Récupération d’énergie mécanique piézoélectrique

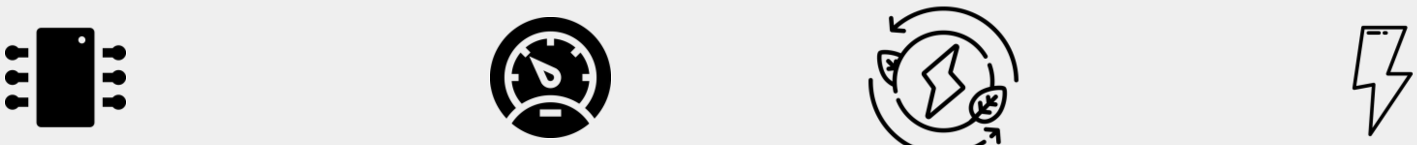
Guylaine POULIN-VITTRANT

GREMAN matériaux microélectronique acoustique nanotechnologies

cnrs université de TOURS INSA INSTITUT NATIONAL DES SCIENCES APPLIQUÉES CENTRE VAL DE LOIRE

https://greman.univ-tours.fr/

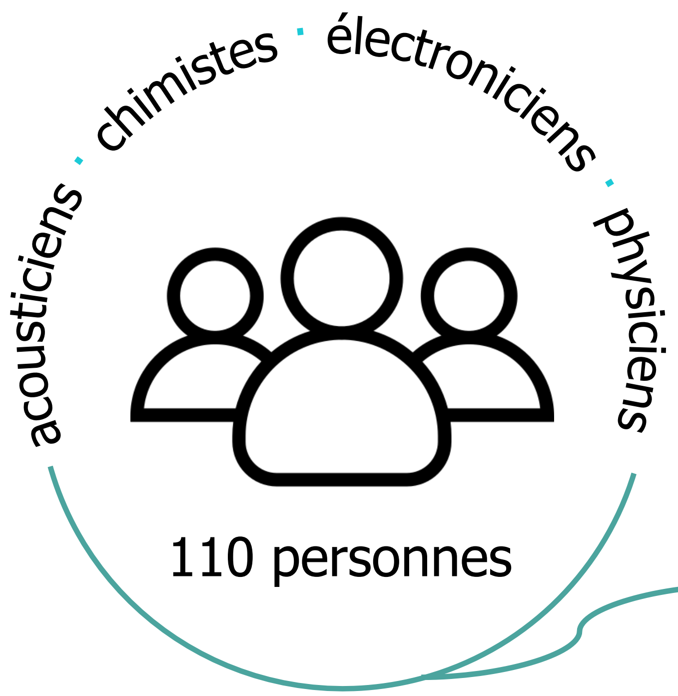
Le monde de demain a besoin de **micro-nanosystèmes …**



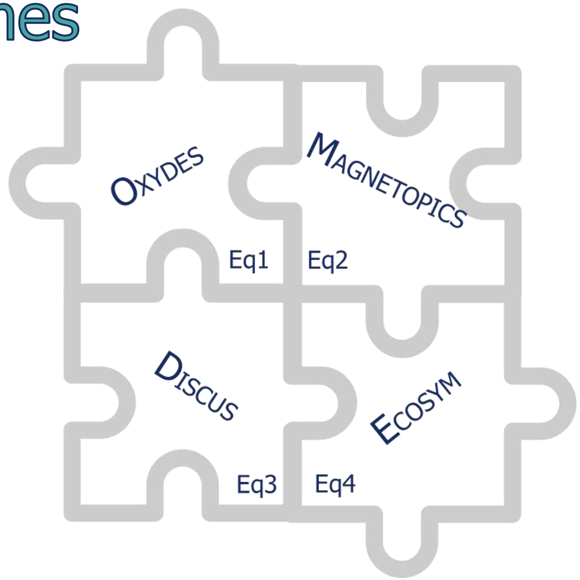
+ intégrables | + performants | + propres | + efficaces en énergie

→ Le **GREMAN** développe 3 champs de recherche:

- Rationalisation de l'énergie
- Matériaux nouveaux
- Conception de composants et de systèmes



Structuration en 4 équipes



Img ©flaticon.com

GREMAN

La recherche au GREMAN - Champs d’application ciblés

Production, stockage & conversion de l’énergie électrique

Electronique nomade & récupération d’énergie

Mesures, contrôles et diagnostics pour l’industrie et la médecine

GREMAN

Le GREMAN - 3 sites géographiques

Tours Sud

UFR Sciences et Techniques

Tours Nord

Site industriel de STMicroelectronics

Blois

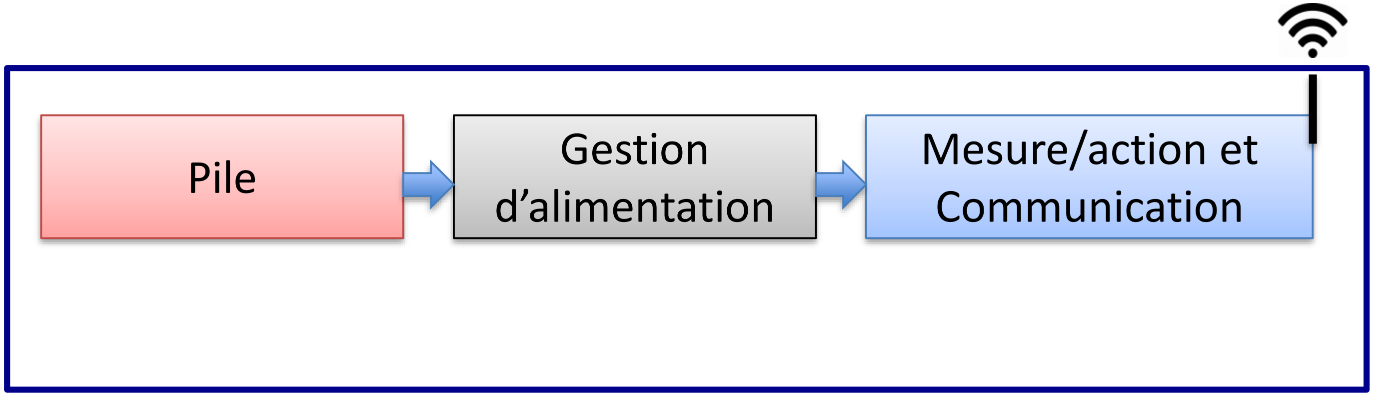
INSA Centre Val de Loire

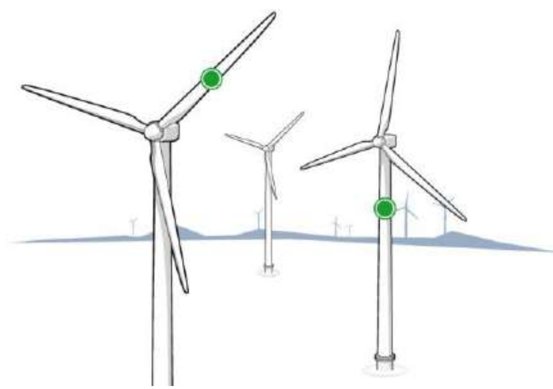
IUT de Blois

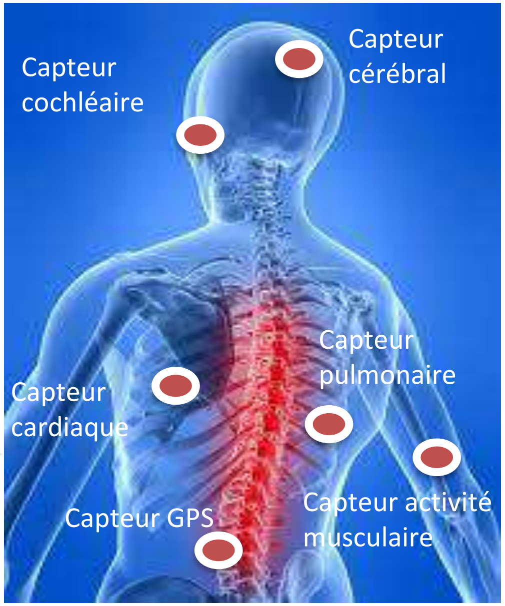
GREMAN

Récupération d'énergie

Une alternative pour l'alimentation des objets communicants

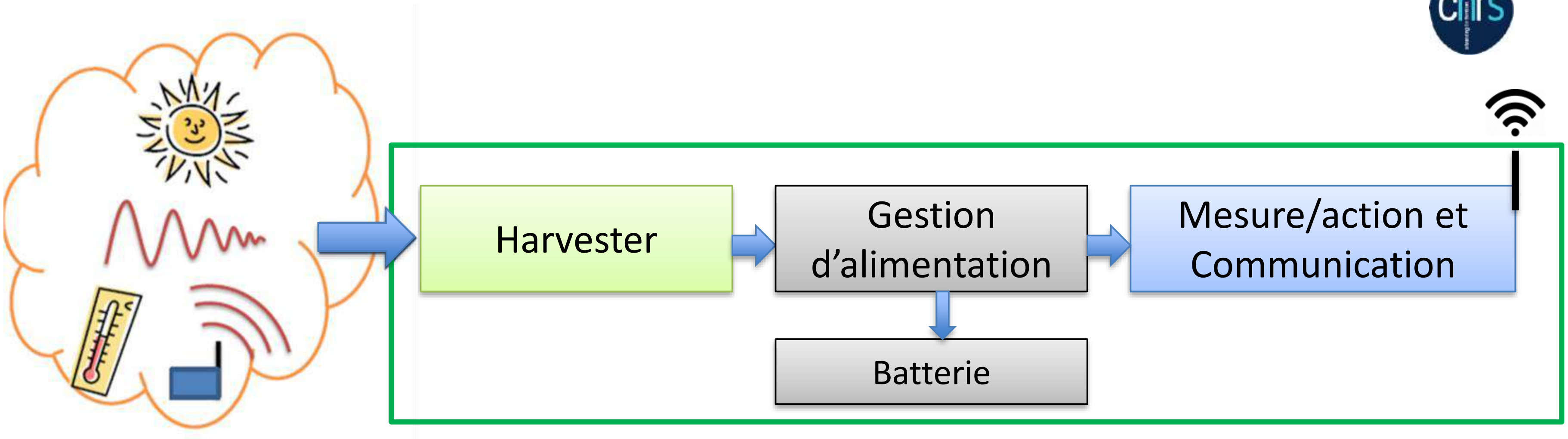






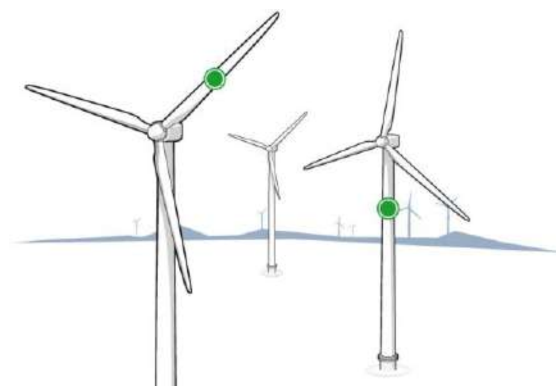
Récupération d'énergie

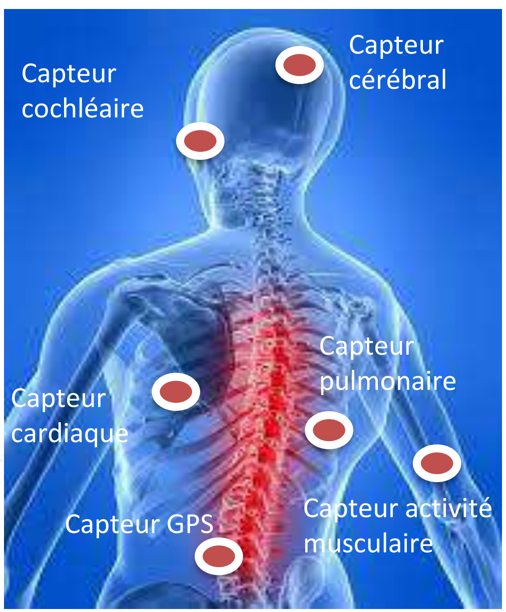
Une alternative pour l'alimentation des objets communicants



Les sources d'énergie

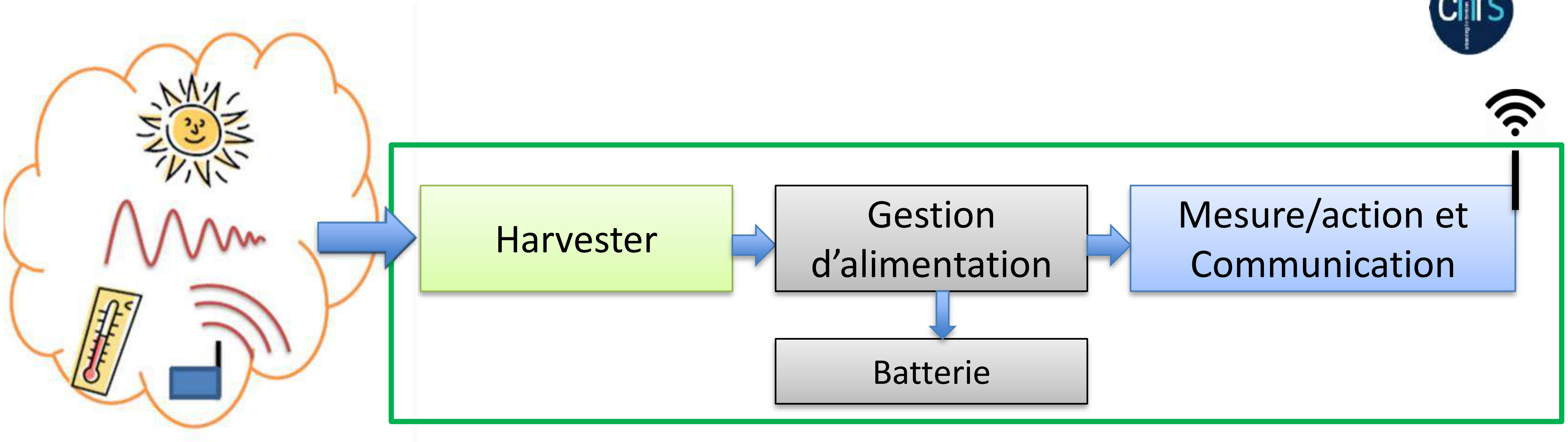
- Rayonnée : lumière, infrarouge, radio fréquence
- **Cinétique : vibration, mouvement**
- Thermique : gradients ou variations de température
- …





Récupération d'énergie

Une alternative pour l'alimentation des objets communicants



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- **Cinétique : vibration, mouvement**
- Thermique : gradients ou variations de température
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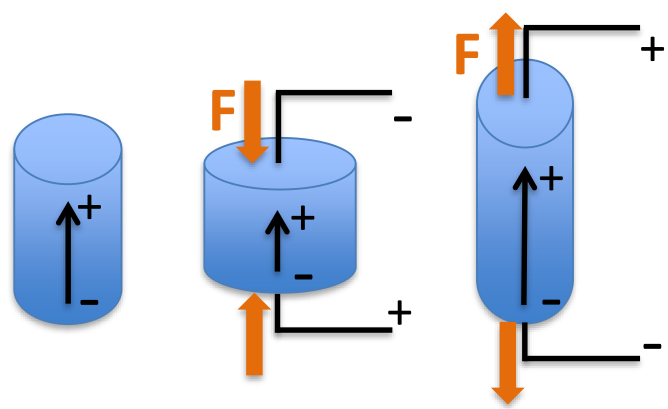


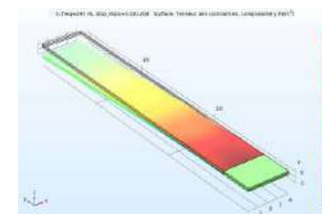
Effet piézoélectrique direct

Récupération d'énergie mécanique par les matériaux piézoélectriques … au GREMAN

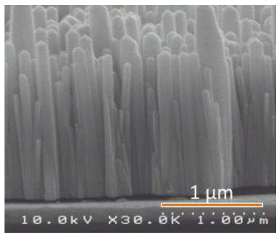
Modélisation

Modèles Analytiques ou Eléments Finis de générateurs piézoélectriques:

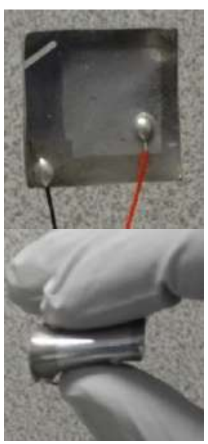
- Composites à nanofils
- Poutres vibrantes à couche piézocéramique

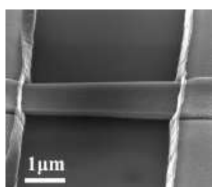


Fabrication



Synthèse de nanostructures ZnO
Fabrication de composants à nanostructures ZnO : nanogénérateurs, transistors





Caractérisation

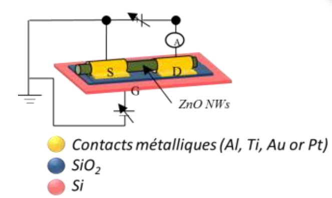
Structurale (DRX, MEB, AFM…)

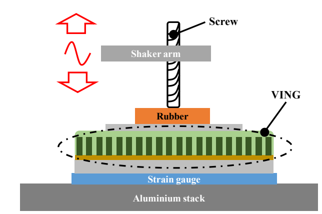
Electrique:

- Spectroscopie d'impédance
- Caractérisation I-V

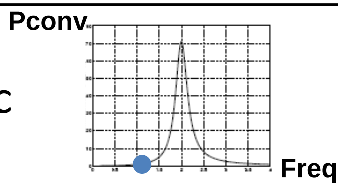
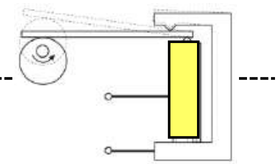
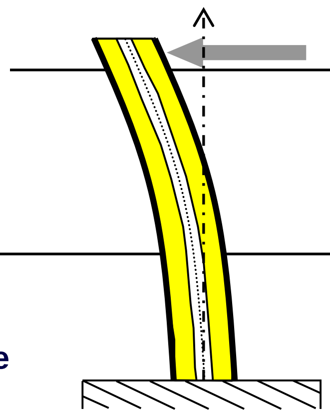
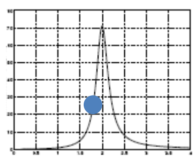
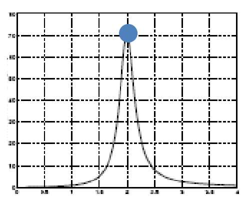
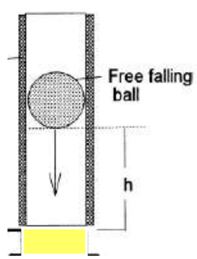
Fonctionnelle:

- Banc de test en vibration
- Banc de test en compression





Mechanical energy harvesting by piezoelectric materials

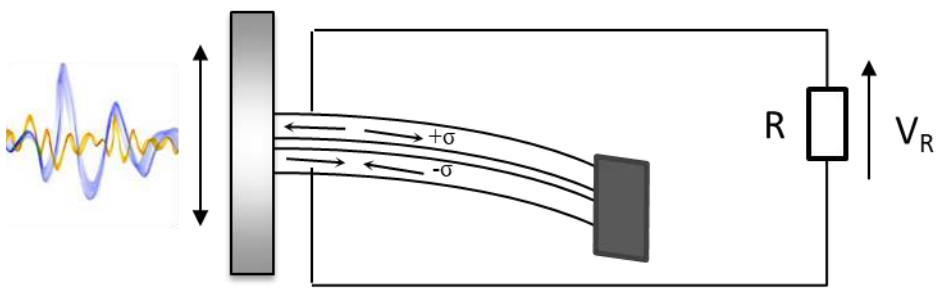
	Compression	Flexion
Quasi-static 	Quasi-static force 	Forced regime at $f < f_{resonance}$ 
Dynamic << resonance 	Dynamic force	
Dynamic at resonance 	 Impact	Forced regime at $f_{resonance}$ <u>or</u> Free vibration
	High stress	Low stress

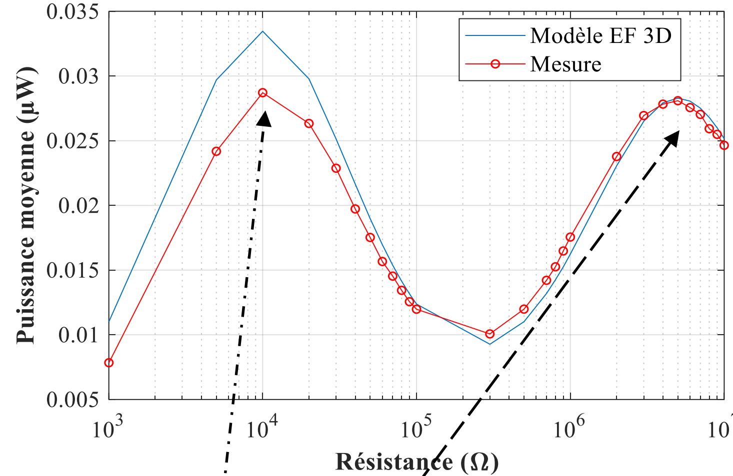
⇨ The type of mechanical excitation will determine the structure, working mode and power level.

Mechanical energy harvesting by piezoelectric materials

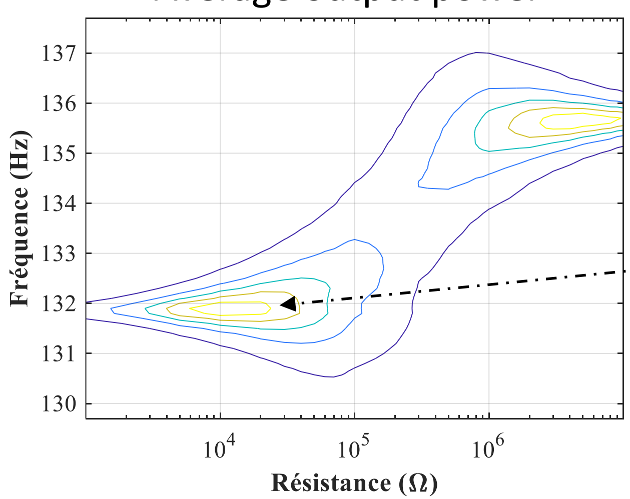
Piezoelectric bimorph :

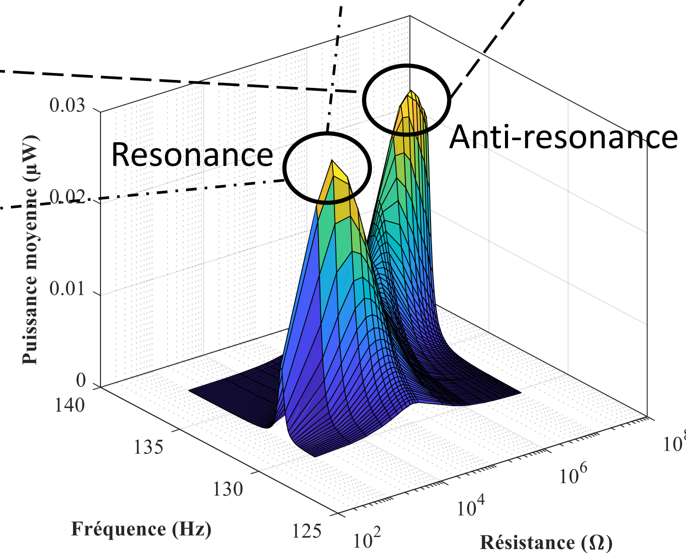
Thien HOANG, PhD thesis, 2019, in collab. with VERMON





Average output power

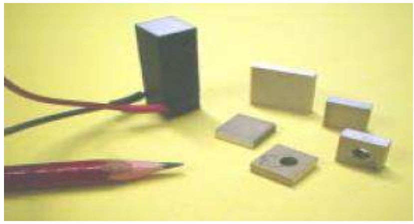




Contact:
maxime.bavencoffe@insa-cvl.fr
guylaine.poulin-vittrant@univ-tours.fr

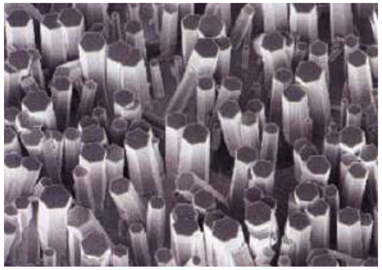
Mechanical energy harvesting by piezoelectric materials

Quartz



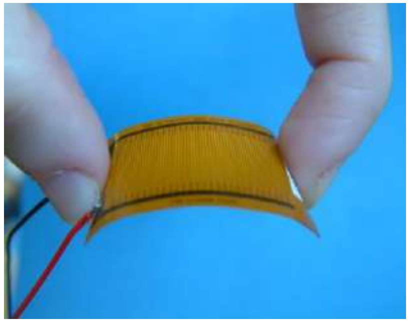
PZT ceramics (50's)

PVDF film (1969)

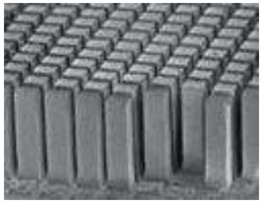


Nanowires
(early 2000)

Monocristals
(early 2000)



Macro Fibre Composites
(early 90's)



Piezocomposites
(early 90's)

Material	Quartz	$BaTiO_3$	PZT	KNN	MFC	PVDF	PZN-9PT	AlN	GaN	ZnO
d_{33} (10^{-12} m/V)	2,3	90	300 à 700	200	400	30	2500	7	1,9	10

Mechanical energy harvesting by piezoelectric materials

Choice of the best piezoelectric material for a given application: Intrinsic figure of merit?

Far from resonance:

$$FoM = d.g \qquad FoM = \frac{d.g}{\tan\delta} \qquad FoM = \frac{d^2}{\varepsilon \tan\delta}$$

⇨ Importance of piezo coefficients but also dielectric permittivity

$$FoM = \frac{d.g}{s_{33}^E} = \frac{W_{conv}}{W_{meca}} = k_{33}^2$$ ⇨ efficiency

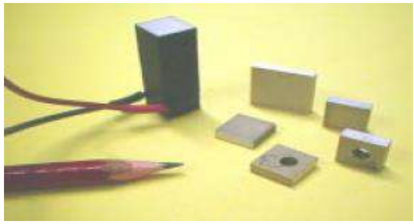
At resonance of a cantilever beam $$FoM = \frac{k_{31}^2 Q_m}{s_{11}^E}$$

⇨ Behind a FoM, some specific conditions (type of excitation and electrical load)

S. Priya, IEEE Trans. Ultrason. Ferro. Freq. Control 57(12) (2010) 2610-2612

Mechanical energy harvesting by piezoelectric materials


Quartz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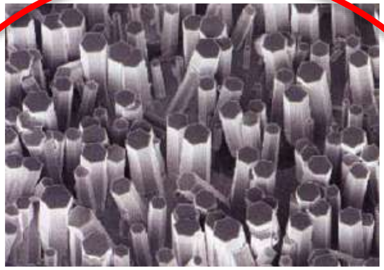
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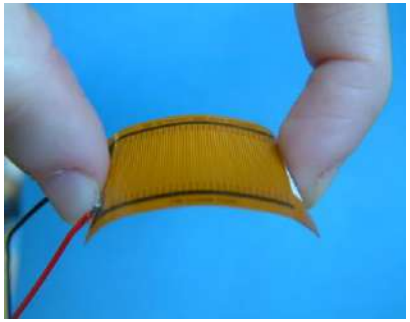
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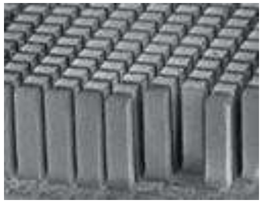
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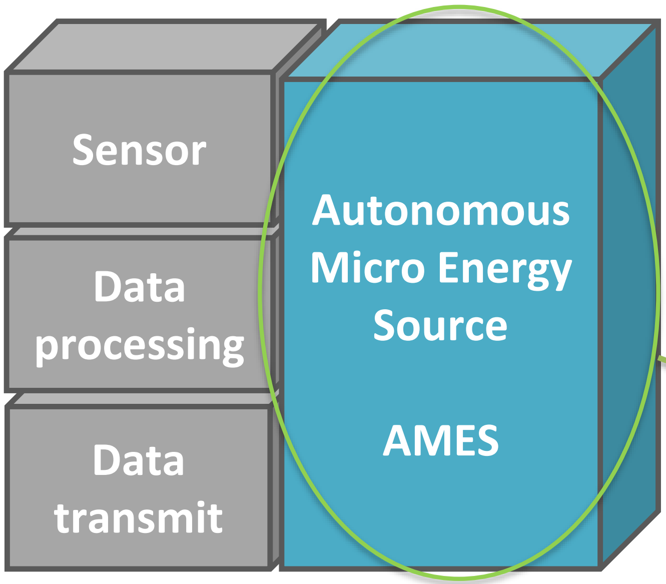
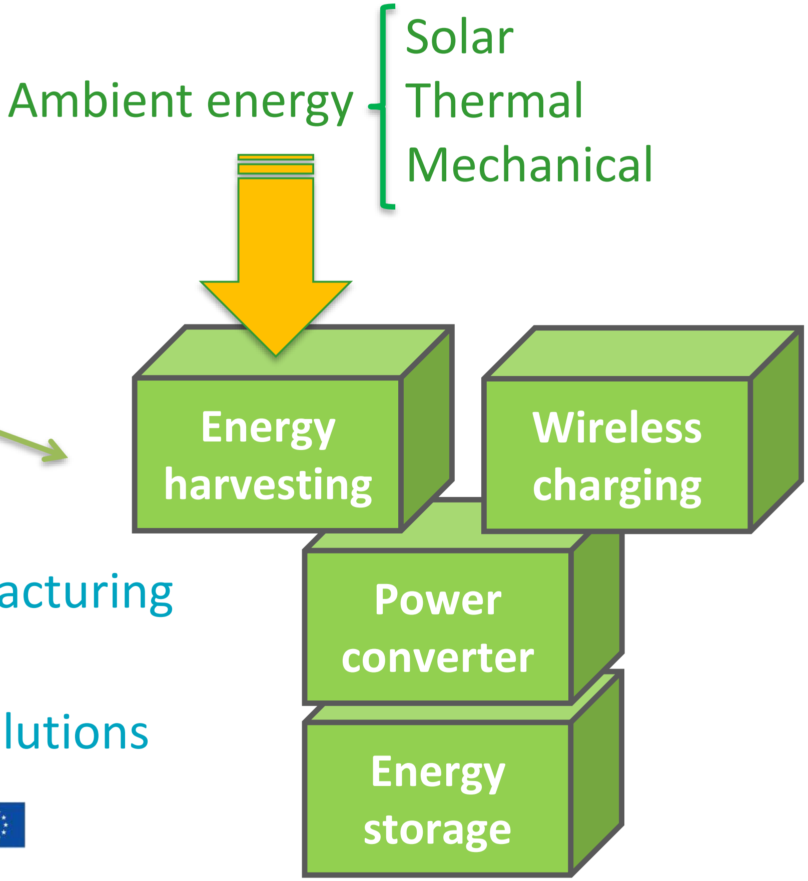
EnSO "Energy for Smart Objects' (ECSEL H2020 project, 2016-2020)

EnSO project is focusing on **Autonomous Micro Energy Sources (AMES)** :





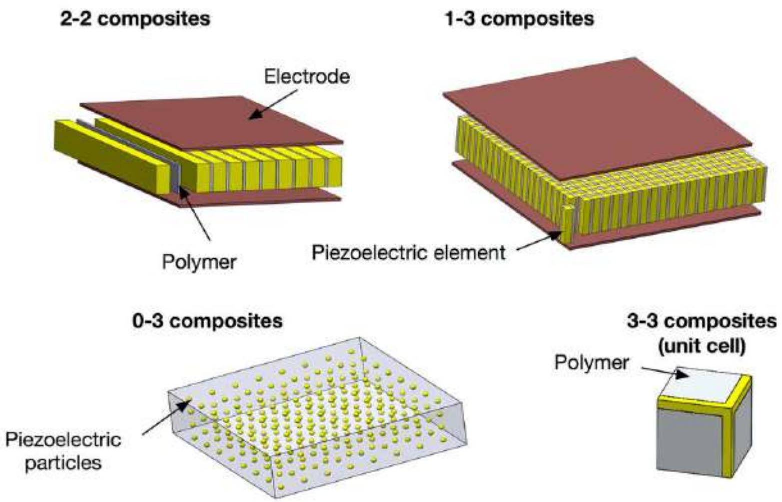
- Demonstrate the competiveness and manufacturing readiness of AMES (large scale pilot line)
- Disseminate and standardize EnSO energy solutions

http://www.enso-ecsel.eu

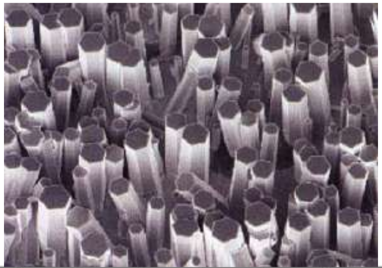
ECSEL Joint Undertaking
Electronic Components and Systems for European Leadership

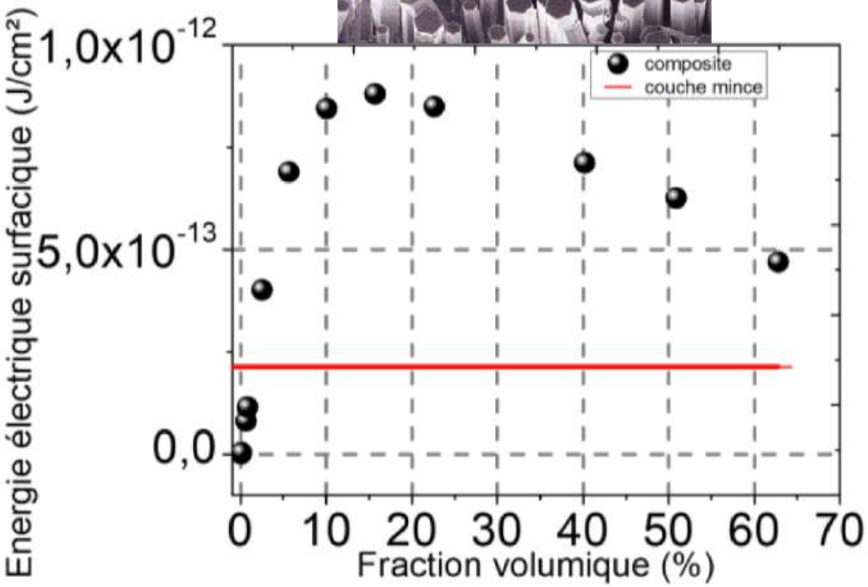
Mechanical energy harvesting by piezoelectric materials

Effect of composite structuration



H J Lee et al., Sensors 2014, 14, 14526-14552



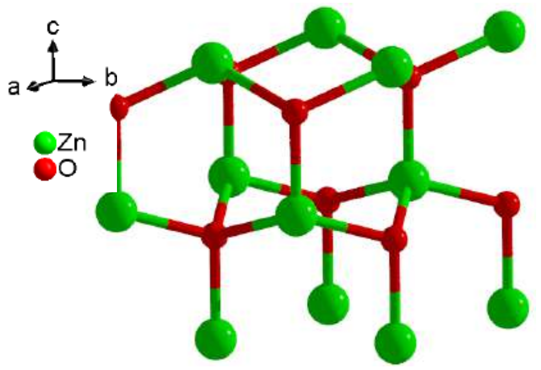


S. Boubenia, Thèse Univ. Tours, 2019

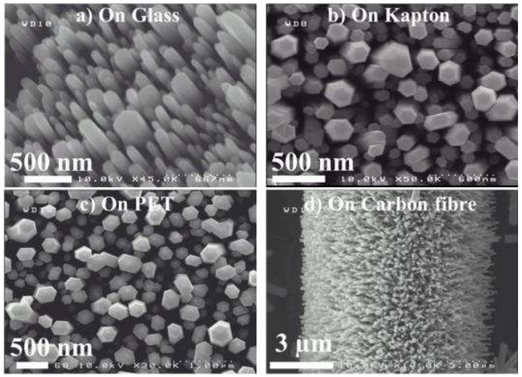
Piezoelectric nanogenerators incorporating ZnO nanowires

Zinc oxide nanostructures : a multi-functional material

Wurtzite type crystal structure of ZnO

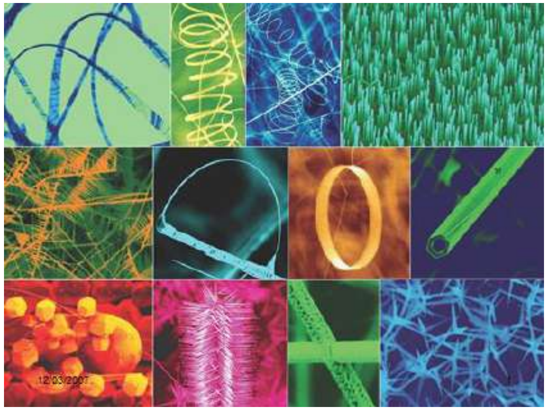


Substrate compatibility



Opoku et al. Nanotechnology 26 (2015) 355704

Large family of nanostructures

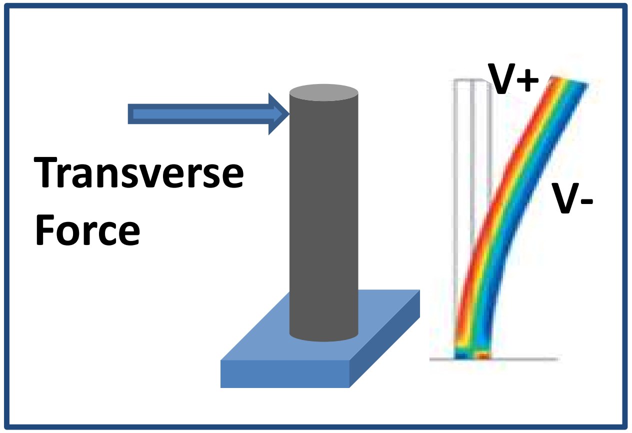


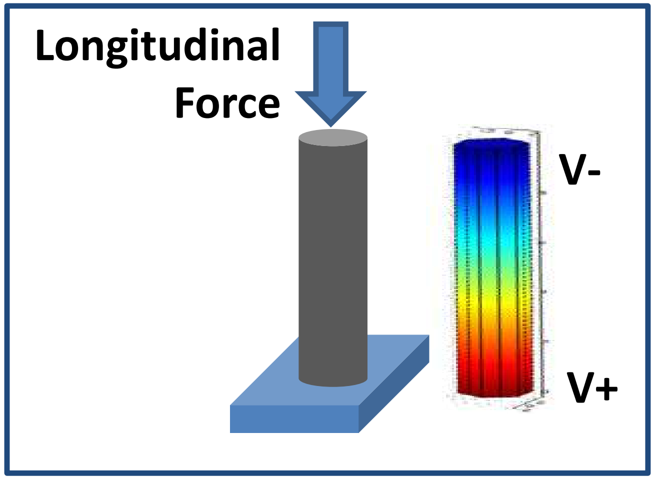
Wang et al., Materials today 7, 6 (2004) 26–33

- ✓ Single-crystalline highly aligned ZnO NWs
- ✓ Large area NWs arrays on a variety of substrates: silicon, glass and plastic
- ✓ Preferentially c-axis oriented perpendicular to the growth substrate
- ✓ Semiconducting : wide band gap of 3.37 eV at room temperature
- ✓ Piezoelectric : higher piezo coefficient than bulk ZnO

Piezoelectric nanogenerators incorporating ZnO nanowires

Zinc oxide nanostructures : a multi-functional material





Main attractions:

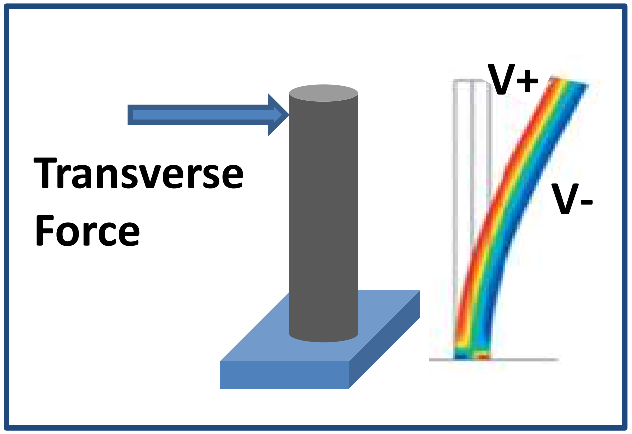
- ❑ Higher piezo coefficient compared to bulk ZnO

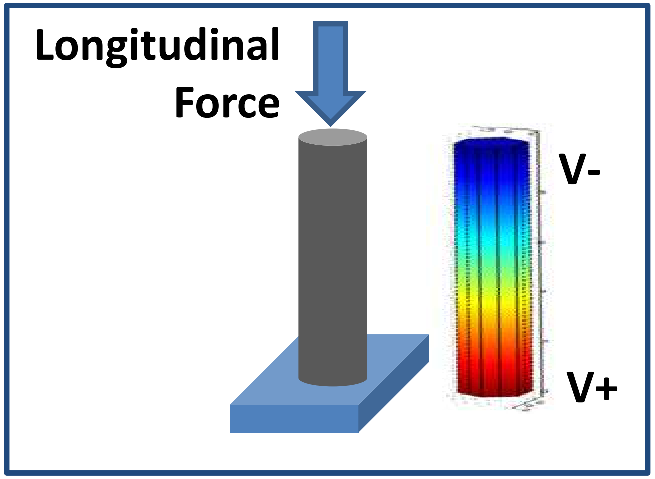
Matériau	Matériau massif (expérimental)		Echelle nanoscopique (expérimental)	
	d_{33} (10^{-12} m/V)	E (GPa)	d_{33} (10^{-12} m/V)	E (GPa)
ZnO	9.93	164	14-26.7	100
GaN	1.86	397	12.8	43.9
PZT	650	N/A	101	46.4-99.3
PVDF	-25	N/A	-38	0.39

E. L. Perez, Thèse Univ. Grenoble Alpes, 2016

Piezoelectric nanogenerators incorporating ZnO nanowires

Zinc oxide nanostructures : a multi-functional material





<u>Main attractions:</u>

- ❑ Higher piezo coefficient compared to bulk ZnO
- ❑ Does not fracture easily [1]
- ❑ Failure of one nanowire (NW) may not compromise operation
- ❑ Energy generation over a range of frequencies (1Hz to some 100 Hz)
- ❑ Biocompatible

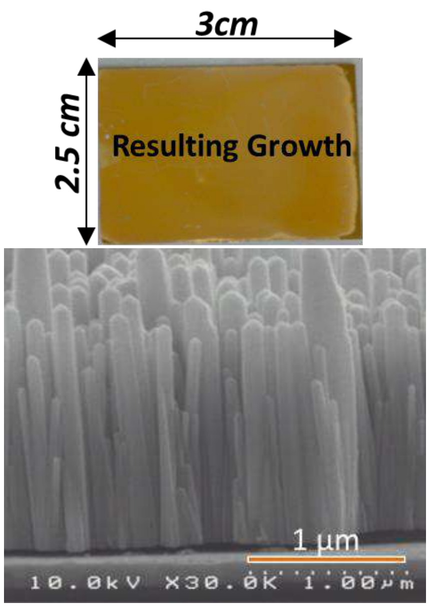
[1] H. D. Espinosa et al., Adv. Mater. 2012, 24, 4656-4675

Piezoelectric nanogenerators incorporating ZnO nanowires

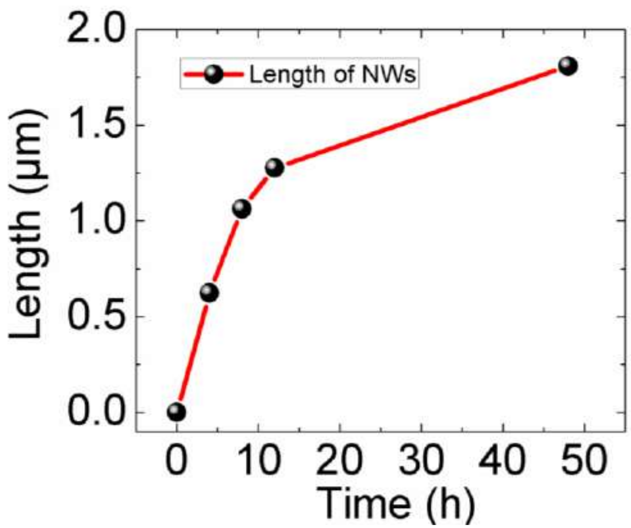
Hydrothermal synthesis of ZnO nanowires (NWs):

Reactants:

- Zinc nitrate hexahydrate : $Zn(NO_3)_2 \cdot 6H_2O$
- HMTA (Hexamethylenetetramine) : $(CH_2)_6N_4$
- Ammonia : NH_4OH



NWs length versus growth time



Major advantages:

- ✓ Low temperature (85-100 ˚C)
- ✓ Compatible with industrial processes

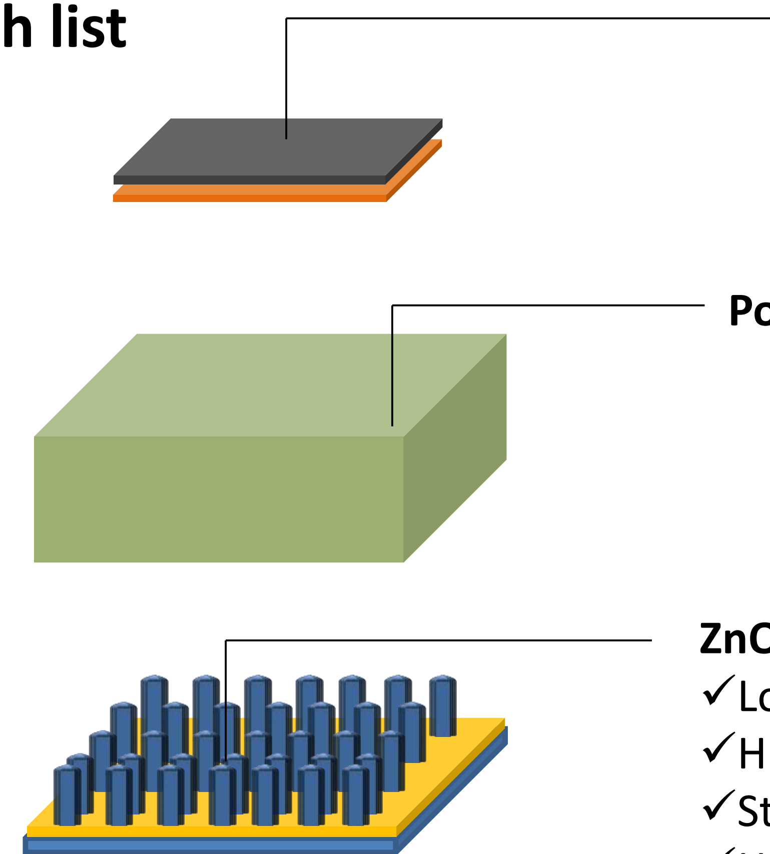
Major limitations:

- ✓ Defects ⇨ decrease of output voltage

Opoku et al., Nanotechnology 26 (2015) 355704
Opoku et al., RSC Adv. 5 (2015) 69925-69931
Boubenia et al., Scientific Reports (2017)

Piezoelectric nanogenerators incorporating ZnO nanowires

Wish list



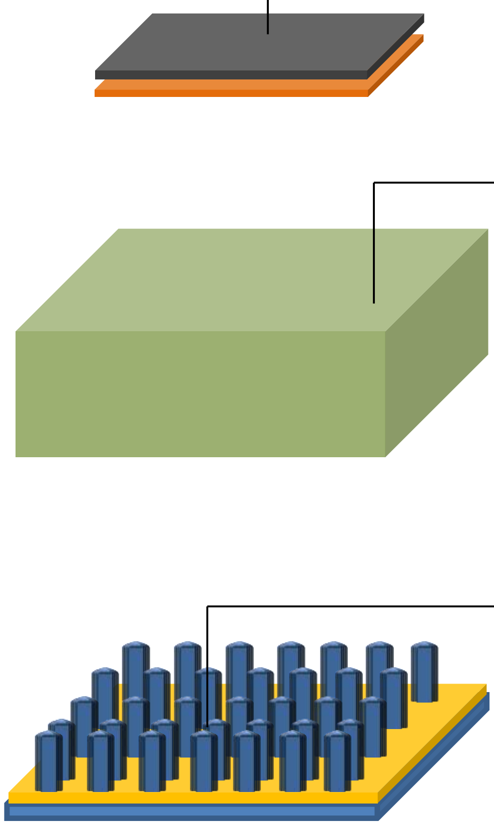
ZnO NWs

✓Low-cost synthesis : hydrothermal synthesis (85°C)
✓Highly orientated along polar axis
✓Strong NW adhesion to substrate
✓High quality ZnO NWs : intensive research on how to decrease the intrinsic N-type doping of ZnO NWs (usually $10^{18}cm^{-3}$) by 1 or 2 decades

All must be performed at temp <100°C

Piezoelectric nanogenerators incorporating ZnO nanowires

Wish list



Top contact

Polymer matrix

- ✓Fully conformal
- ✓Strong adhesion
- ✓Simple deposition
- ✓Allow NWs to flex
- ✓Creates capacitive coupling

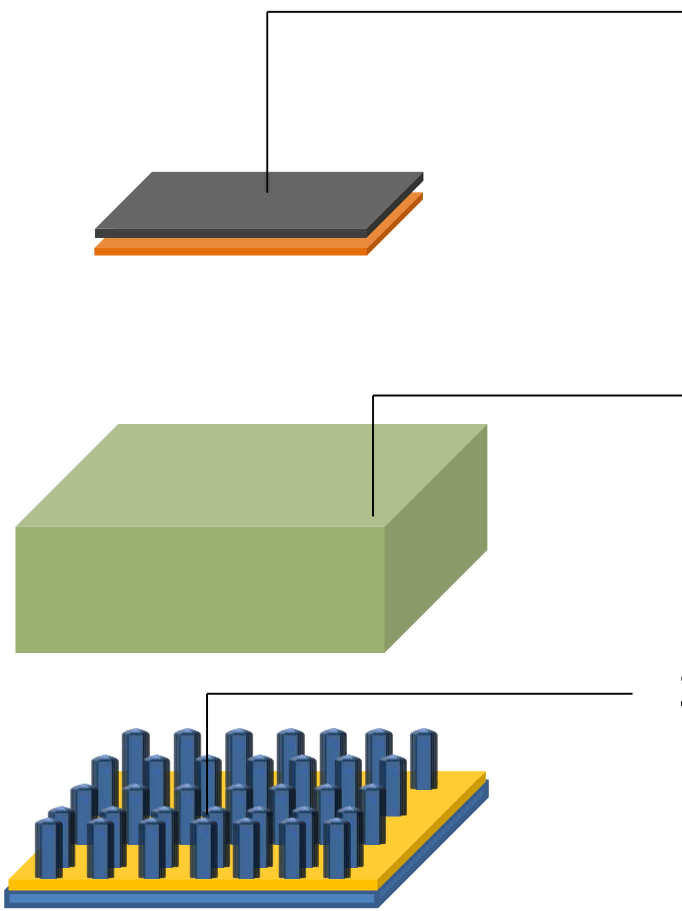
Parylene C deposited by CVD (Chemical Vapor Deposition)

ZnO NWs

All must be performed at temp <100ºC

Piezoelectric nanogenerators incorporating ZnO nanowires

Wish list



Top contact

- ✓Good adhesion on polymer
- ✓Electrically conductive
- ✓Mechanically robust

} Ti/Al electrode deposited by sputtering

- ✓Flexible if the whole NG is ⇨ research on flexible electronics

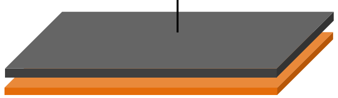
Polymer matrix

ZnO NWs

All must be performed at temp <100ºC

Piezoelectric nanogenerators incorporating ZnO nanowires

Wish list



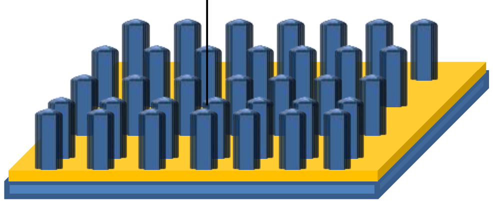
Top contact

- ✓Good adhesion on polymer
- ✓Electrically conductive
- ✓Mechanically robust

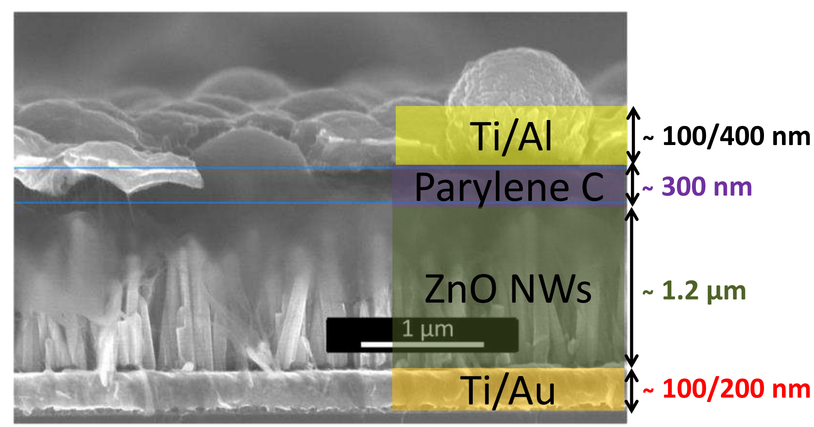
Ti/Al electrode deposited by sputtering

- ✓Flexible if the whole NG is ⇨ research on flexible electronics

Polymer matrix



ZnO NWs



Manufacturing process : video available on https://youtu.be/n9-4dSQrveU

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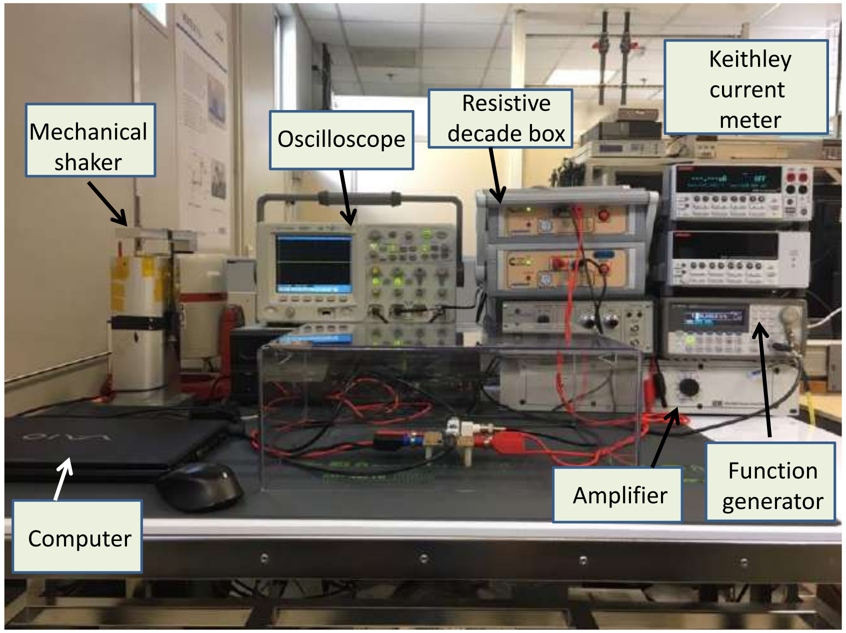
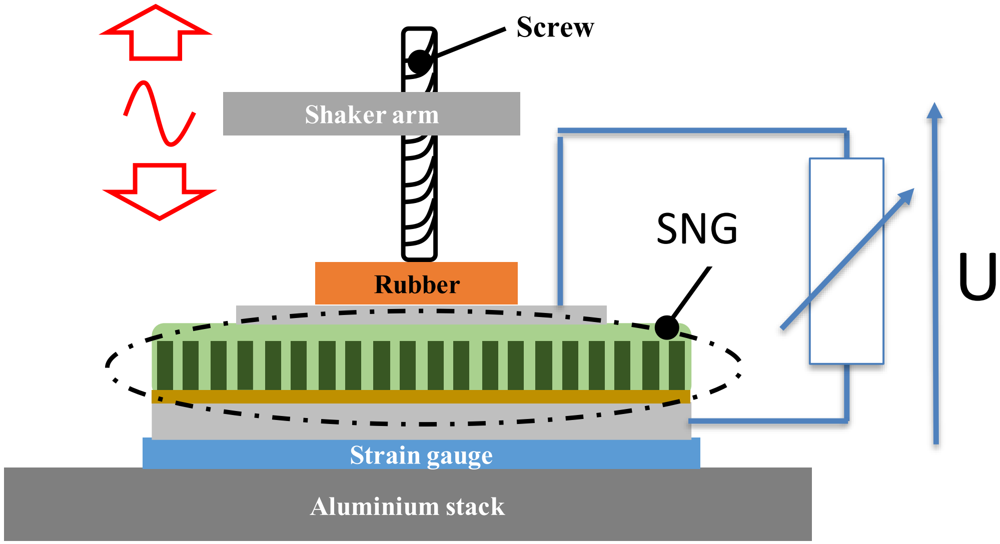
Dedicated test bench for piezogenerators





- Compressive force in contact or impact mode up to 13N, 10Hz
- Voltage measured via a high input impedance double buffer circuit
- Variable resistive load up to 130 MΩ

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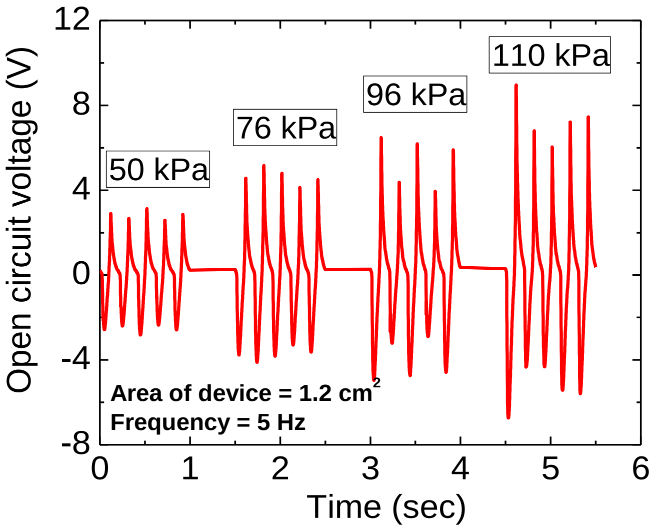
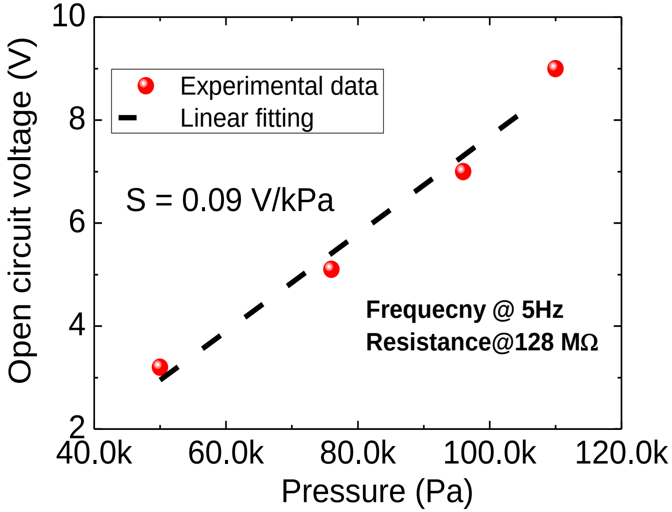
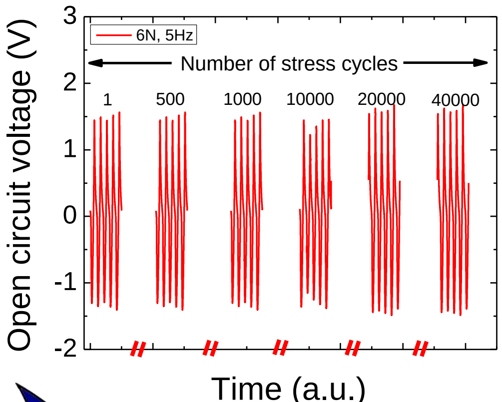
Varying compressive force

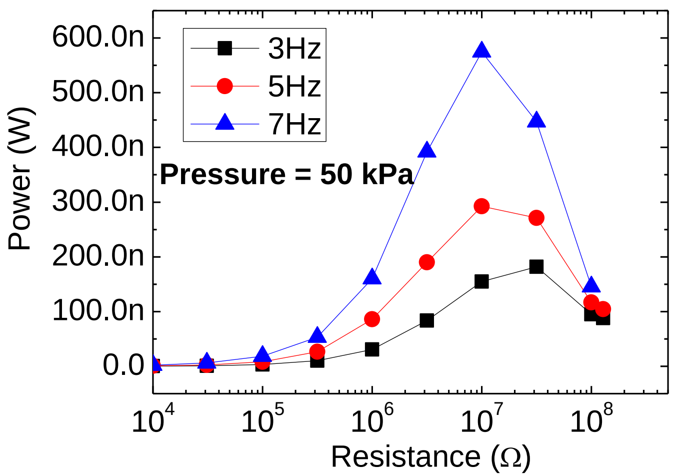




Durability test



Power vs load resistance



- High pressure sensitivity of ~0.1 V/kPa
- @ 3 N, 7 Hz, 1 cm^2:

Peak power : 0.6 µW

Average power : 0.1 µW

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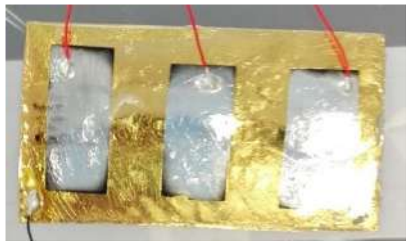
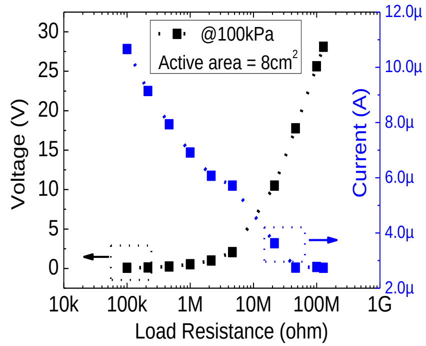
Large area device on bank cards

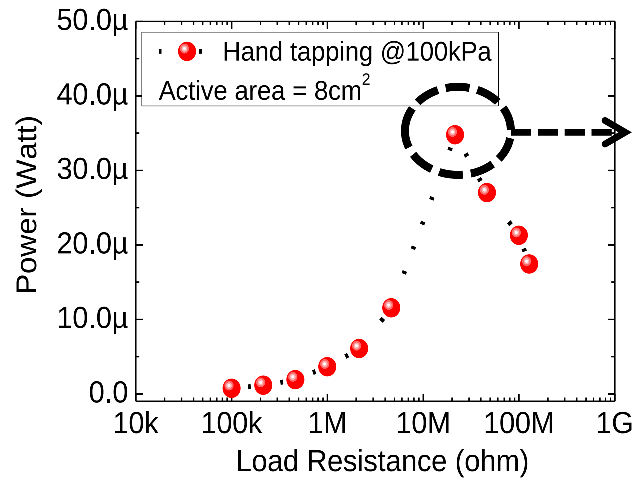
Front side

Back side



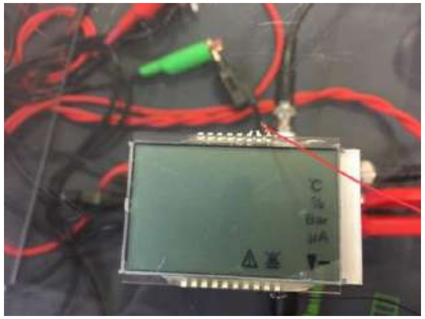
Hand excitation





35 µW

Direct connection with LCD



Drive electronic devices such as Liquid Crystal Display

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http://www.nanofil-flexible.fr/

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