3	79.2
OTNES2018	InP	Axial	p-InP	Au-catalyzed	SiO_x:Al	**15.0**	0.73	26.64	72.4
WALLENTIN2013	InP	Axial	p-InP	Au-catalyzed	SiOx	**13.8**	0.779	24.6	72.4
GAO2019	InP	Axial	p-InP	SAE	none	9.23	**0.55**	22.5	**75**
DASTJERDI2016	GaAs	Radial	p-Si	Ga-catalyzed	AlInP	4.1	**0.45**	22.8	**40**
YAO2015	GaAs/Si	Tandem Axial	Si n-p	SAE	none	11.1	0.956	20.64	**57.8**
WOOD2017	GaAsP/Si	Tandem Radial	Si p-n	Ga-catalyzed	AlInP	3.51	1.16	7.65	**39.6**

Andrea Cattoni, C2N-CNRS

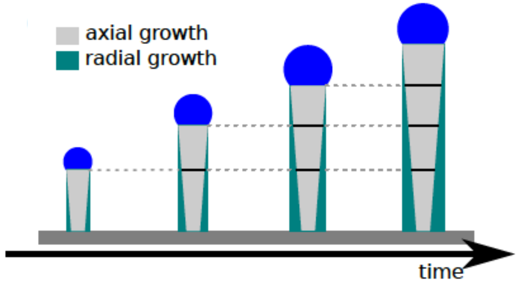
Selective growth: selectivity, yield



Growth dynamics and shadowing effects



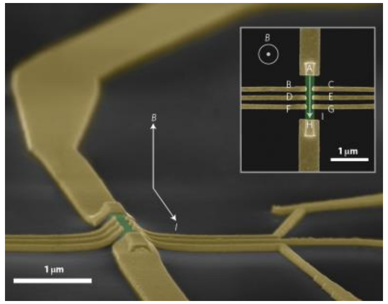
Growth mechanism

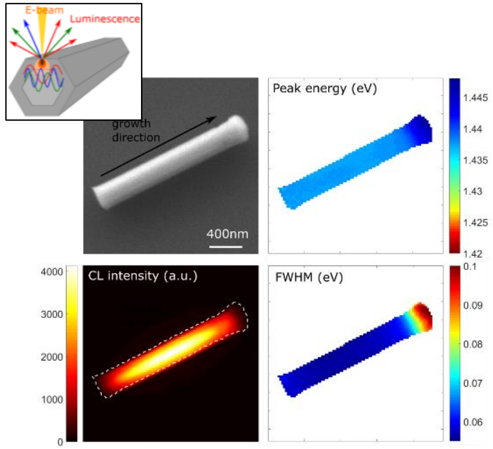


Potentially problematic for ternary if VLS≠VS !

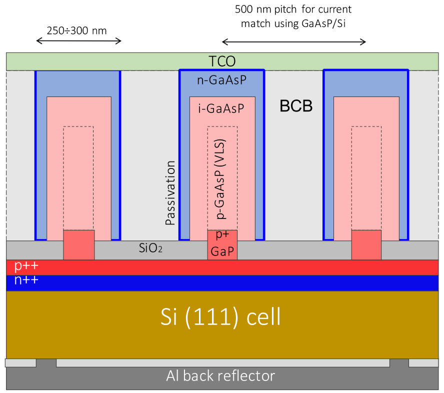
Control and determination of **doping**

- Amphoteric behaviour of Si
- Inhomogeneous incorporation by VLS (?)

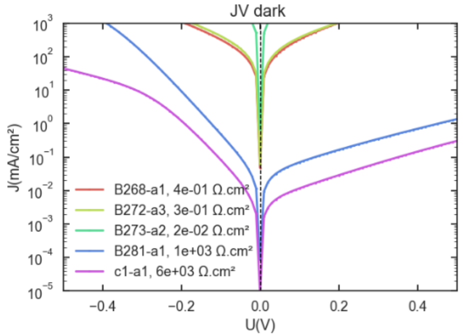




Device fabrication: planarization, TCO/III-V contact



TCO/III-V low resistance only for $n > 1 \times 10^{19}\ cm^{-3}$



4. Mechanical ⇔ Electric

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Vincent Consonni LMGP, UGA, CNRS

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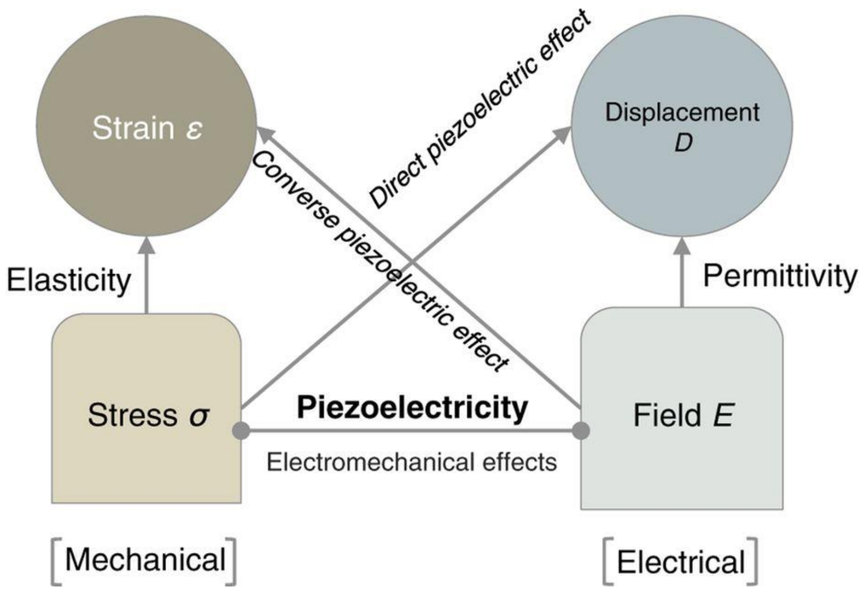
Piezoelectric nanogenerators

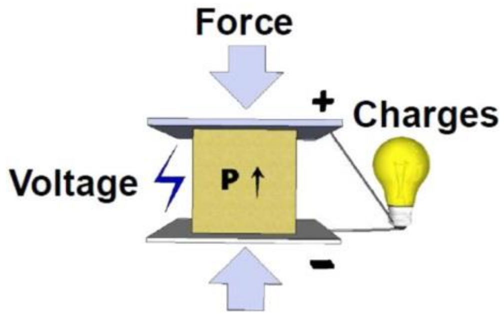
Reminder of the basics

✓ **Piezoelectricity**

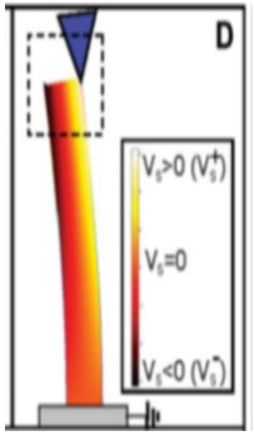
Principle: electricity resulting from pressure and vice-versa



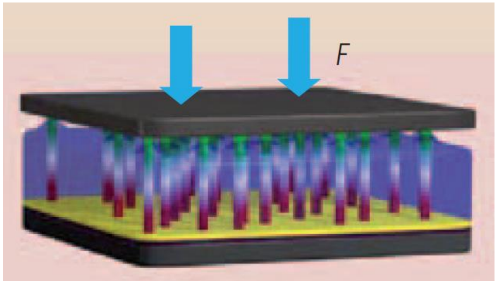
Part of the Heckman Diagram, Jong et al., Sci. data (2015)
doi:10.1038/sdata.2015.53



$d_{ij} = dP / d\sigma$ (C/N)



Z. L. Wang et al. Science (2006)
doi:10.1126/science.1124005



S. Xu et al., Nat. Nanotech. (2010) 5, 366-373
doi:10.1038/NNANO.2010.46

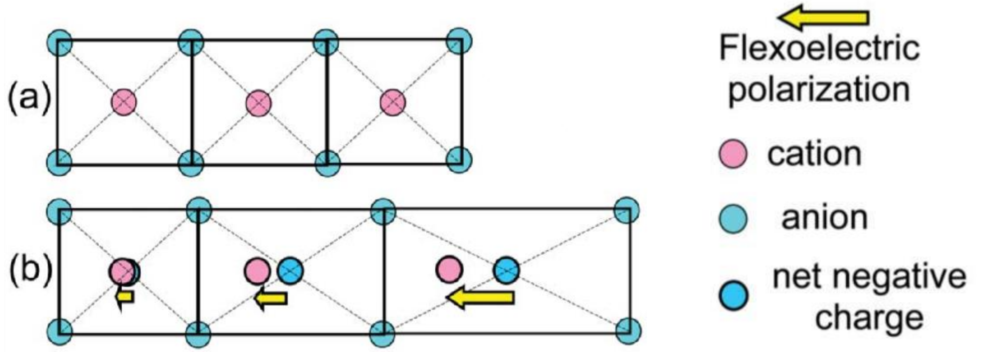
Flexoelectric generators

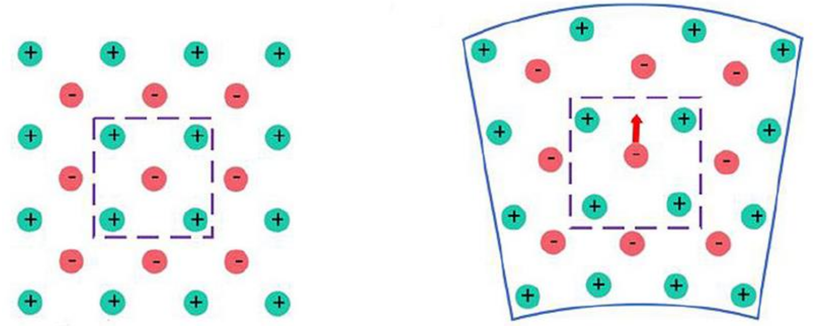
Reminder of the basics

- Direct effect: Strain gradient ⇒ additional polarization
  (centers of + and – charges no more at the same place)

$$P_i = \varepsilon_0 \chi_{ij} E_j + e_{ijk} u_{jk} + \mu_{klij} u_{kl,j} \text{ with } u_{jk} = (U_{jk} + U_{kj})/2$$

- Converse effect n°1: electric field ⇒ additional 2nd order stress
- Converse effect n°2: gradient of electric field /polarization ⇒ additional stress / strain





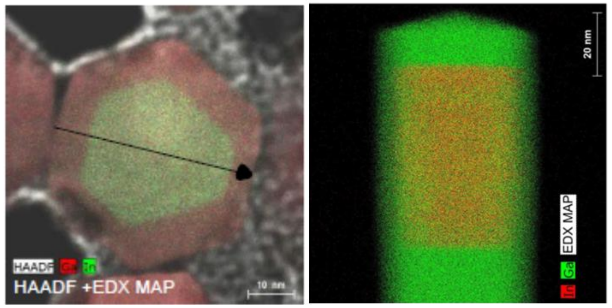
- 'Competitive' with piezoelectricity at nanoscale due to a reduction of the denominator of the gradient + effective surface piezoelectricity + bigger effect for high dielectric susceptibility materials $(\mu \sim \chi\, e/a)$
- Applications targeted: thermal energy harvesting, flexible strain gradient sensors, possibly with heterostructures of 2D materials
- Problems: wide variations in the notations among authors (even dimensions can be different!)
- Reviews: Wang et al., Progress in Materials Science, 106, 100570, (2019)
  Jiang, X., Huang, W., and Zhang, S., Nano Energy, 2(6), 1079–1092 (2013)
- Book: Tagantsev & Yudin (eds.) Flexoelectricity in solids, From Theory to Applications, World Scientific, ISBN-10: 9814719315

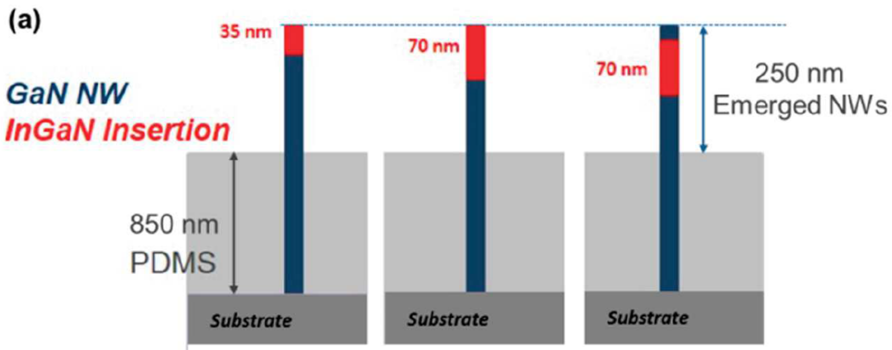
Piezoelectric nanogenerators

Last trends

- ✓ **Heterostructured NWs**

The piezo-conversion of InGaN/GaN NWs is 30% more efficient than GaN

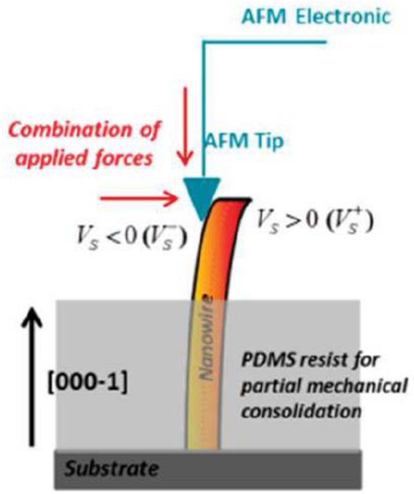


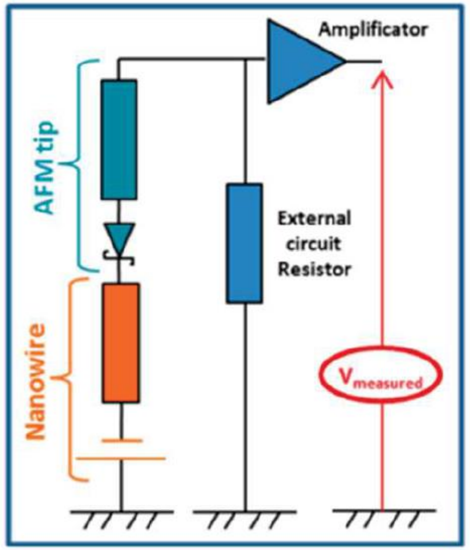


The piezoelectric response of InGaN/GaN NWs is function of the InGaN insertion thickness and position (InGaN : higher piezo coefficient than GaN)

+ better energy harvesting with PtSi/GaN Schottky diode (than PtSi/InGaN)

Piezo-Conversion mode





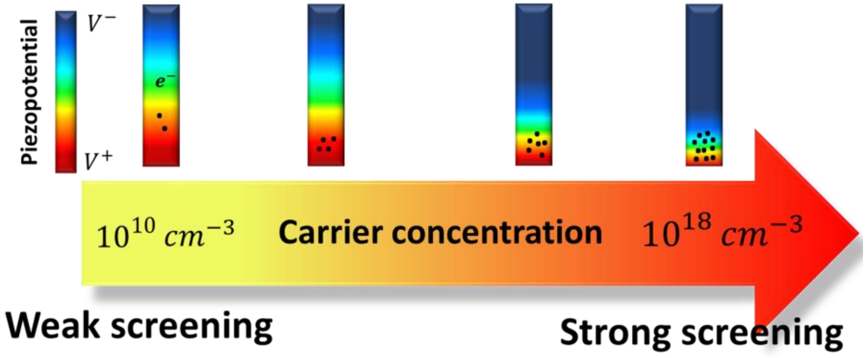
N. Jegenyes et al., Nanomaterials 8(6) (2018) 367, doi: 10.3390/nano8060367

Piezoelectric nanogenerators

Last trends: doping of NWs

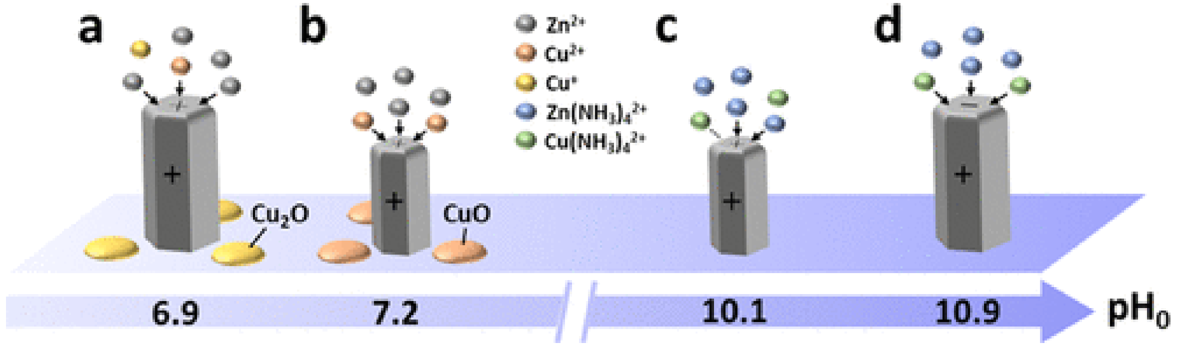
Intrinsic doping of NW [1,2] + Intentional doping for further enhancement of piezoelectric conversion properties [3,4]

[1] S. Boubenia, Thèse Univ. Tours, 2019, hal.archives-ouvertes.fr/tel-02975514
[2] J. Villafuerte et al. The Journal of Physical Chemistry C 124, 16652-16662 (2020)
[3] X. Li et al., Nanomaterials 2018, 8, 188, doi:10.3390/nano8040188
[4] S. Goel, B. Kumar, J. of Alloys and Compounds 816 (2020) 152491



G. Tian et al. Nano Letters 20, 4270-4277 (2020)

In ZnO: the high free electron density coming mainly from hydrogen should be decreased.



Compensating doping with Cu to decrease the free electron density in ZnO NWs grown by chemical bath deposition

C. Lausecker et al. Inorganic Chemistry 60, 1612-1623 (2021)

A couple of open issues to be addressed…

i) How intrinsic and intentional doping is coupled?

ii) How to efficiently activate the intentional doping in ZnO NWs while optimizing their surface properties and without damaging their structural properties?

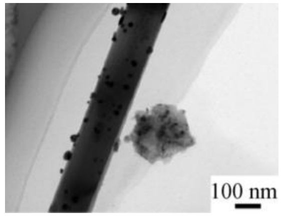
iii) Need for fundamental investigations on the intentional doping combined with applied investigations on piezoelectric devices: which exact relationship?

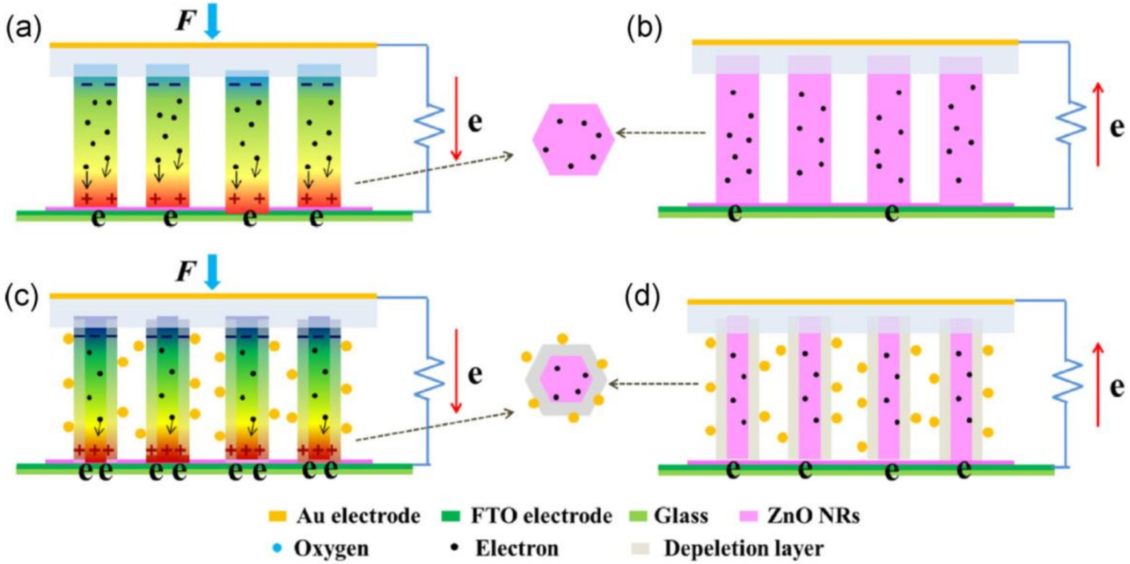
Piezoelectric nanogenerators

Last trends : NWs functionalization

Modification of the surface state of the NWs ⇨ their piezoelectric properties & the properties of their electrical contacts are modulated.

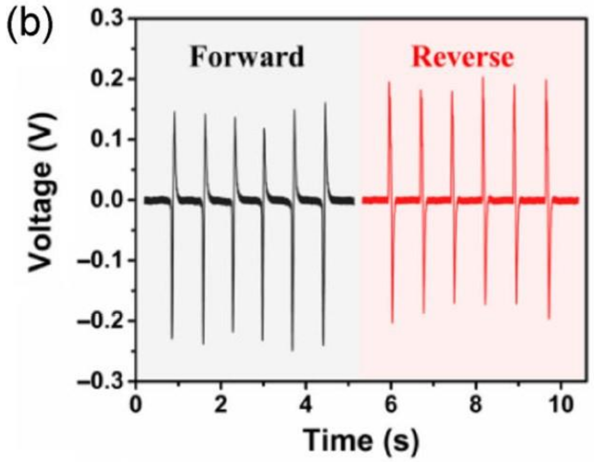
Ex: use of gold to functionalize the surface of ZnO NWs





Weakening of the piezopotential screening
effect by forming Schottky junctions on the ZnO surface

Voltage generated by pristine NWs



Piezoelectric nanogenerators

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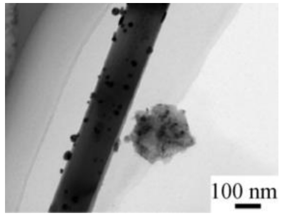
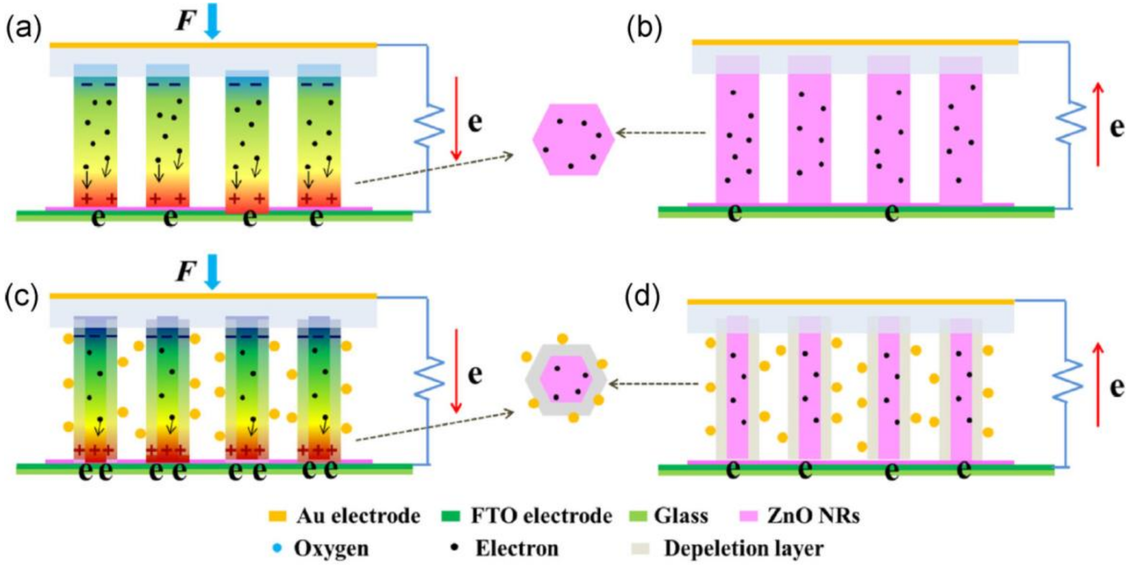
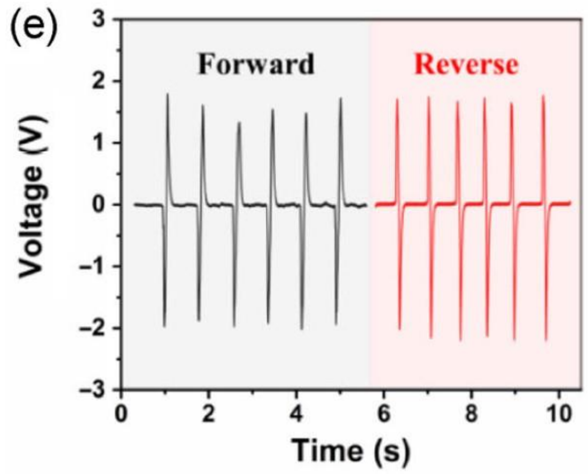




Voltage generated by decorated NWs



S. Lu et al., Nano Res. 9, 372 (2016), DOI 10.1007/s12274-015-0916-6

⇨ increased harvested energy

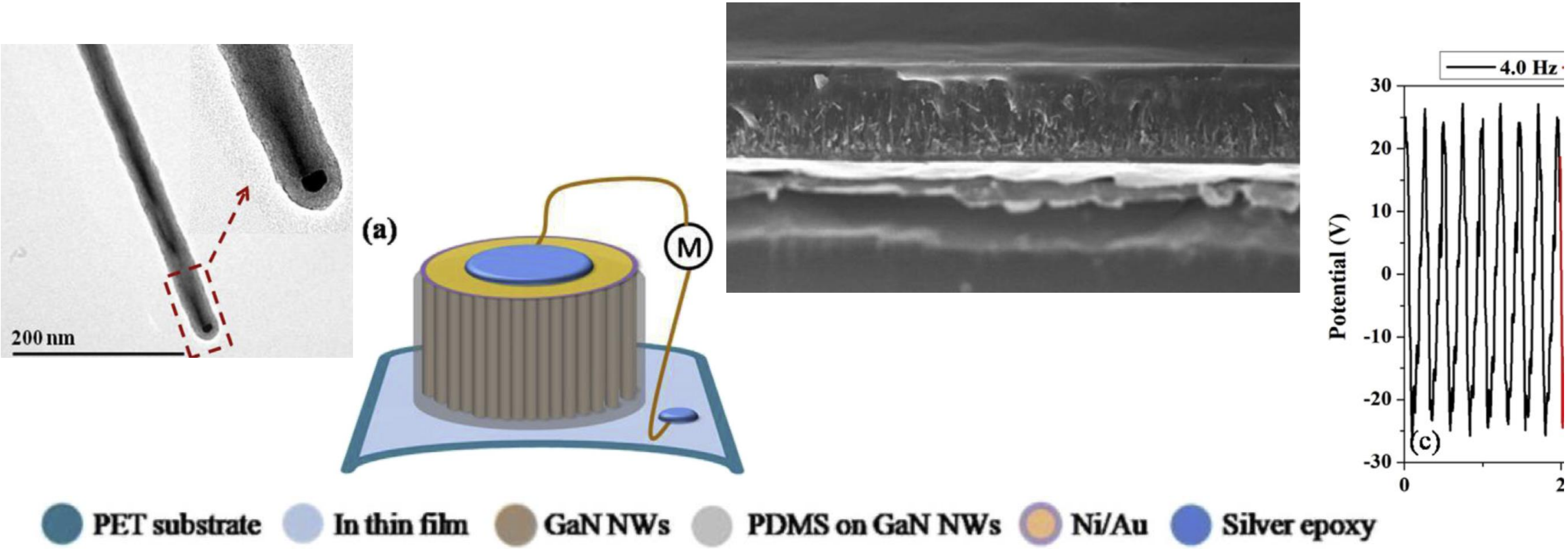
Piezoelectric nanogenerators

Last trends : NWs functionalization

Functionalization of GaN NWs with a V_2O_5 shell:

p-type V_2O_5 shell on the n-GaN NWs to suppress the internal carrier screening

p-n heterojunction ⇨ control of the depletion volume



Bending of flexible device

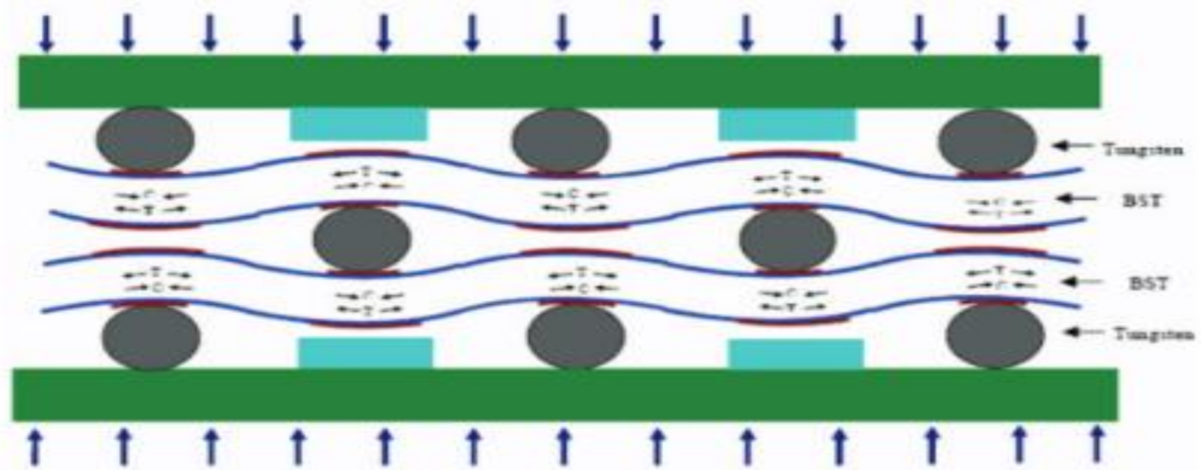
Max output voltage 27 V for core-shell NWs (9 V for pristine NWs)

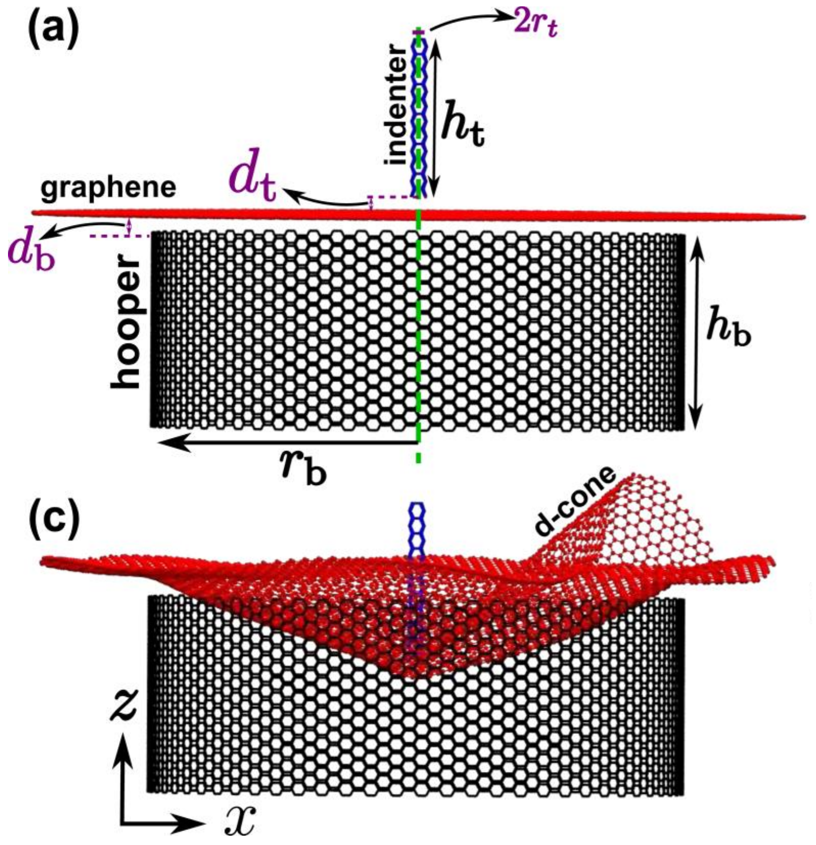
Harvested power? Conditions of tests?

A. Waseem et al., Nano Energy 60, 413 (2019), https://doi.org/10.1016/j.nanoen.2019.03.075

Flexoelectric nanogenerators

Last trends: Using flexoelectricity for nanogenerators





Nano-composite with a non homogeneous deformation (analogous to a piezoelectric material). Design of *Chu et al. J. Appl. Phys.* ***106****(10), 104109 (2009)* could be used with 2D-materials.

☹ Fired-on electrodes can give down to 1% the flexoelectric response of sputtered electrodes *Tian et al. J. Appl. Phys.* ***129****, 194103 (2021)*

Trends: design of multifunctional materials, flexoelectricity in thin films and nanostructures, implications for biology & soft matter, experimental methods in characterizing flexoelectricity, *General flexo-type couplings* (flexomagnetism, photoflexoelectricity,…), *Flexoelectric-mediated effects, Complex systems sustaining large strain gradients* (from the description of the 2021 special topic on "Trends in flexoelectricity" in J. App. Phys. and *table of contents of* *Wang et al., Progress in Materials Science, 106, 100570, (2019)*)

B. Javvaji et al., "Flexoelectric electricity generation by crumpling graphene", *J. Appl. Phys.* ***129****, 225107 (2021)* (MD simulation) electrical energy density of 4,871.10^{-6} J/m^2 for strain energy density of 1,341.10^{-6} J/m^2

Piezo / Flexoelectric nanogenerators

SWOT analysis

FORCES

- Modeling at the nanowire and device levels
- Characterization at nanowire scale and at device scale
- Strong community in France

WEAKNESSES

- Large literature but many articles just propose a device without optimisation
- Characterization at device scale: lack of standardisation
- Manufacturing: lack of reproducibility

OPPORTUNITIES

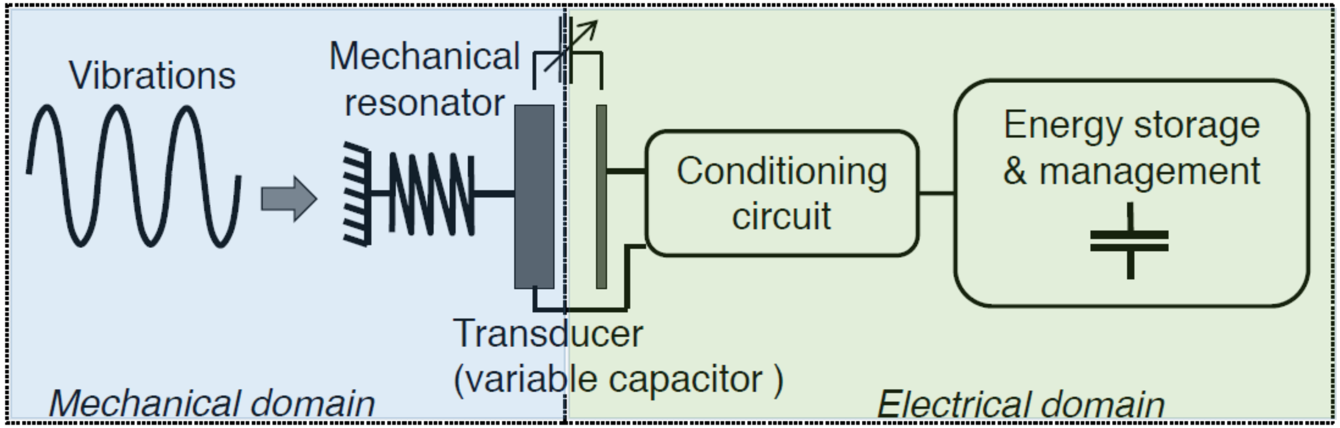
- Modeling: interfaces (surface charges, mechanics…), polymers (if composite structure)
- Coupling of flexoelectricity with other fields e.g. flexomagnetism, photoflexoelectricity
- Networking between different communities : mechanical energy harvesting, materials science, nano-mechanics…

RISKS

- No industrialisation
- « old subject » (≈ 2006) ⇨ increasing difficulties to get fundings without breakthrough concepts or higher TRL level

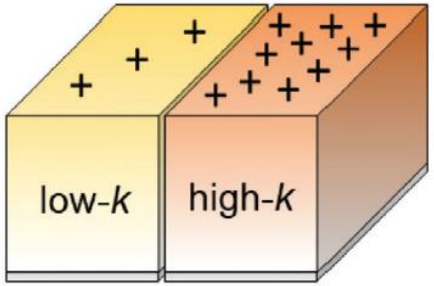
Electrostatic Kinetic Energy Harvesters (e-KEH)

Principle:



[P. Basset, D. Galayko *et al*, ISTE-Wiley, 2016]

- A biased-capacitor varies because of an external mechanical force
  - → The negative work of the electrostatic force acting on the mobile electrode = to the mechanical-to-electrical converted energy
- The converted energy is maximized with:
  - a high capacitance variation of the electrostatic transducer (C_{max}/C_{min})
  - a high bias voltage
    - → electret with high-*K* material (ε)
    - → electret with high surface-charge density (σ)



Electrostatic Kinetic Energy Harvesters (e-KEH)

How to improve e-KEH at the material level?

- During fabrication:
  - Injections of ions/electrons in the electret → σ++
  - Add of nanoparticles inside the electret
    - → Improve permittivity → C_{max} ++
    - → and/or charge storage and/or triboelectric affinity → σ++
  - Flexibility of dielectric material (elastomer) → C_{max} / C_{min} ++
- « At work »: tribo-electrification →σ++
  - → Mano/micro surface structuration of "tribo"-electret and contact electrode
  - → Effect of self-assembly monolayer or 2D-material at the contact interface

A couple of open issues to be addressed…

- durability of charge trapping
- durability of contact surface (tribo)
- high-voltage limit (material, circuit, application)
- resistance to harsh environments
- mechanical vibration frequency
- impedance matching et power management

Round table discussion

Open questions coming from each sub-topics

Scientific issues at the interface between "thermal engineering sciences" and "electrical engineering sciences", with difficulties to be expert on all aspects (thermal / electrical ; modeling / fabrication / experiments).
How to work together at this interface in a sustainable way (beyond the duration of collaborative projects).

How to increase TRL
Need for device fabrication to address integration issues and demonstrate the potential of thermoelectric microgenerator conversion
Pyro: in addition to the materials aspect, connect with the device workshop (WG6) to increase the yields

Difficulty to measure the overall transport properties of individual thermoelectric nanomaterials, specific need for thermal conductivity
Electrocalorics: interesting to connect with the people who do TDTR for possible direct measurements

Sub-Theme Thermoelectrics = How to predict transport properties of hybrid systems (counductive polymers /nanostructures)

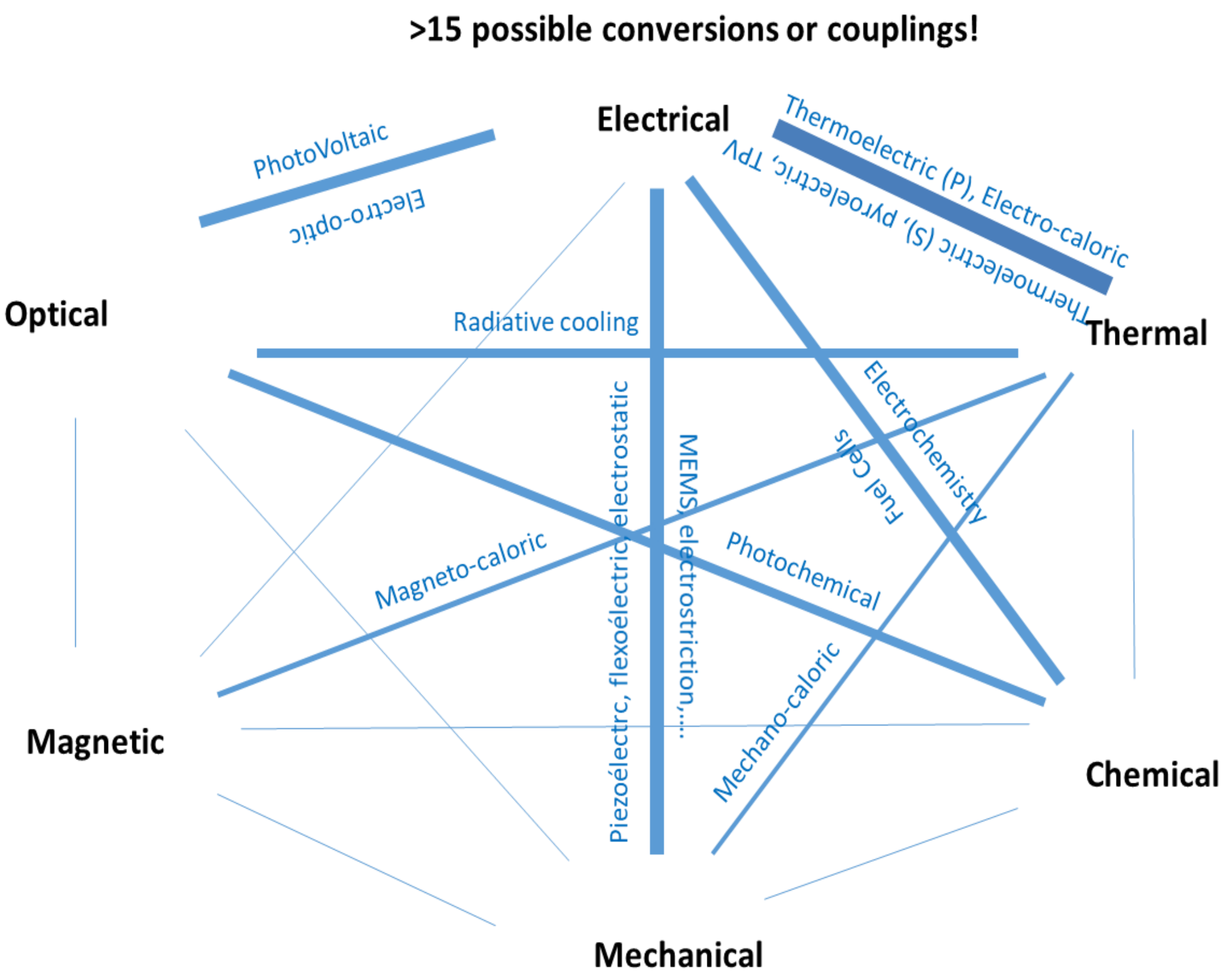
Sustainable inter-lab teams (see slide)? Scientific animation workshops by sub-themes ?

Sub-theme Electro-caloric/Pyro = Are there members of the GDR who work on pyro/electro/calorics and who could contact us?

Sub-theme piezo/flexoelectricity = Modeling & characterization: need for harmonization, beyond piezo/flexo... working group with other physical couplings
Piezoelectricity but also in TE and elsewhere? Multidisciplinary aspect = going from material to device, requires multidisciplinary skills

Sub-theme Thermoionic = Relevance of an efficiency or power density metrics for thermoionic devices ?

“Hybrid”: multi-carriers energy conversion



- **Other Hybrid/multiple carriers energy conversions ?...**
- **Motivations :**

synergetic effect, similarities, enhancement of the global efficiency

- **Questions : for which purposes/applications ?**

Environmental matters

What about the green sustainability ?

- The nature of the materials (abundance, scarcity)
- The question of the safety of the nanomaterials, biocompatibility, public acceptance ?
- the synthesis/processes of the materials
- The fabrication technology
- Life cycle analysis

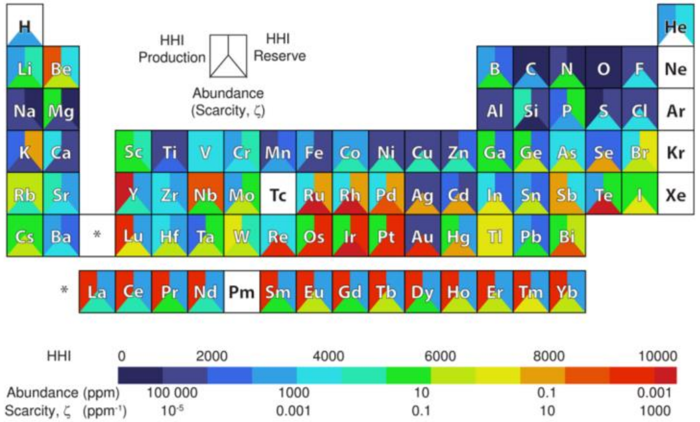


Figure 1. Periodic table indicating elemental scarcity and the HHI (production, reserves) indices for most elements. Values were calculated using USGS statistics from 2011, or if unavailable, from statistics no earlier than 2009.

Chem. Mater. 2013, 25, 15, 2911–2920

Données coût environnemental des procédés de fabrication salle blanche, sous vide, chemicals

Comment associer ACV dans un projet ?

interdisciplinary issues

Strengthen links/interactions with the other Work Groups of the GDR NAME

- Devices WP #6
- Elaboration and Measurements WP #1
- Standardization/normalization of converted energy density (WP#? axis A2 of the GDR : Mesures/Métrologie)

Follow-up WP #3 ?
Identification of sub-groups? Which topics? Which actions? For which target?