2nd

EU-JAPAN DIGITAL WEEK 2026

23 March - 30 March 2026

Tokyo, Japan

The EU-Japan Digital Week is organised as part of the EU-Japan Digital Partnership

ZnO thin films and nanowires for piezoelectric energy transducer applications

Gustavo Ardila

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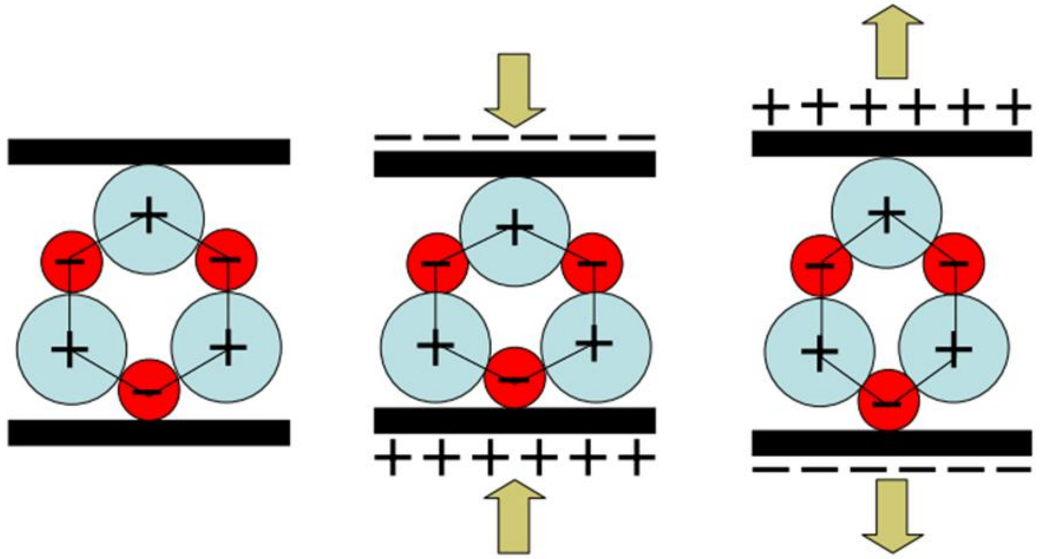
Context – Piezoelectric energy conversion

Materials with non-centrosymmetric crystal structure (ex: Quartz, PZT, AlN, GaN, ZnO, etc.)



1) Direct effect : Force → Electric field

Sensors and energy harvesting

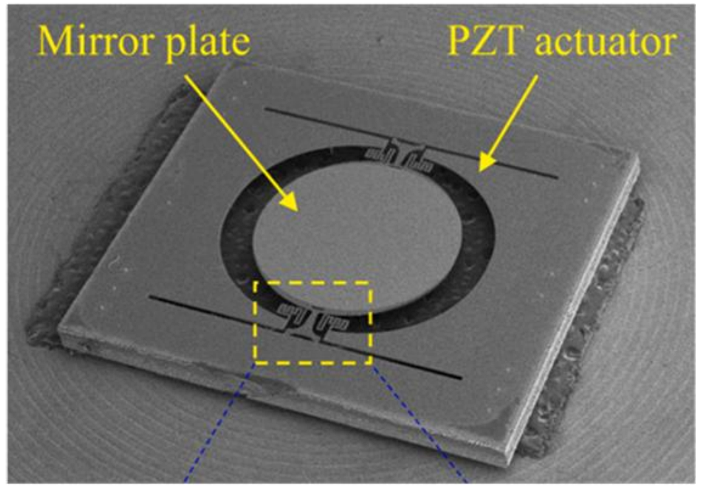
2) Reverse effect : Electric field → strain

Actuators

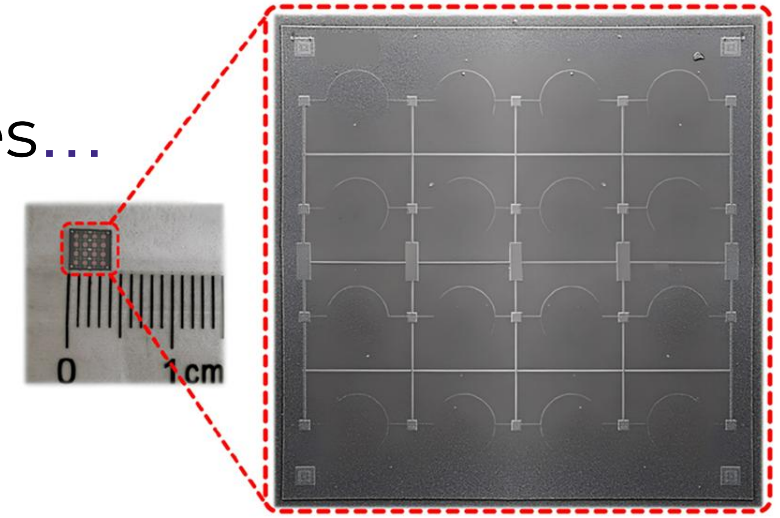
Applications

Thin piezo-films in...

Haptics, microphones...



MEMS scanning mirror **[1]**



Ultrasound sensors (PMUT) **[2]**

[1] Cheng et al. Sensor actuat a-phys, 2023

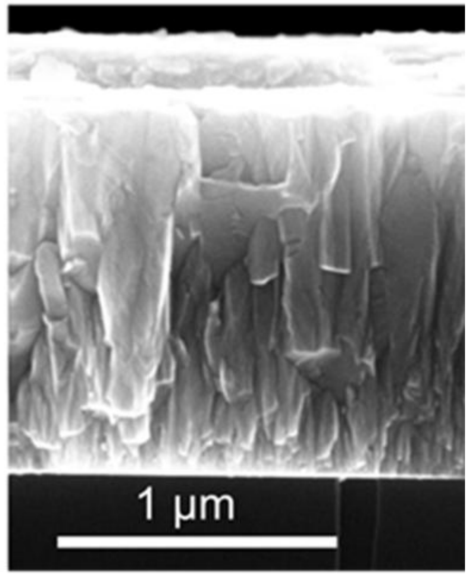
[2] Zhang et al.IEEE Internet of things J., 12, 16, 2025

Context – Piezoelectric energy conversion

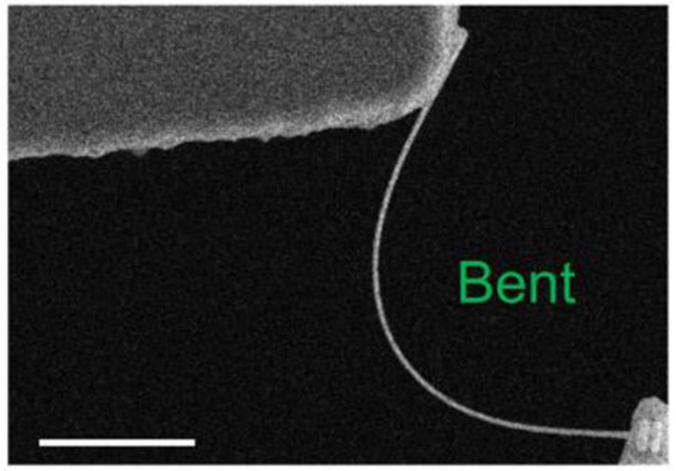
Materials with non-centrosymmetric crystal structure (ex: Quartz, PZT, AlN, GaN, ZnO, etc.)

- Replace toxic components : (Restriction of Hazardous Substances Directive in Europe (RoHS 2011) limits Pb element

- Use non critical materials, abundant and biocompatible



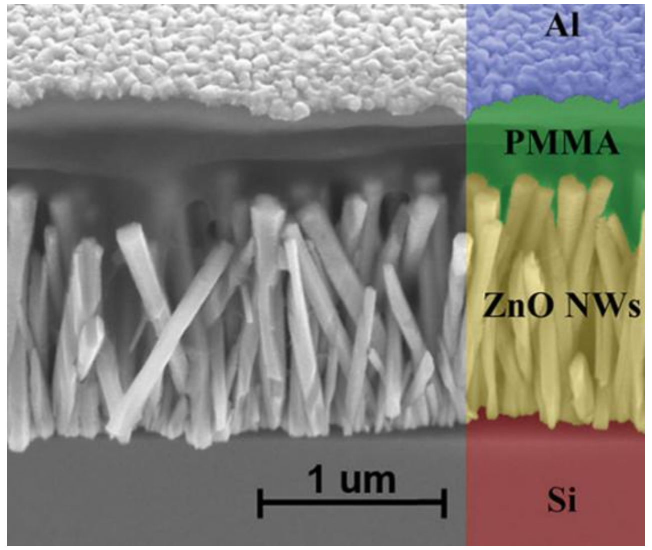
ZnO thin films [1]



ZnO nanowires (NWs) [2]

Advantage of piezo NWs

- Higher flexibility
- High sensitivity to small forces
- Enhanced piezoelectric properties…



Nanocomposites [3]

[1] H. Ocku et al. Submitted, 2025

[2] G. Cheng et al., Nature Nanotech. 10 2015

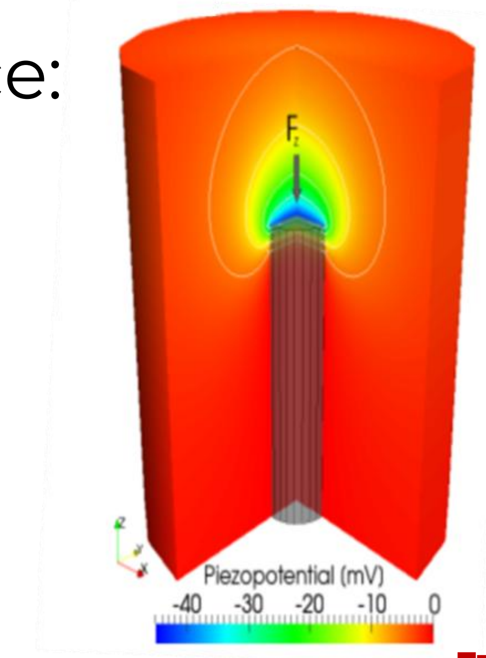
[3] R. Tao et al., Semicond. Sci. Technol. 32(6), p. 064003 2017; M. Manrique et al., Nano Trends 9 p. 100066 2025

Context – Piezoelectric energy conversion

Materials with non-centrosymmetric crystal structure (ex: Quartz, PZT, AlN, GaN, ZnO, etc.)

- ZnO is a semiconductor (unintentionally doped during the growth). n-doped

Reduce piezo performance: "screening"



[1]

[1] Romano G. et al. 22, 465401, 2011

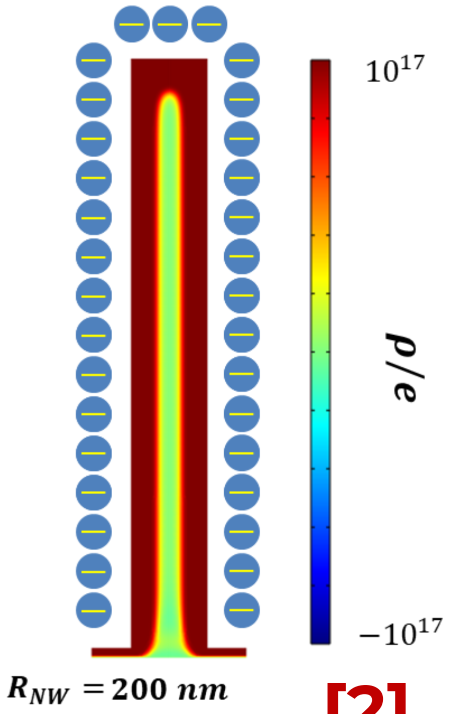
[2] T. Jalabert et al., Nanotechnology 34 115402 2023

[3] R. Tao et al., Adv. Electron. Mater., 4(1), p. 1700299 2018

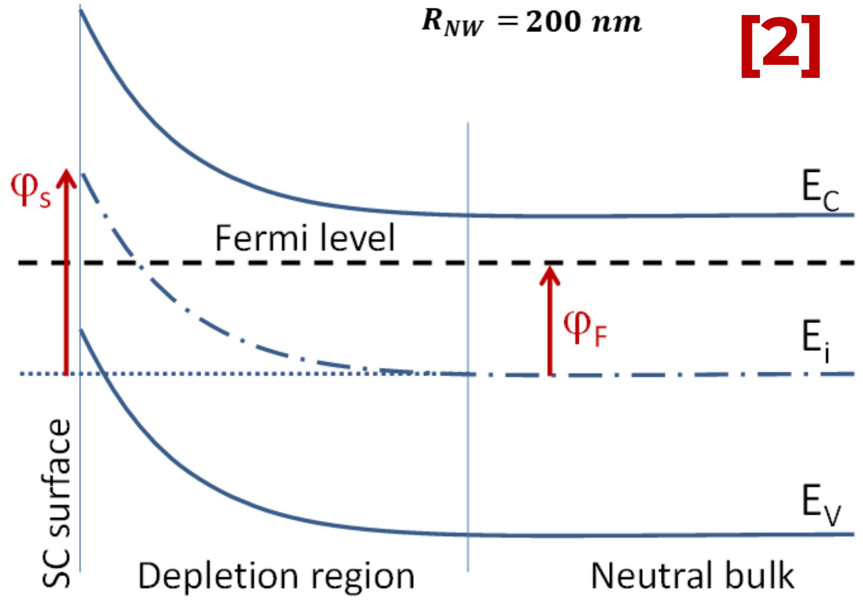
Context – Piezoelectric energy conversion

Materials with non-centrosymmetric crystal structure (ex: Quartz, PZT, AlN, GaN, ZnO, etc.)

- ZnO is a semiconductor (unintentionally doped during the growth). n-doped → Reduce piezo performance: "screening" ☹
- Surface states (surface traps) depletion zone inside the semiconductor → Compensate "screening" ☺



[2]



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[1] Romano G. et al. 22, 465401, 2011

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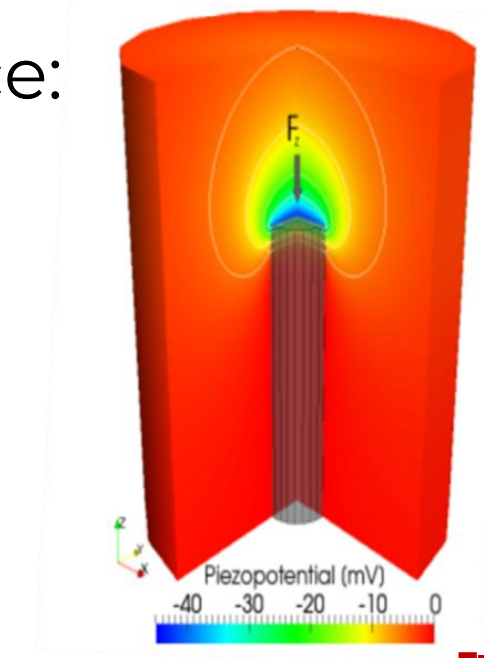
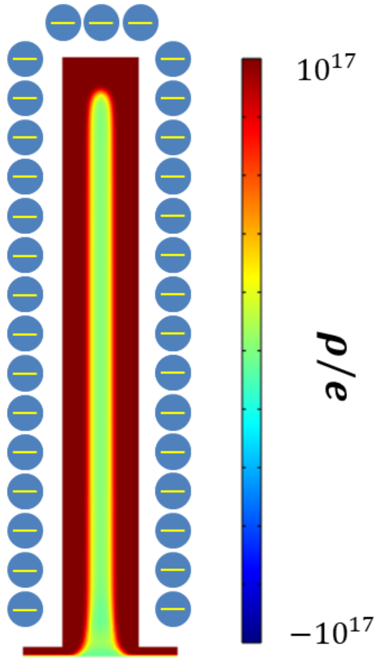
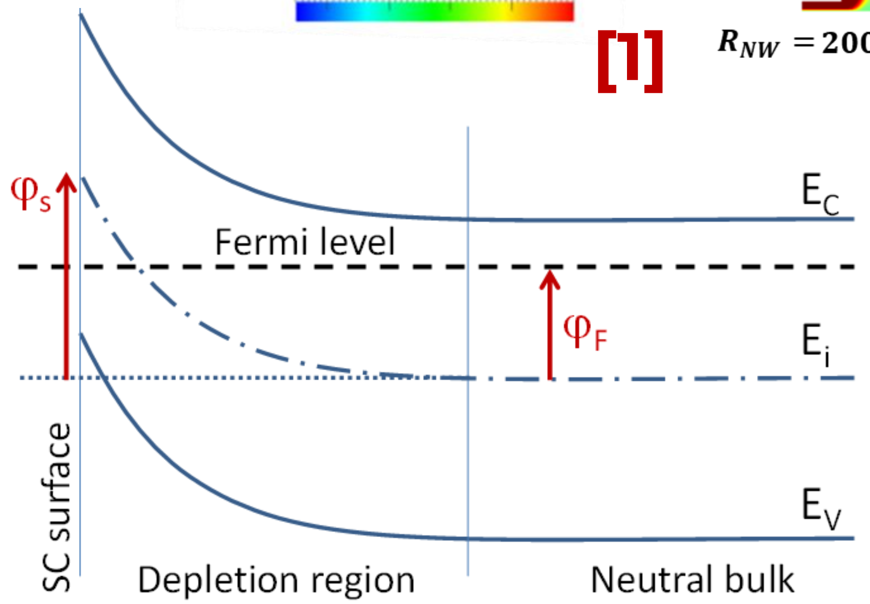


[1]



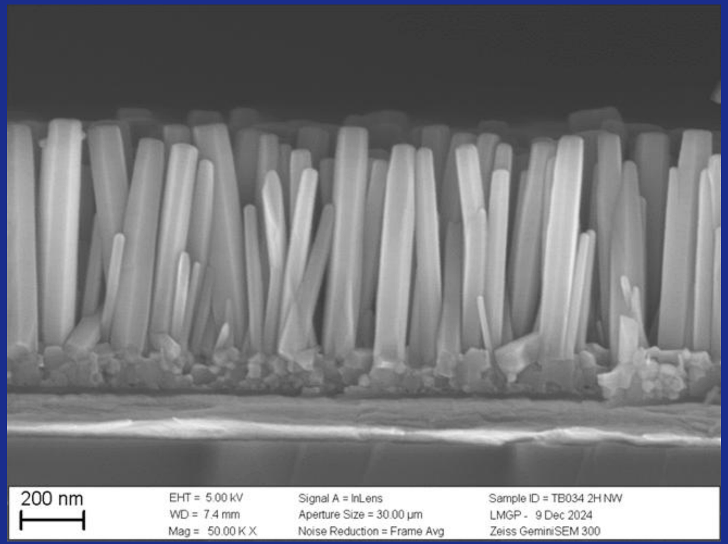
[2]

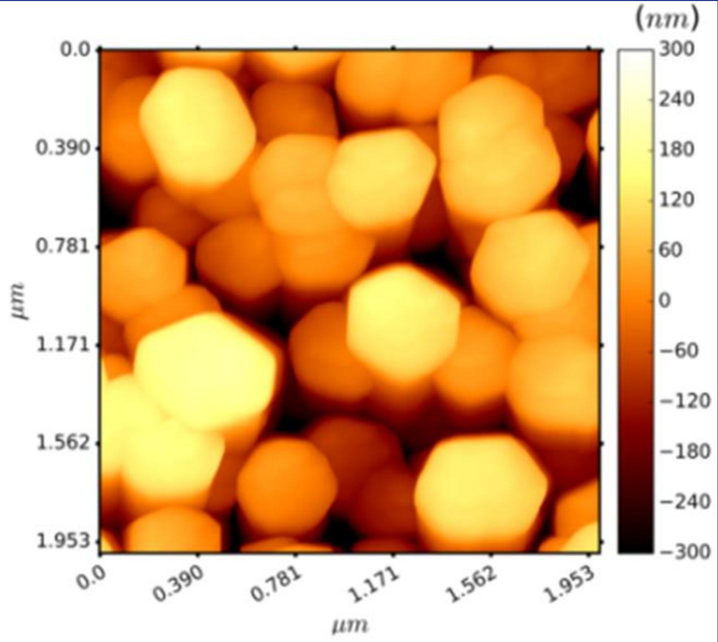


[3]

- Strong interaction between semiconductor and piezoelectric properties
- Experiments and models : Provide guidelines for performance optimization

[1] Romano G. et al. 22, 465401, 2011
[2] T. Jalabert et al., Nanotechnology 34 115402 2023
[3] R. Tao et al., Adv. Electron. Mater., 4(1), p. 1700299 2018



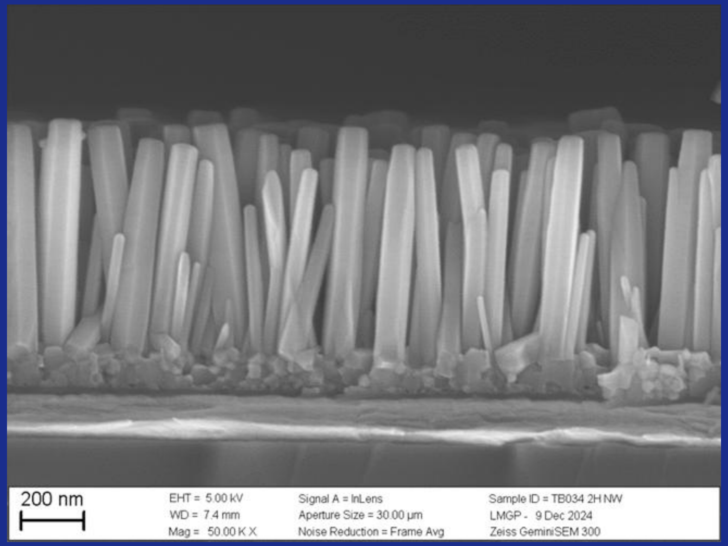


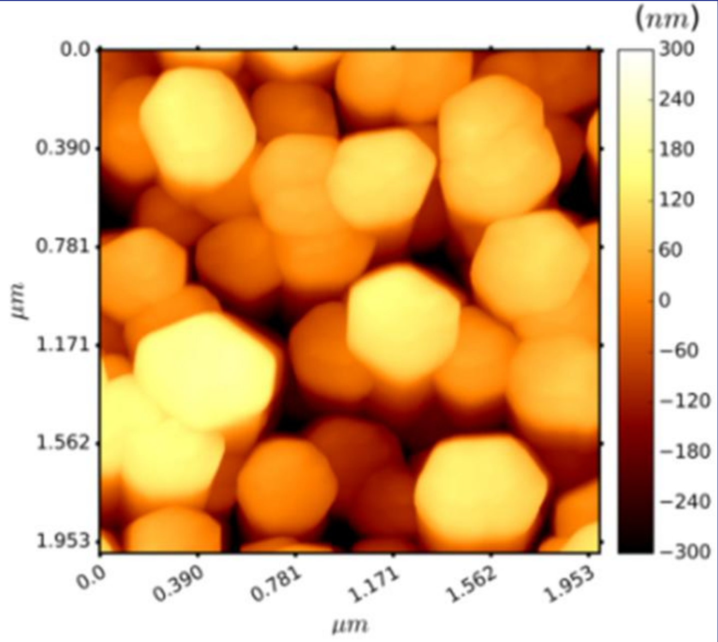
Outline

1 Samples : ZnO Nanowires and thin film fabrication

2
- AFM characterization techniques
- PFM, SMIM, C-AFM, KPFM
- Correlation with models

3 Conclusions and perspectives





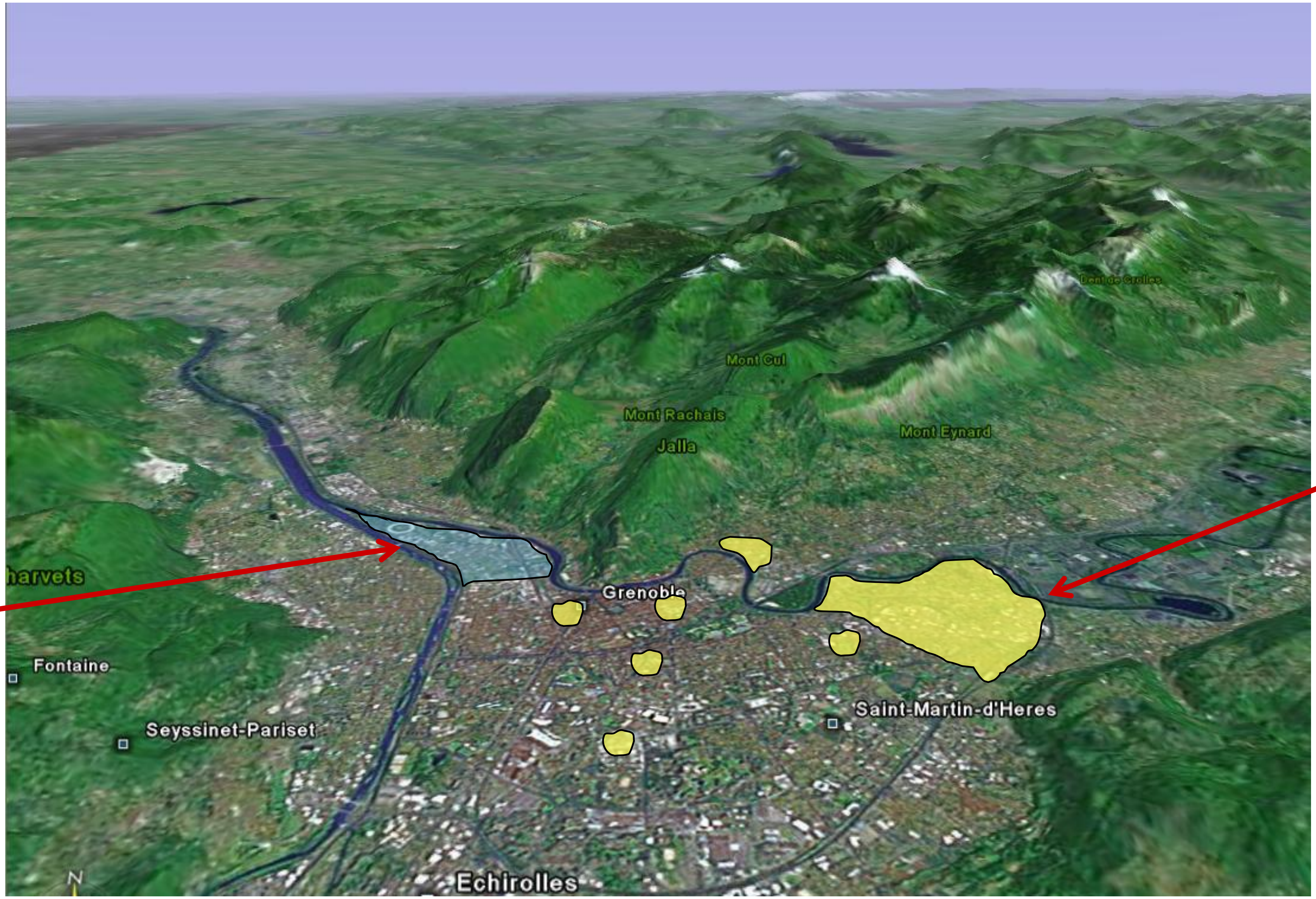
Outline

1 Samples : ZnO Nanowires and thin film fabrication

Grenoble Alpes University

~5500 Academic + adminstrative staff
~45000 Students

GIANT
Minatec



UGA Université Grenoble Alpes

GRENOBLE INP UGA

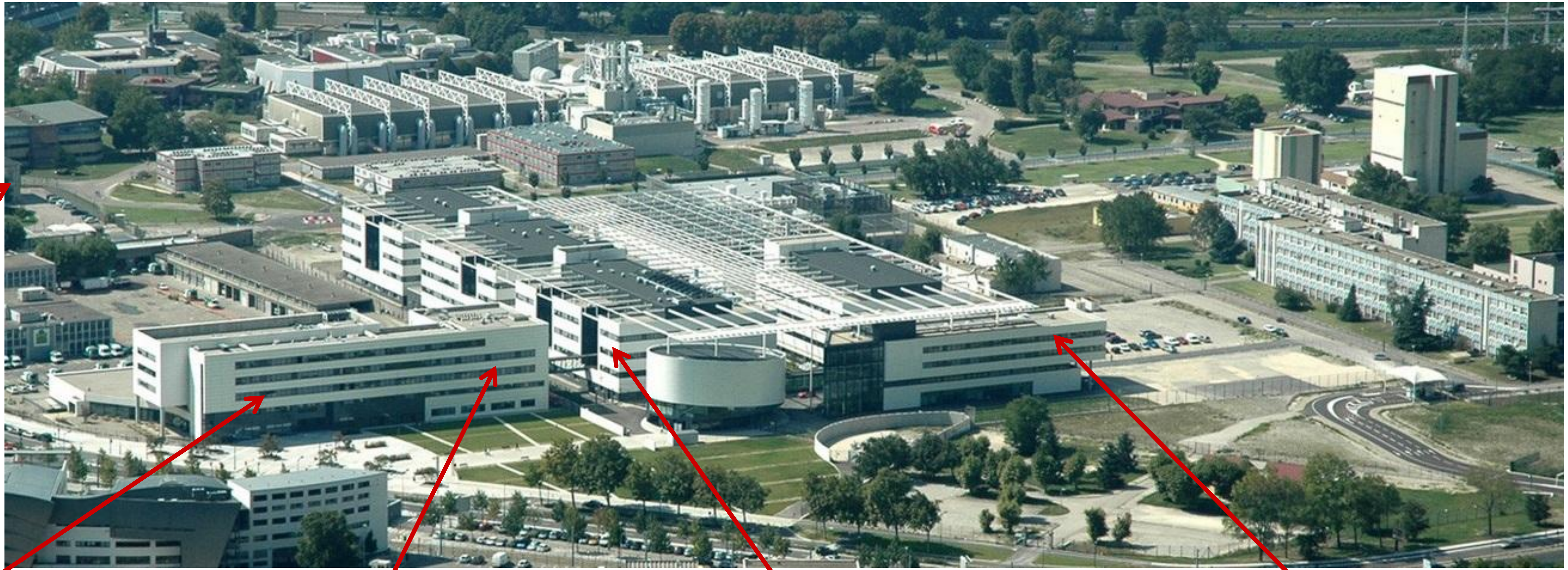
Grenoble and research GIANT Campus

✓ Towards GIANT:
(30k people)

Energy + Biology + Economy + Fundamental science + **Micro nano technology**

MINATEC

CROMA in MINATEC



LTM
LABORATOIRE DES TECHNOLOGIES DE LA MICROÉLECTRONIQUE

Integration Technologies, microelectronics

Phelma

GRENOBLE INP UGA

LMGP

Material science

croma

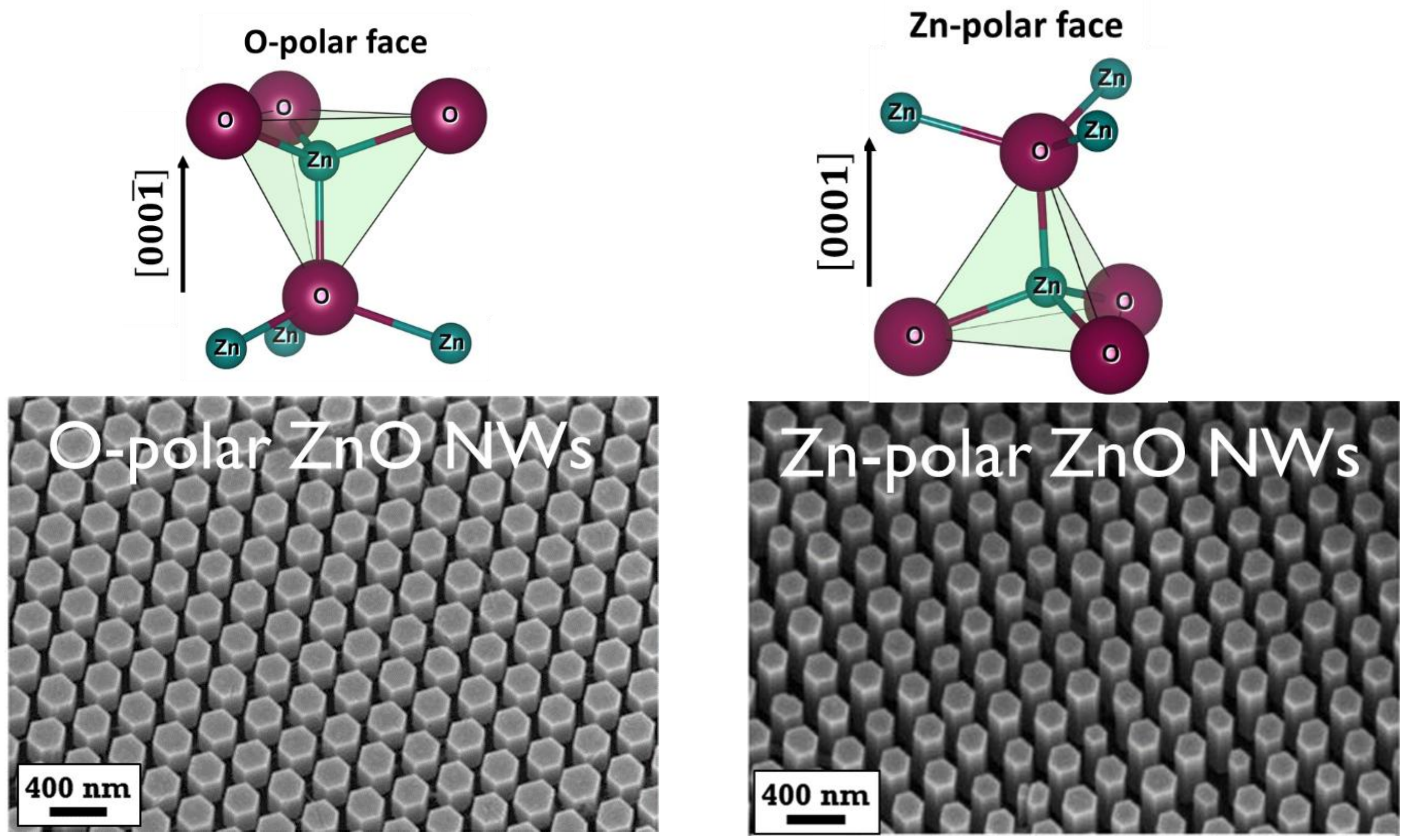
Characterization, simulation + clean room facilities

leti
cea tech

ZnO Nanowires

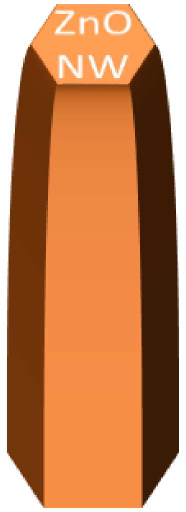
***1.** Substrate + ZnO Seed Layer*

***2.** Substrate + ZnO Seed Layer + As-Grown ZnO Nanowires*



Polarity control **[1]**

V. Consonni, LMGP



Acceptors

Cu(II) species

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

Sb(III) species

J. Villafuerte *et al.* Nano Energy 114, 108599 (2023)

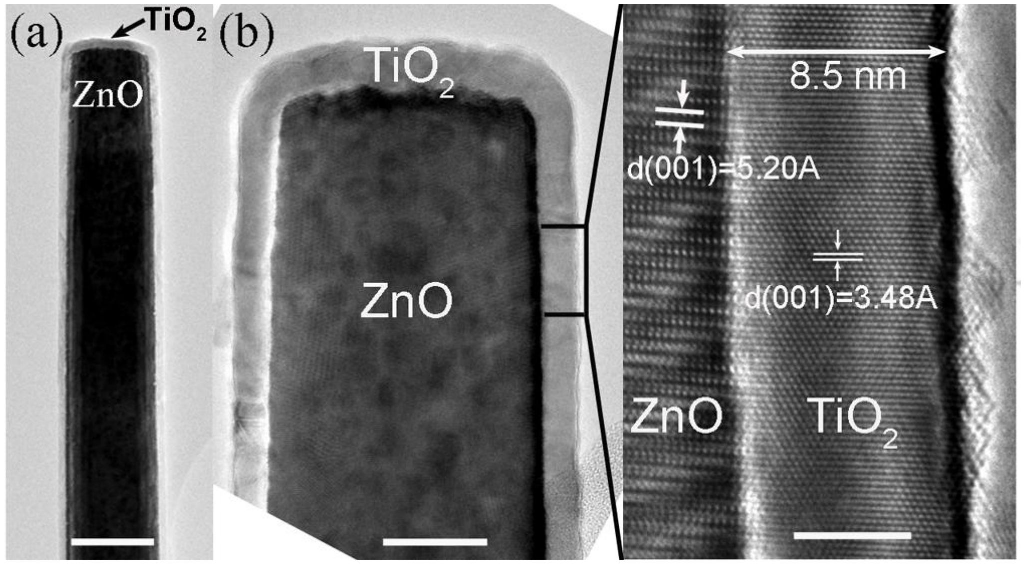
Control doping concentrations
Key for piezoelectricity

The incorporation into ZnO nanowires is achieved by optimizing the pH value to promote electrostatic and chemical forces favoring the adsorption of chemical species containing the dopants

[1] V. Consonni et al. ACS Nano 8, 4761 (2014)

ZnO Nanowires

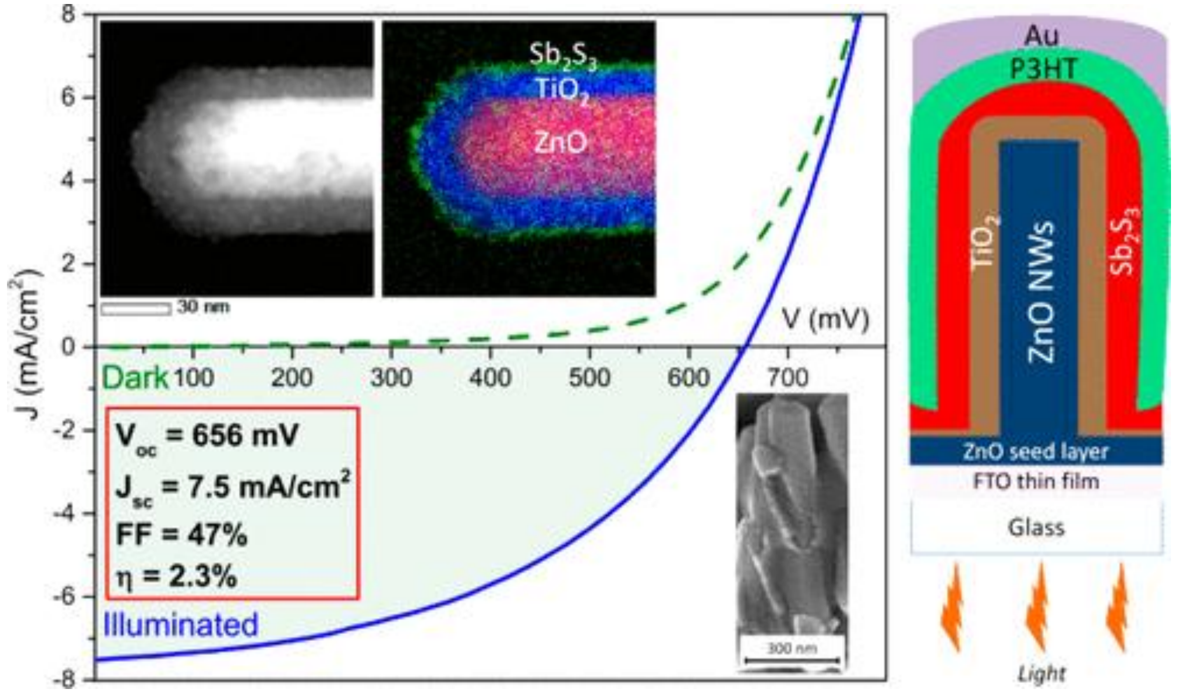
Epitaxial TiO_2 passivation layer



T. Cossuet *et al*. J. of Phys. Chem. 124, 13447 (2020)

V. Consonni, LMGP

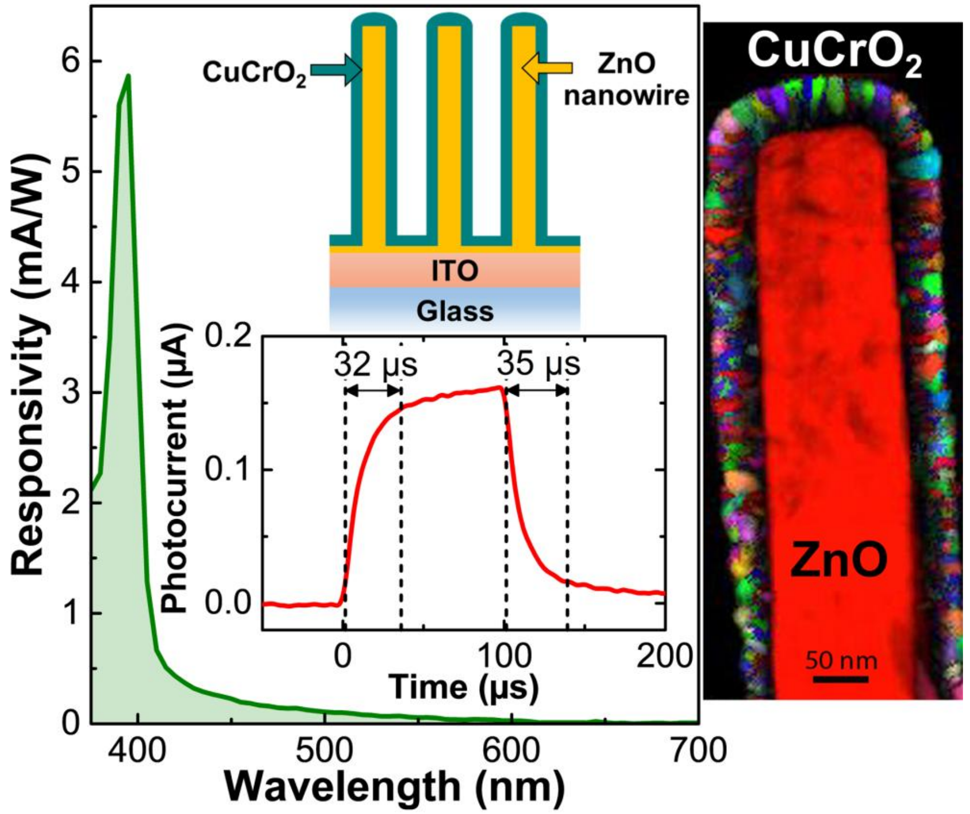
ZnO / TiO_2 / Sb_2S_3 core-shell heterostructures for ETA solar cells



R. Parize *et al*. J. of Phys. Chem. 121, 9672 (2017)

Control surface states
Key for piezoelectricity

ZnO / $CuCrO_2$ core-shell heterostructures for self-powered UV photodetectors

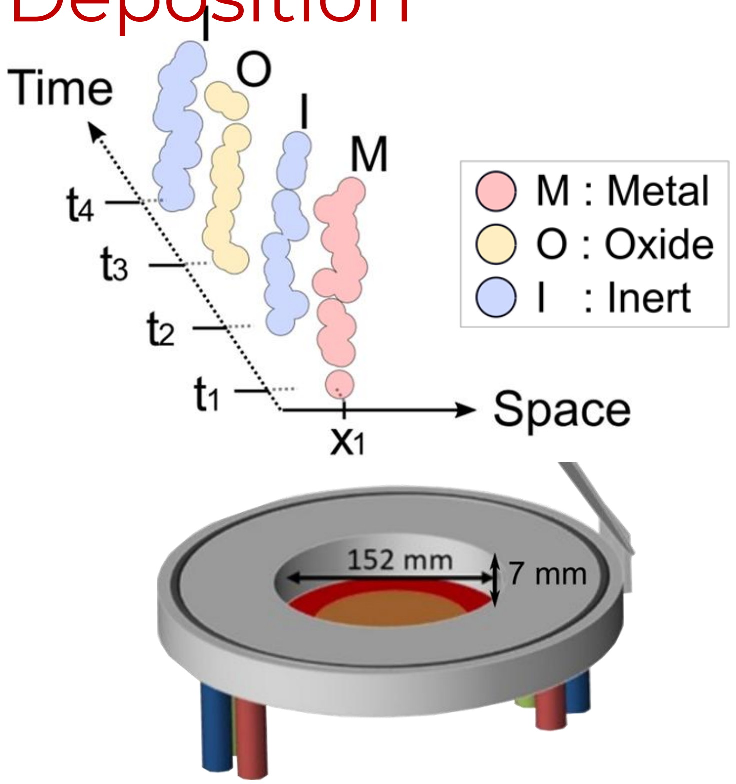


T. Cossuet *et al*. Adv. Func. Mater. 28, 1803142 (2018)

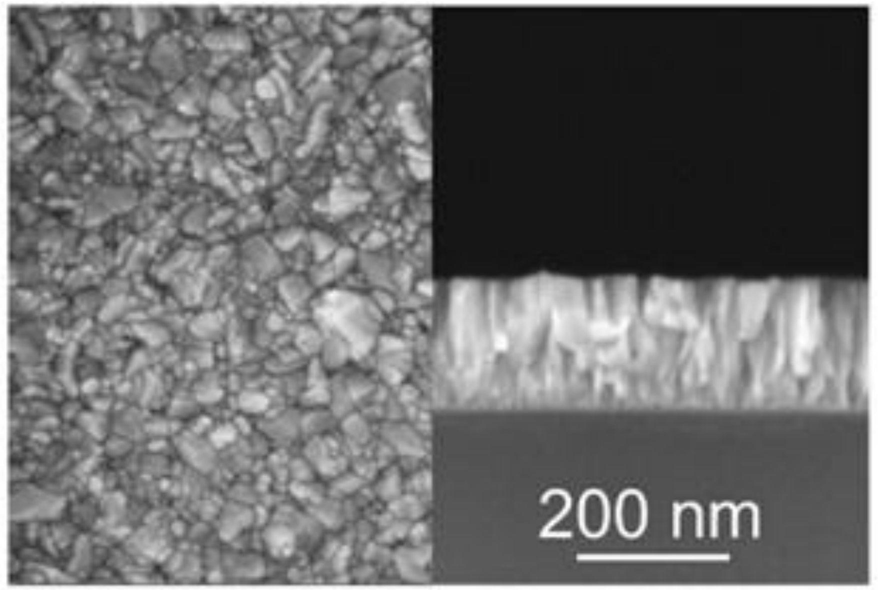
Thin films : ALD vs. SALD

D. Muñoz, LMGP

Atomic Layer Deposition



- Requires chamber/ evacuation system for efficient purging step
- Slow deposition speed
- Isolated and static



ALD of ZnO [1]

[1] Q. C. Bui et al. Materialia 31 2023
[2] D. Muñoz et al., Mater. Horiz. 1(3) 2014
[3] H. Ocku et al. Submitted
[4] H. Ocku et al. App. Surf. Sci. 696 2025

Thin films : ALD vs. SALD

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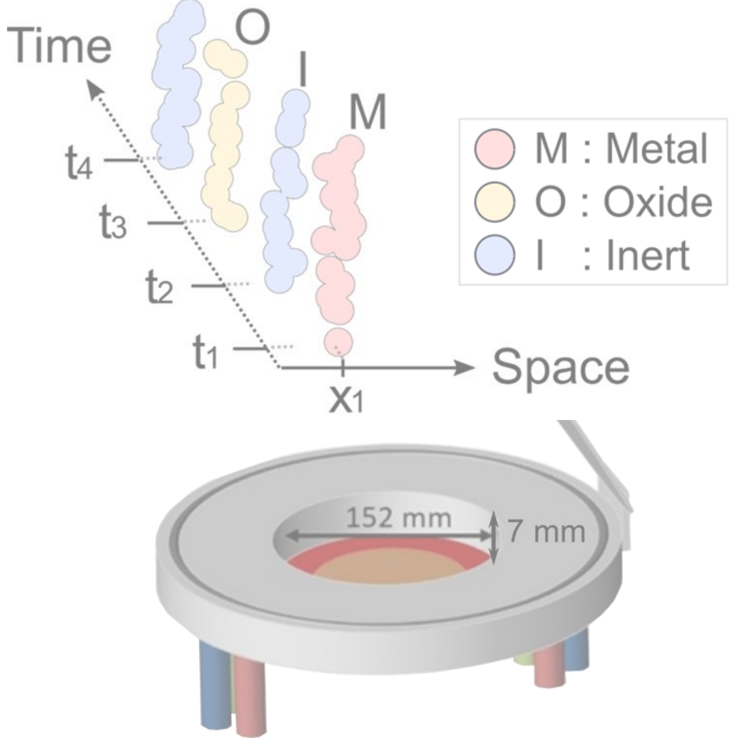

- Requires chamber/ evacuation system for efficient purging step
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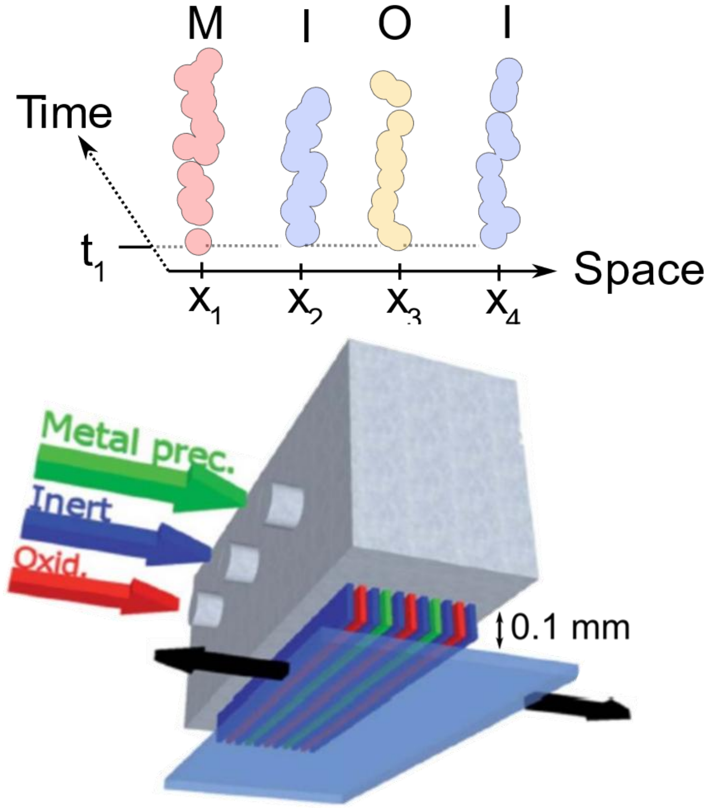
Spatial - ALD

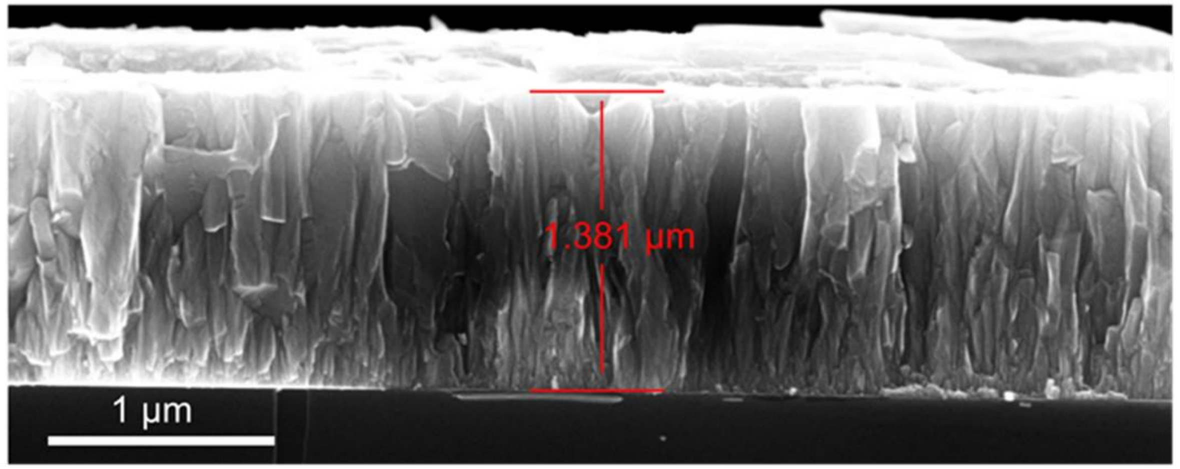


- No chamber, close-proximity method direct deposition at atm. pressure
- Faster deposition speed (< 100 x) [2]
- Open-air, dynamic

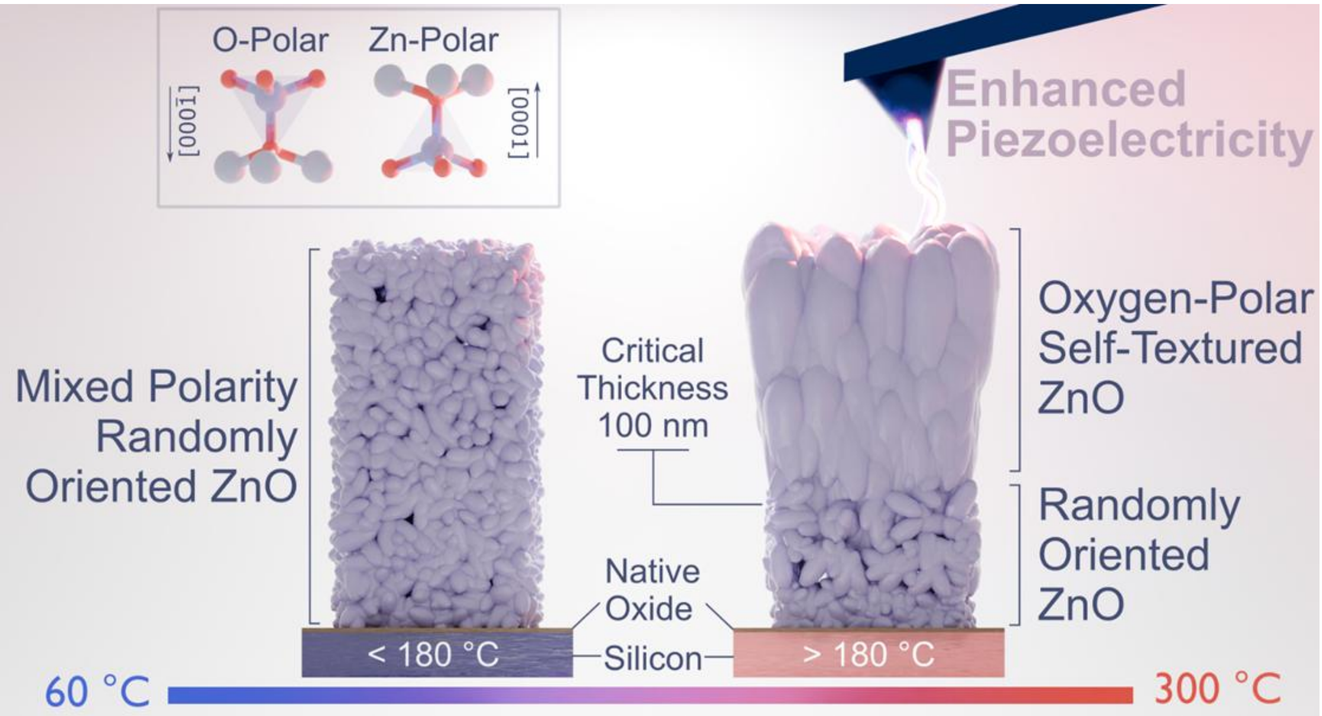
Spatial-ALD

D. Muñoz, LMGP

ZnO Thick layers [3]



Control polarity [4]



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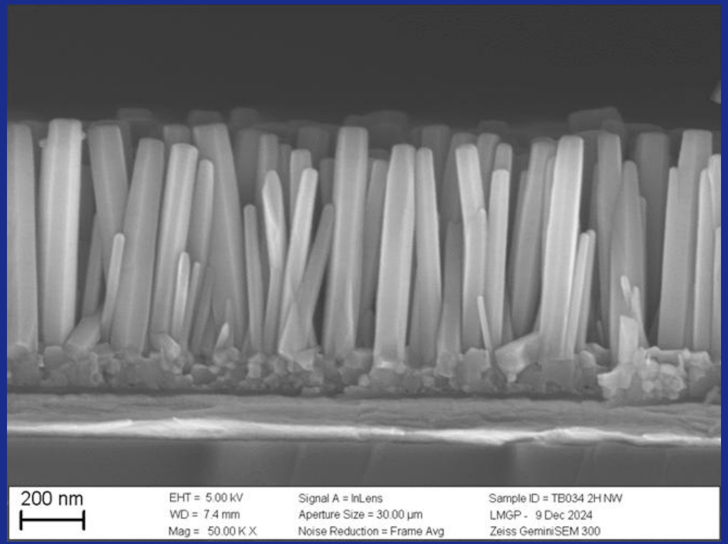

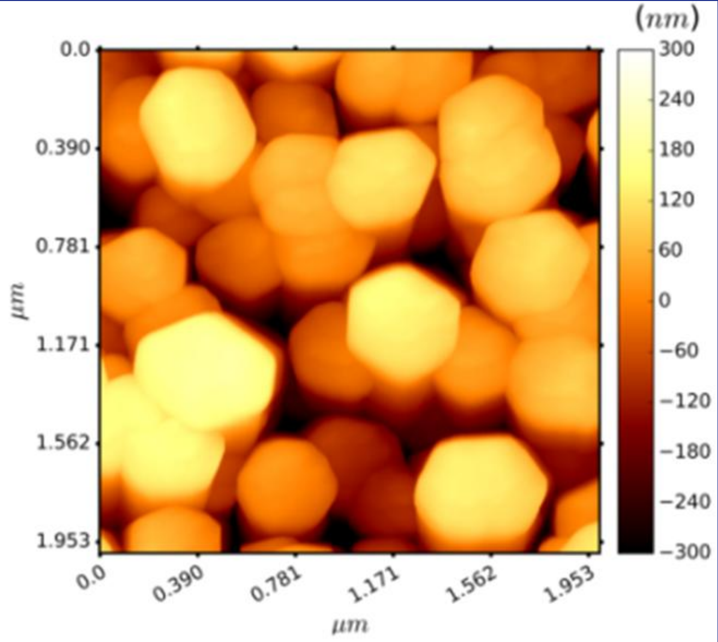

Outline

2

- AFM characterization techniques
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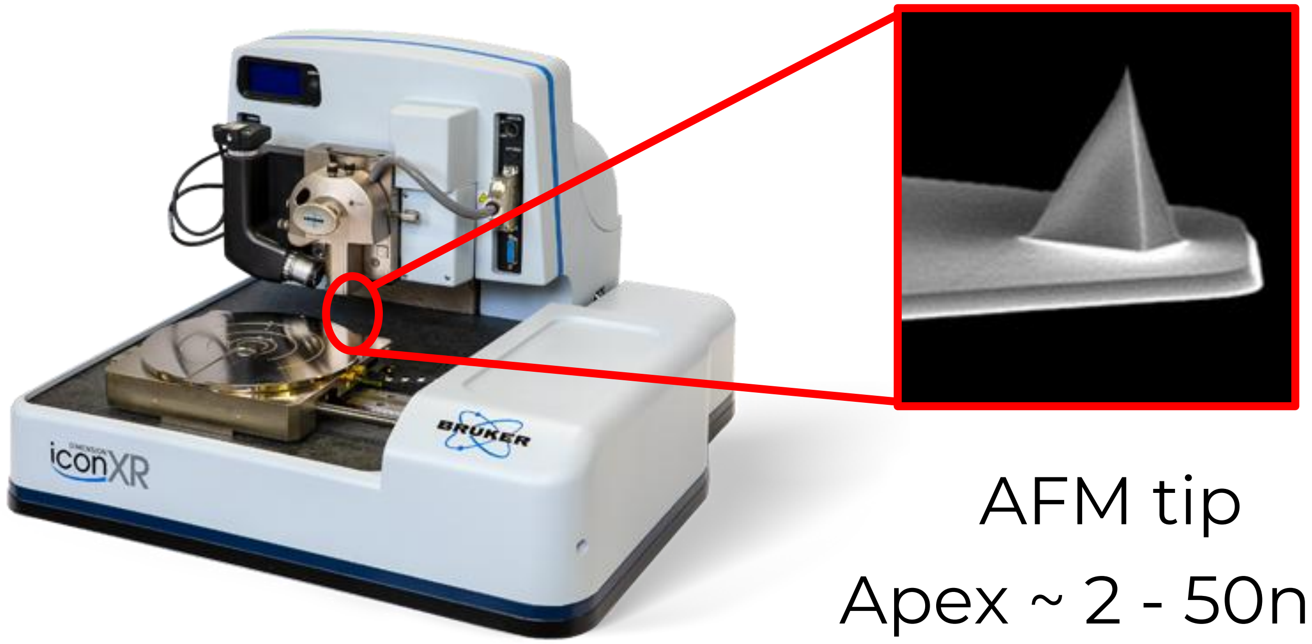
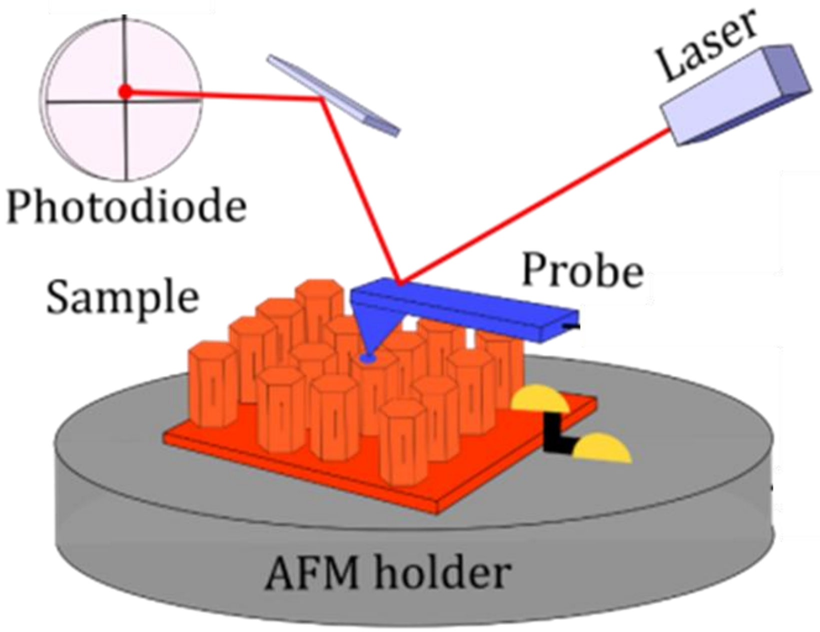
- Correlation with models

AFM – Atomic Force Microscopy

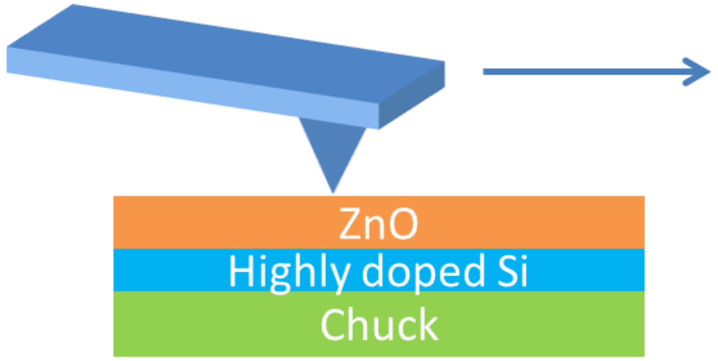


AFM tip

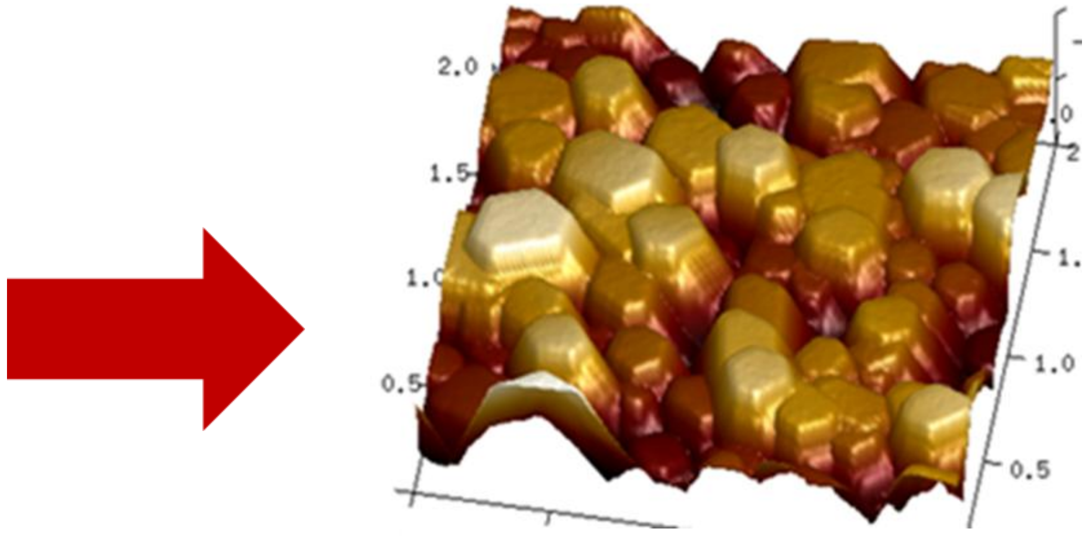
Apex ~ 2 - 50nm



Topography modes

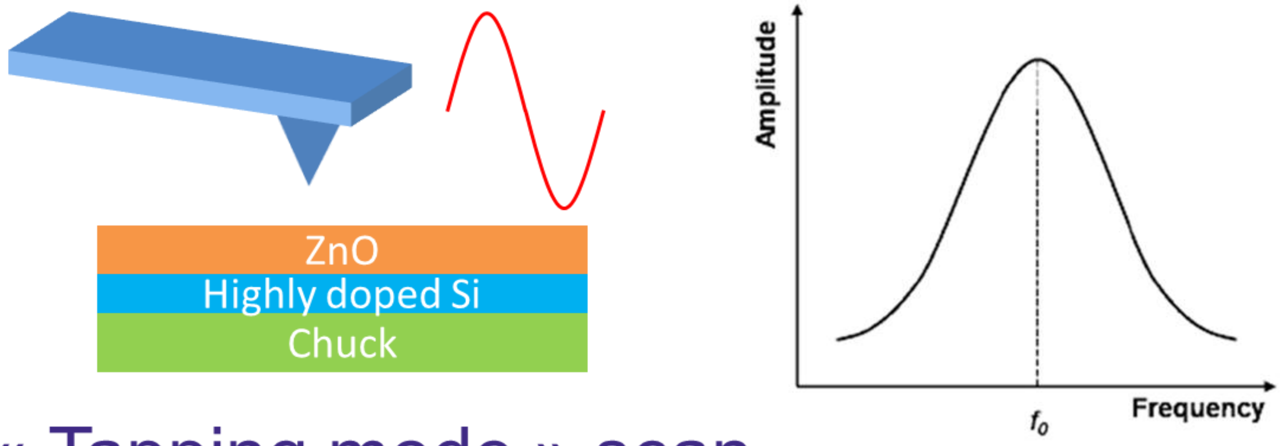


« Contact mode » scan



Topography image example.

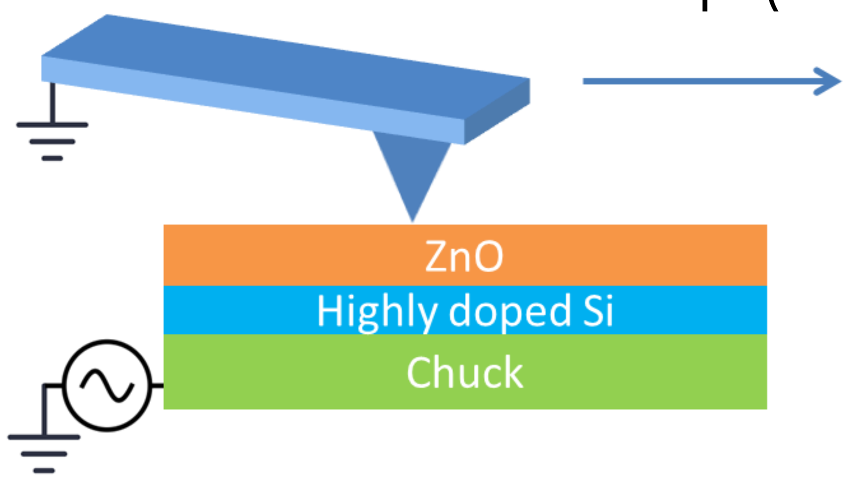
Resolution (lat. 1nm, vert. 0.1nm)



« Tapping mode » scan

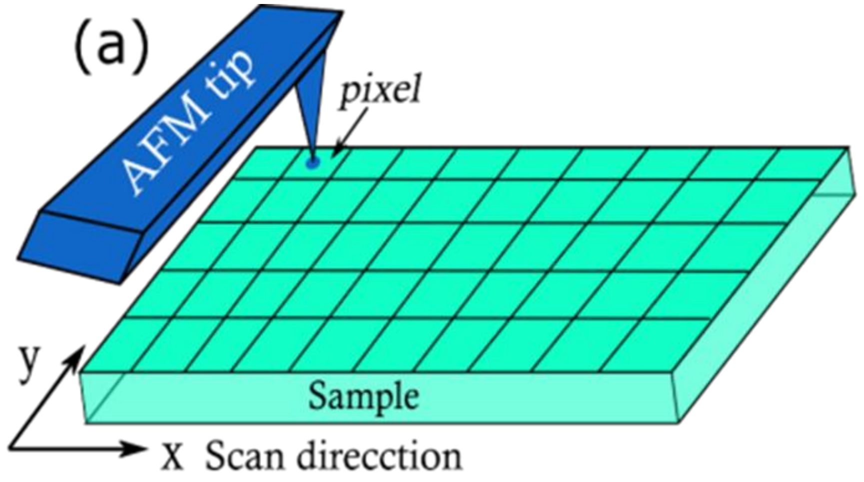
AFM – Electromechanical modes - Data Cube

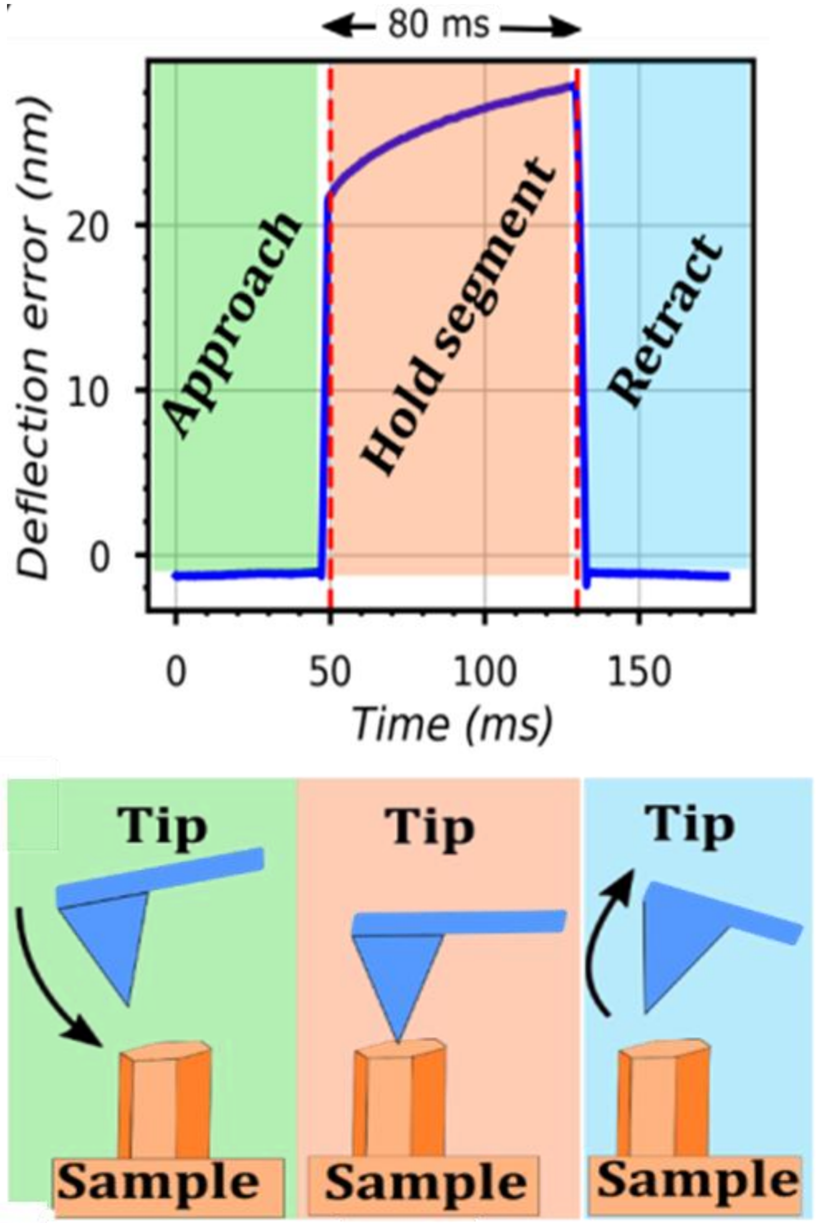
« Contact mode » scan



Lateral bending, NW collapse

"Data Cube" mode





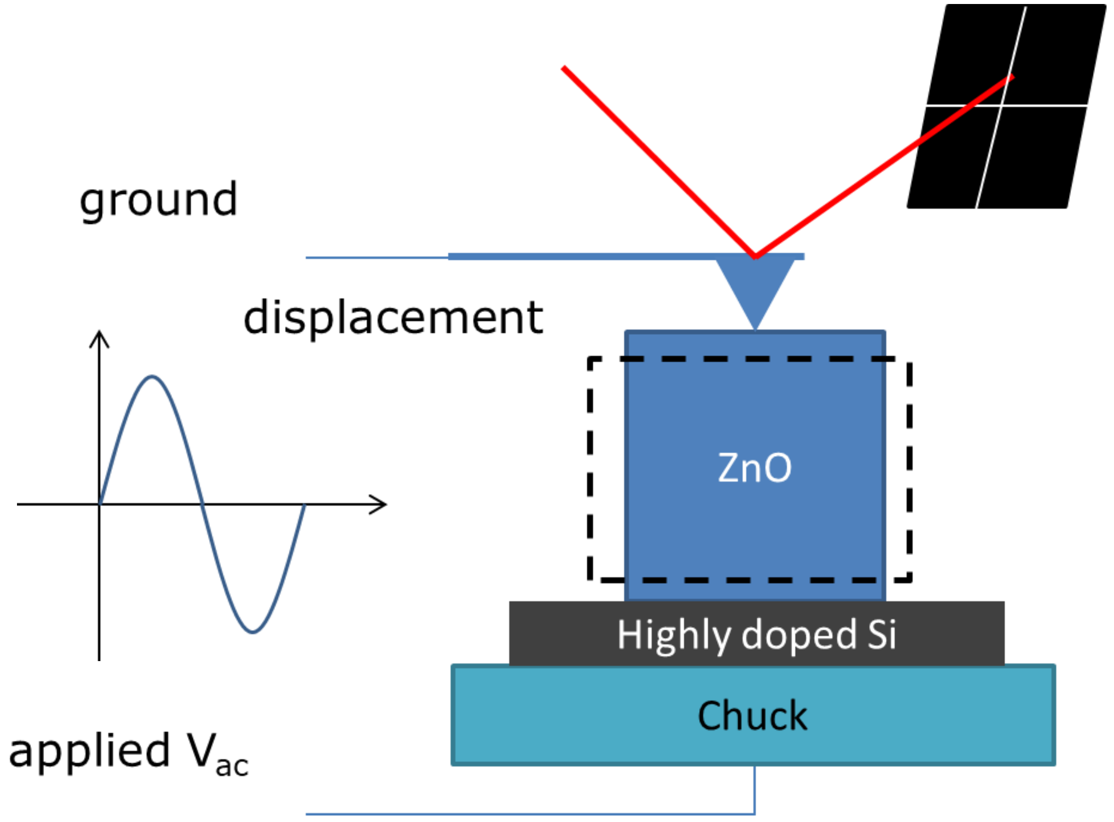
- ✓ Combination with electrical modes
- ✓ Spectroscopy

[1] [2]

[1] A. J. Lopez Garcia et al., Nanomaterials, vol. 11(6), p.1430 2021

[2] T. Jalabert et al., Nanotechnology 34 115402 2023

PFM – Piezoresponse Force Microscopy (1/4)

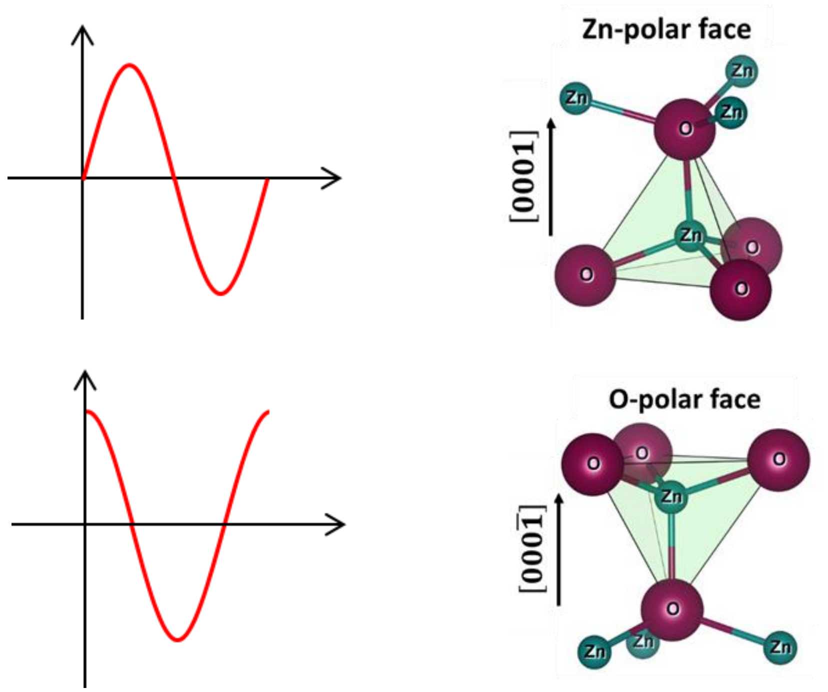


- ✓ AC voltage an AFM conductive tip and the bottom electrode or substrate
- ✓ Converse piezoelectric effect : the material will deform vertically.
- ✓ This deformation is measured by the AFM.

d[m/V]

Deformation / voltage	→	Piezoelectric properties
Phase between signals	→	c-axis orientation

deformation

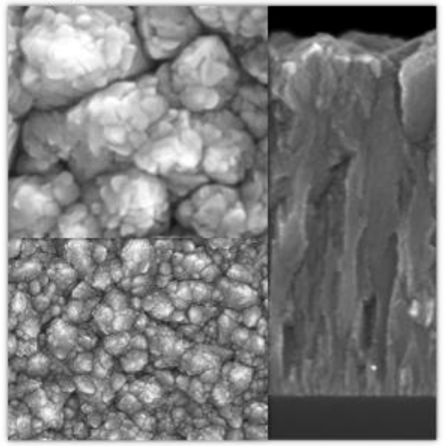


Homogenous polarity is important for applications!

PFM – Piezoresponse Force Microscopy (2/4)

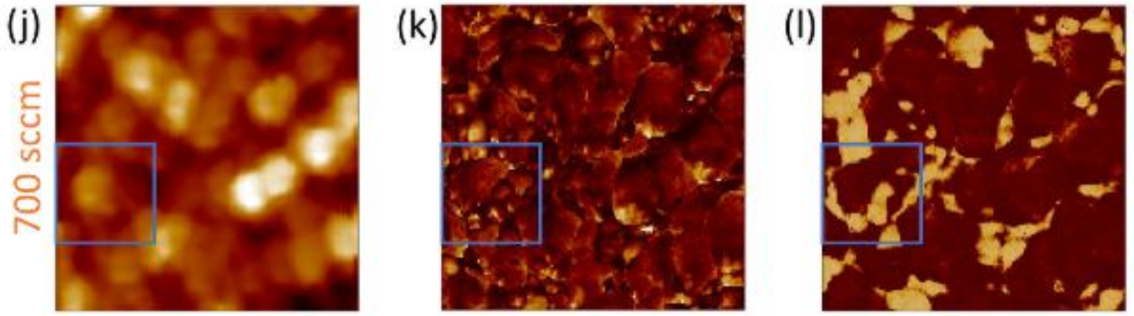
ZnO NWs vs thin film

Thin films (MOCVD)



900nm thick

Conditions:
O_2 700sccm
DEZn 0.5g/min
T = 500°C



Topography

Amplitude

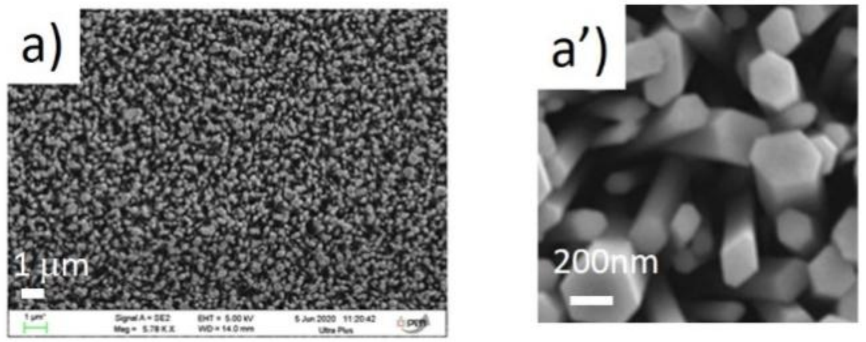
$d_{33}^{eff} \sim$ 1.6pm/V

Phase

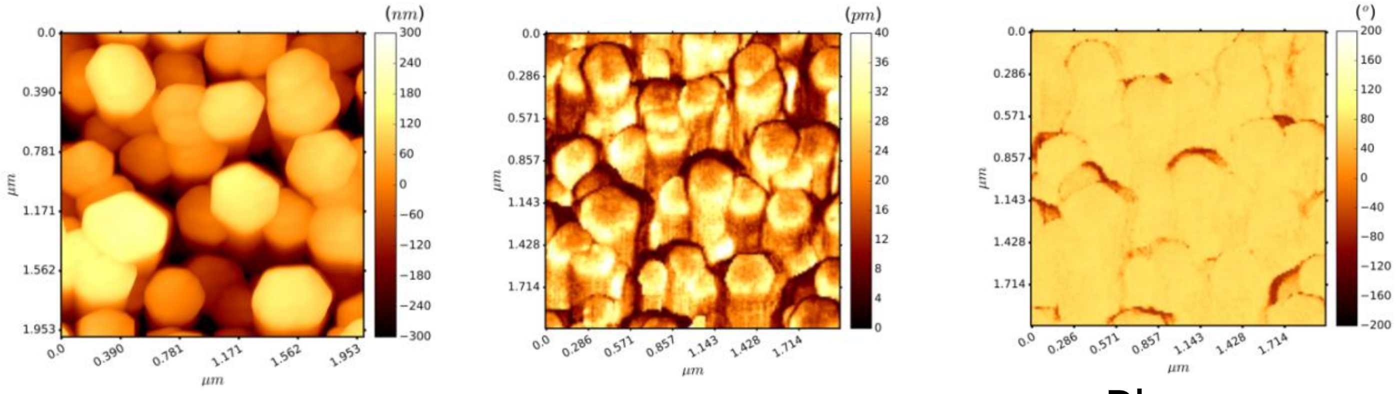
Zn and O polarity

[1]

ZnO NWs (CBD and MOCVD)



3µm long, 200nm wide



Topography

Amplitude

$d_{33}^{eff} \sim$ 4.6pm/V

Phase

Zn polarity

[2]

$d_{33}^{eff} \sim$ 4.4pm/V

1µm long, 60nm wide NWs (MOCVD) [3]

Overall, better performance from NWs vs. Thin films

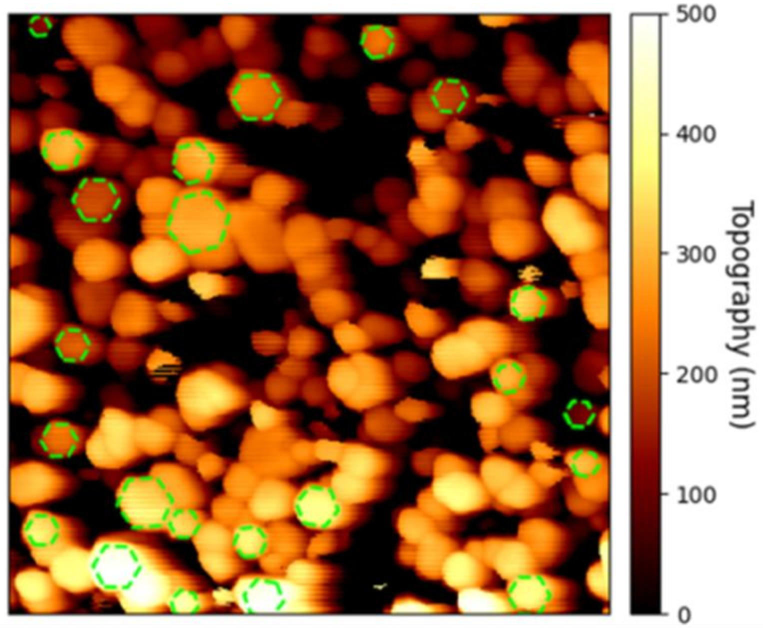
[1] Q. Ch. Bui et al., Mater. Adv. 2021
[2] A. Lopez et al., Nanomaterials 2021
[3] Q. Ch. Bui et al., Appl. Mater. Interfaces 2020

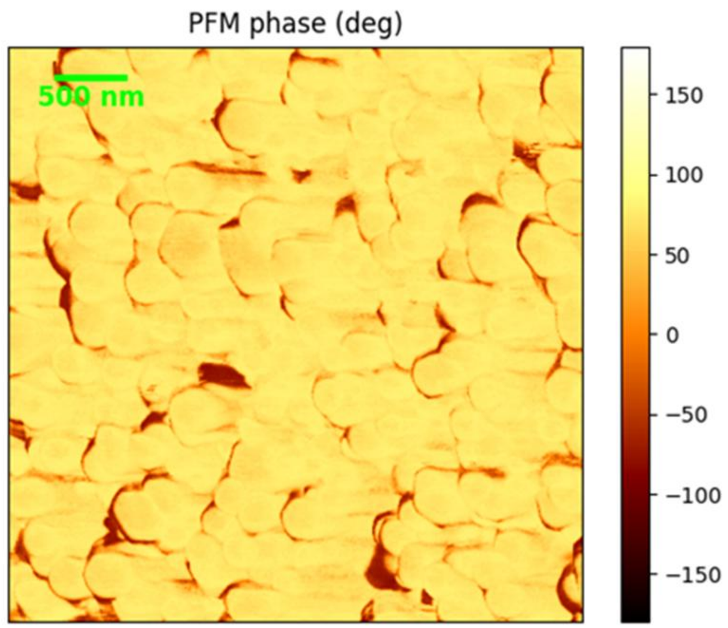
PFM – Piezoresponse Force Microscopy (3/4)

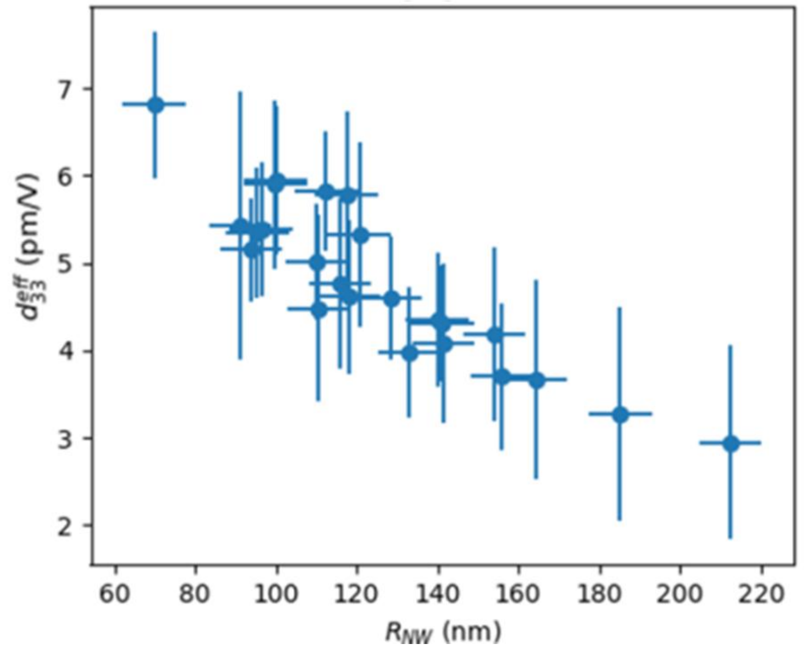
Effect of ZnO NWs radius
Experiments

ZnO NWs (CDB)

Seed layer – Ebeam Evaporation







[1]

- Clear trend in function of the NW radius
- Homogeneous positive phase (Zn-polar)

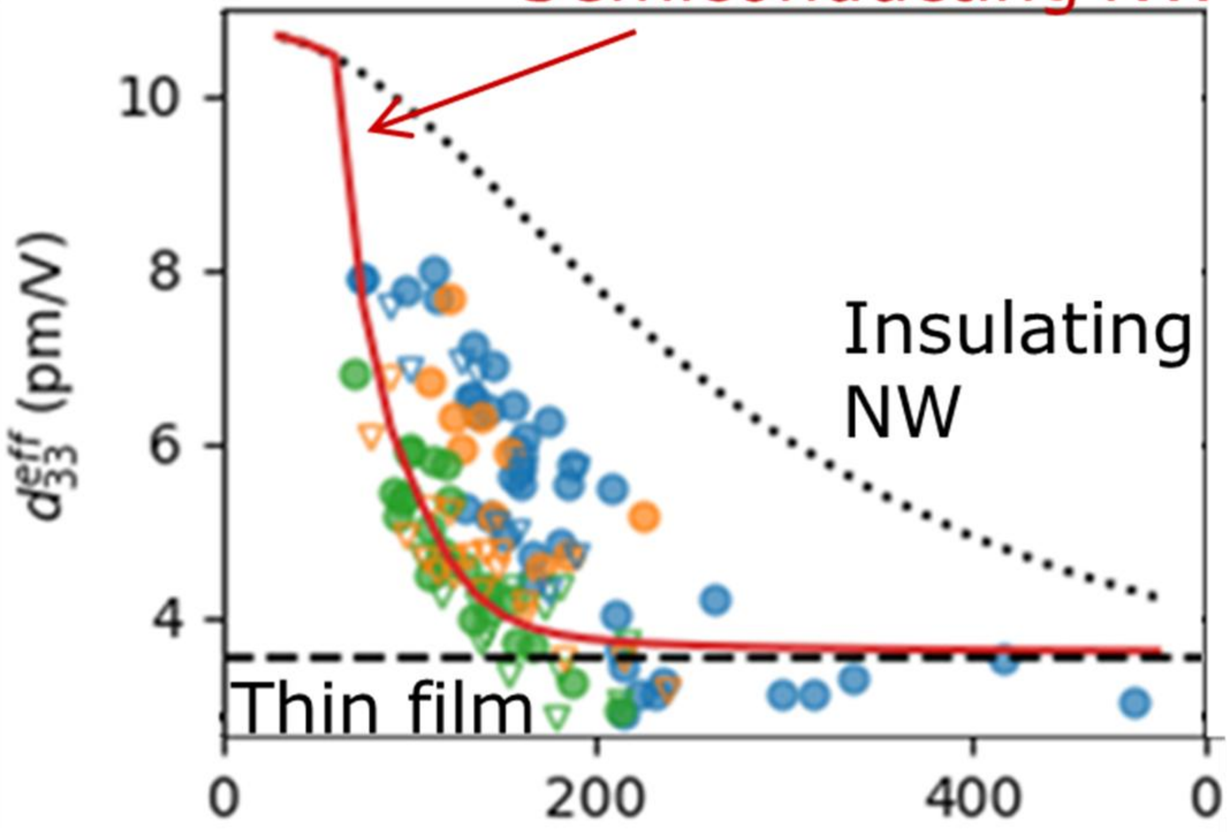
[1] T. Jalabert et al., Nanotechnology 2023

PFM – Piezoresponse Force Microscopy (4/4)

Effect of ZnO NWs radius : Experiments vs. simulations

ZnO NWs (CDB)

Seed layer – Ebeam Evaporation



COMSOL FEM simulation

Simulation parameters (CBD):

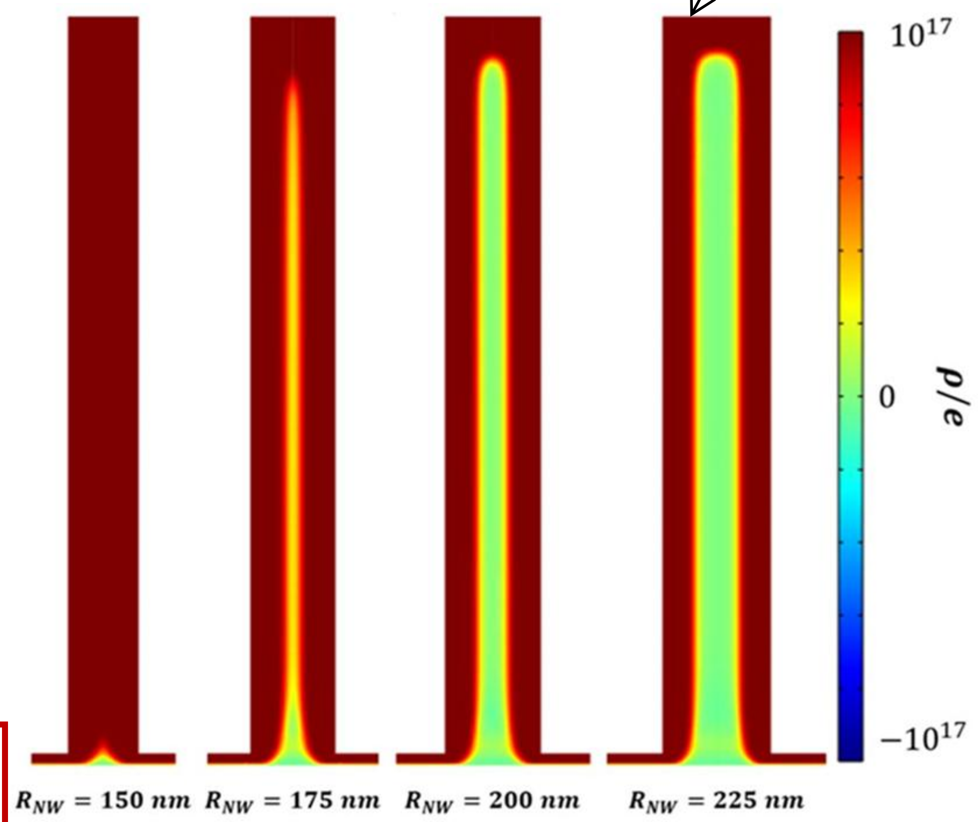
$N_{it}=10^{13}\ eV^{-1}.cm^{-2}$

$N_d=10^{17}\ cm^{-3}$

Challenge:

- Mesure doping, surface traps
- Validate the models

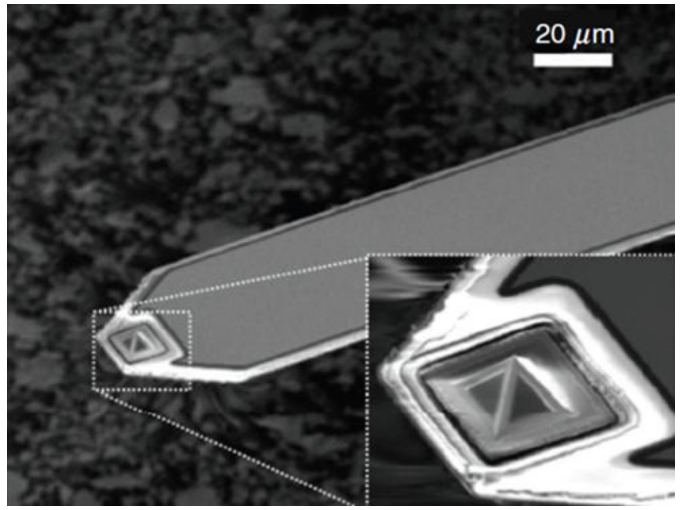
Depletion zone

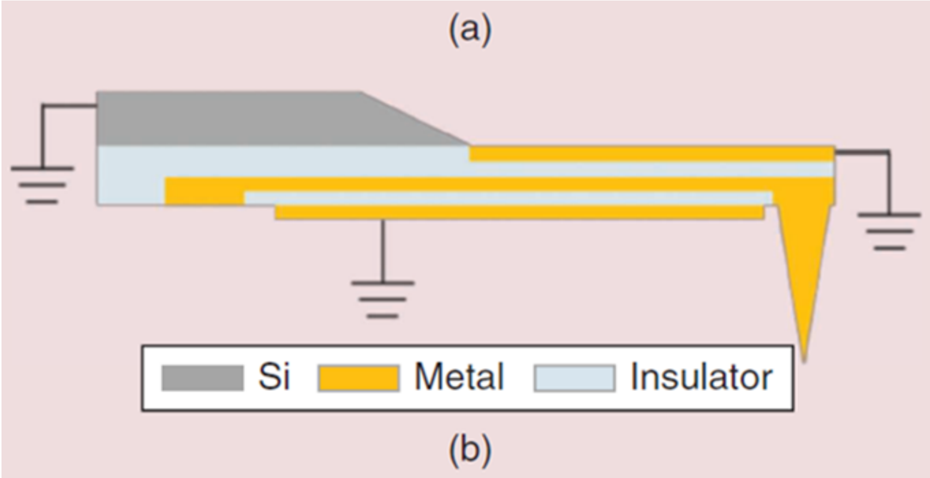


[1]

[1] T. Jalabert et al., Nanotechnology 2023

SMIM: Scanning Microwave Impedance Microscopy (1/4)

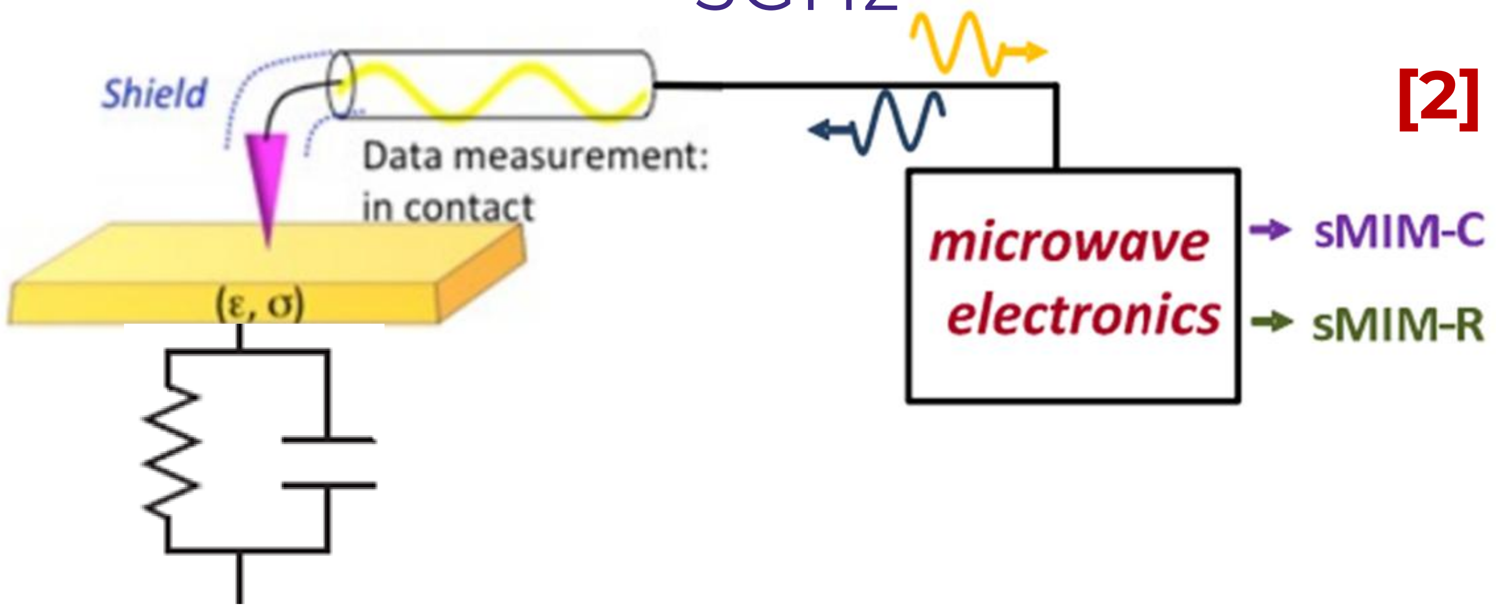




[1]

Shielded AFM tips (SMIM 300)

$$Y = \frac{1}{R} + j\omega C$$



[2]

sMIM (Imaginary) : Capacitance, dielectric properties

$$C = \epsilon \times \frac{A}{d}$$

sMIM (Real) : Conductivity/resistivity

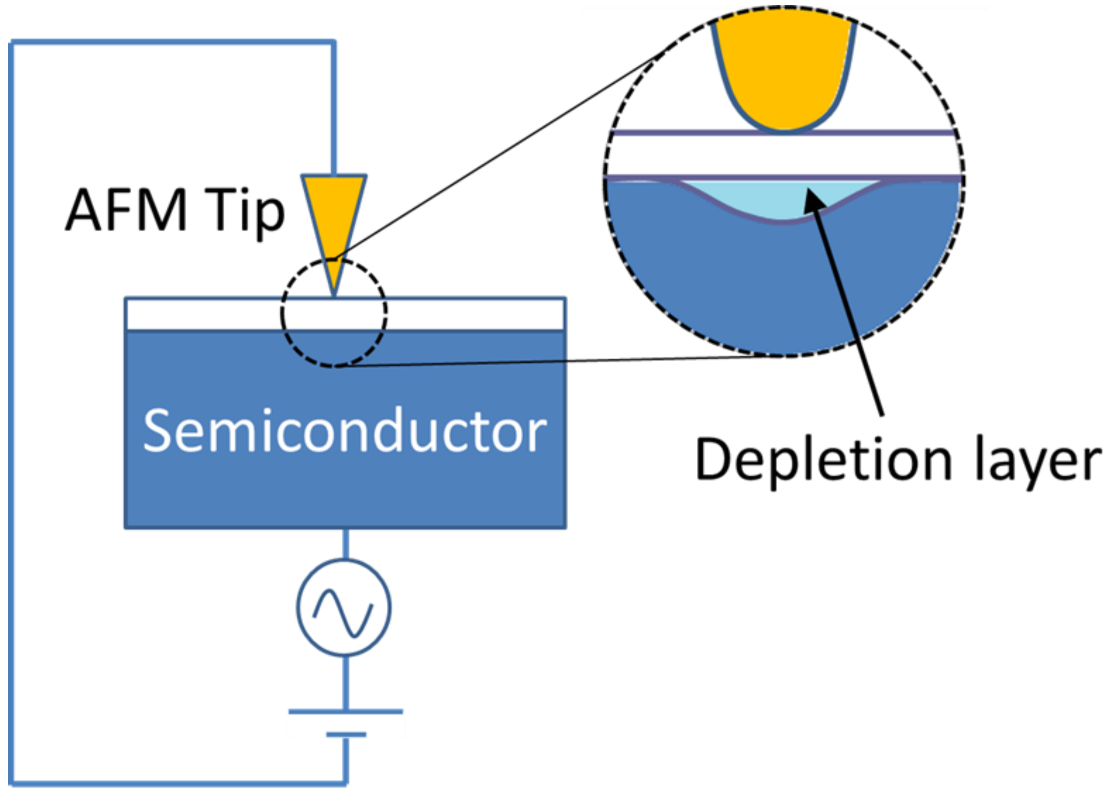
$$R = \frac{1}{\sigma} \times \frac{d}{A}$$

[1] R. C. Chintala et al., IEEE Microwave Mag., 21(10), 22-35 2020

[2] S. Friedman et al., Proc. of SPIE Vol. 9173 917308-1, 2014

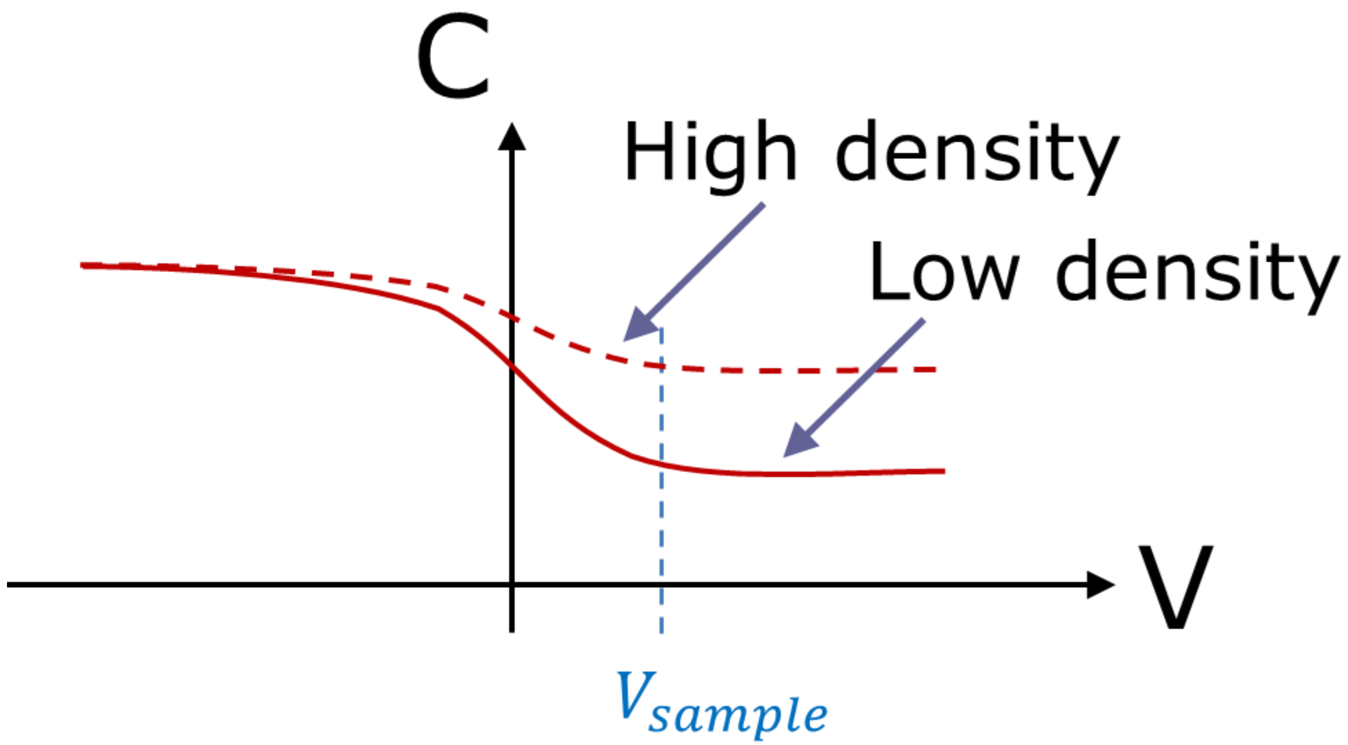
SMIM: Scanning Microwave Impedance Microscopy (2/4)

Study of semiconductor materials with SMIM



The depletion layer thickness depends on the doping level, so does the capacitance in the depletion region

n-doped semiconductor

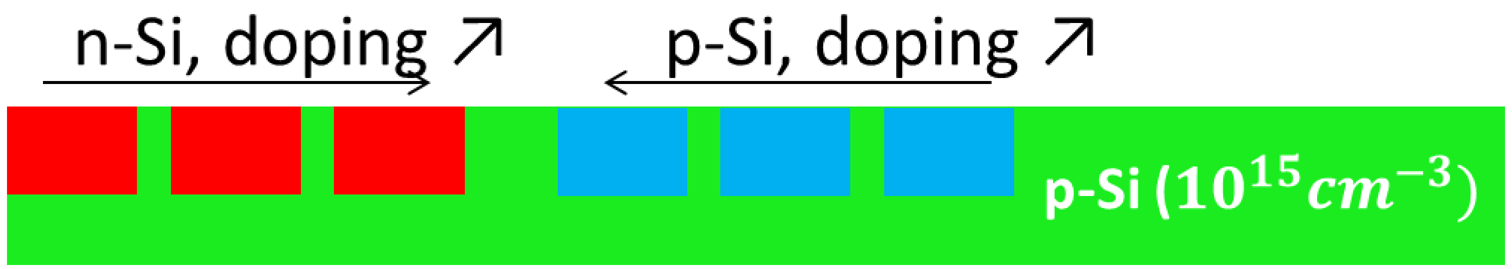


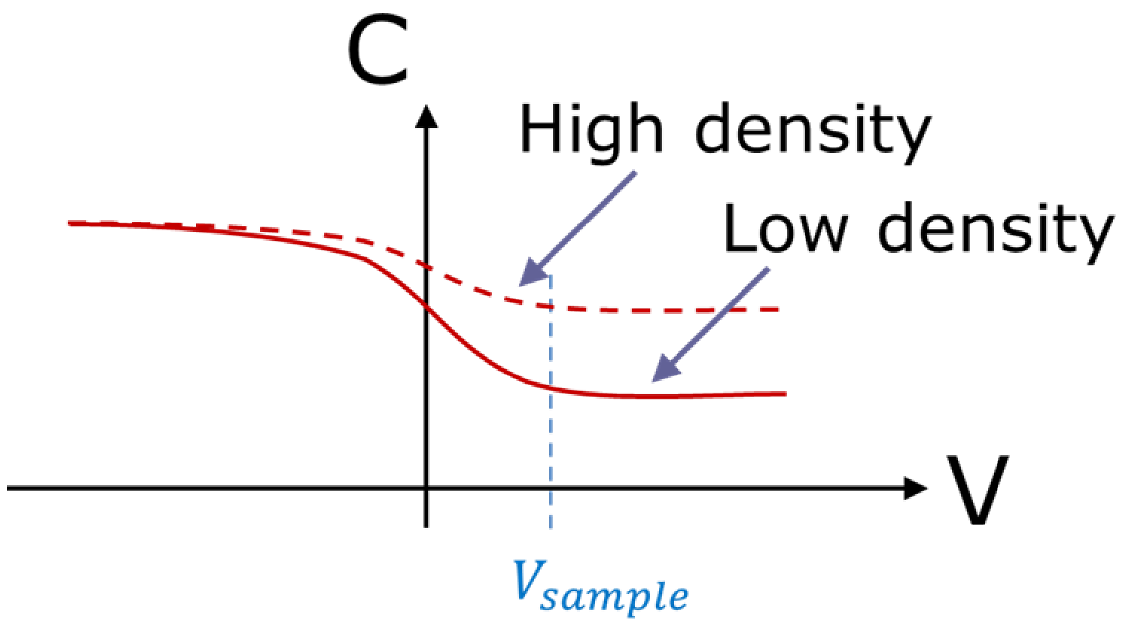
SMIM allows carrier profiling

SMIM: Scanning Microwave Impedance Microscopy (3/4)

SMIM measurements on a reference Si sample (INFINEON)
Known doping concentrations

Cut View

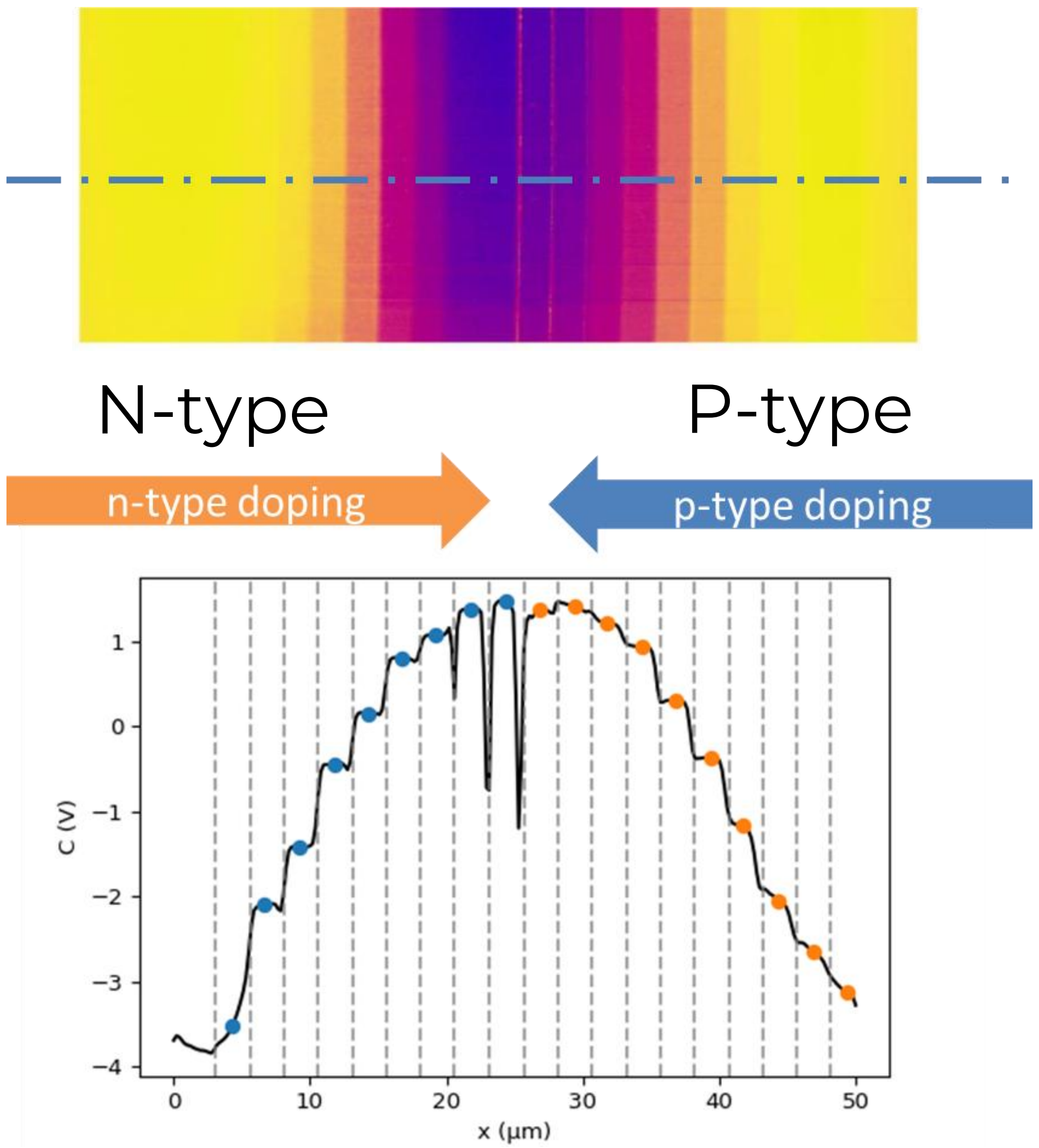




n-doped semiconductor

✓ Spectroscopy

SMIM-C at the sample surface

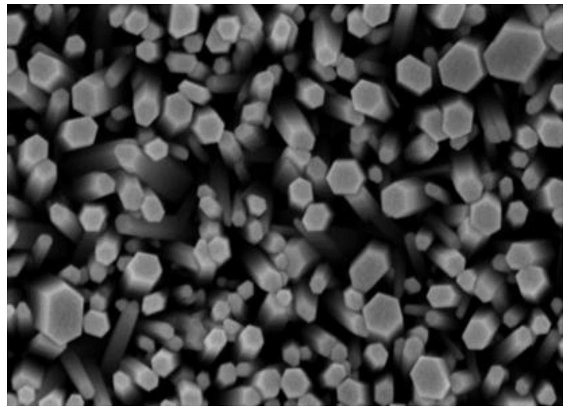


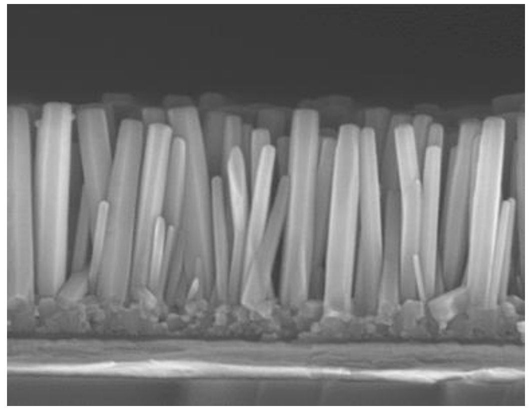
Contact mode, V_{sample} = 0V

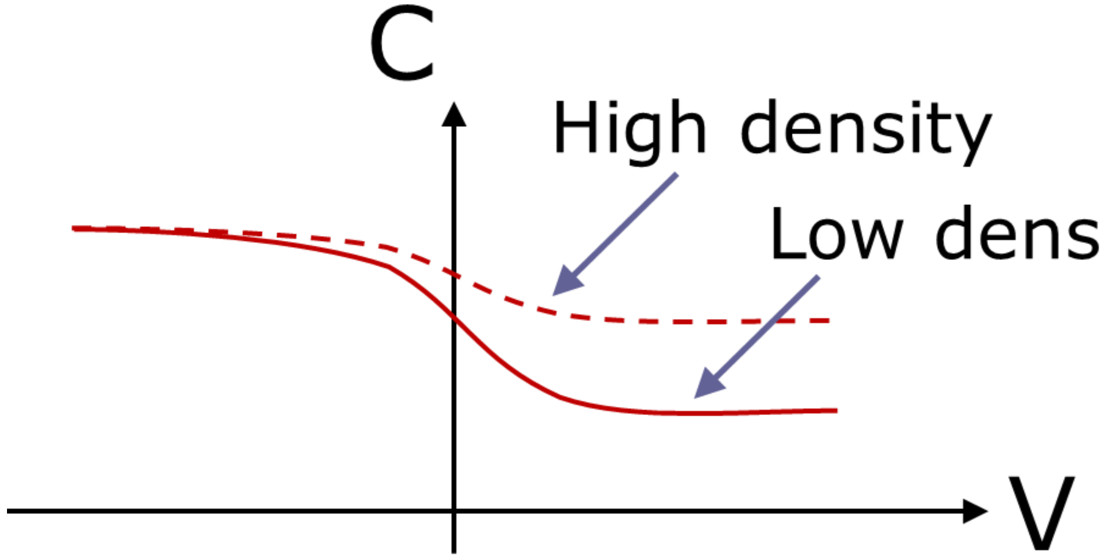
SMIM: Scanning Microwave Impedance Microscopy (4/4)

SMIM Data cube measurements on ZnO NWs (preliminary results)

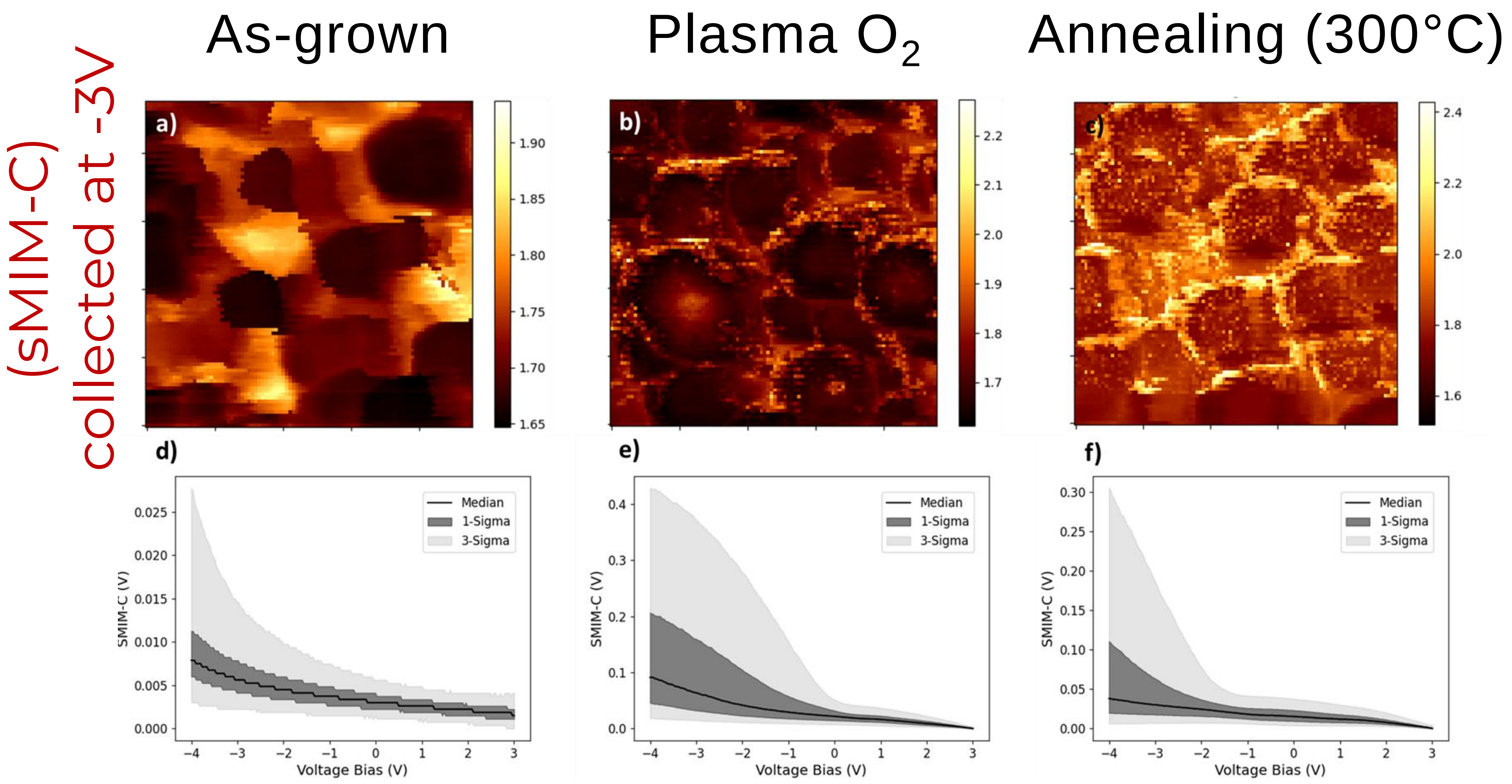
Post-growth treatment



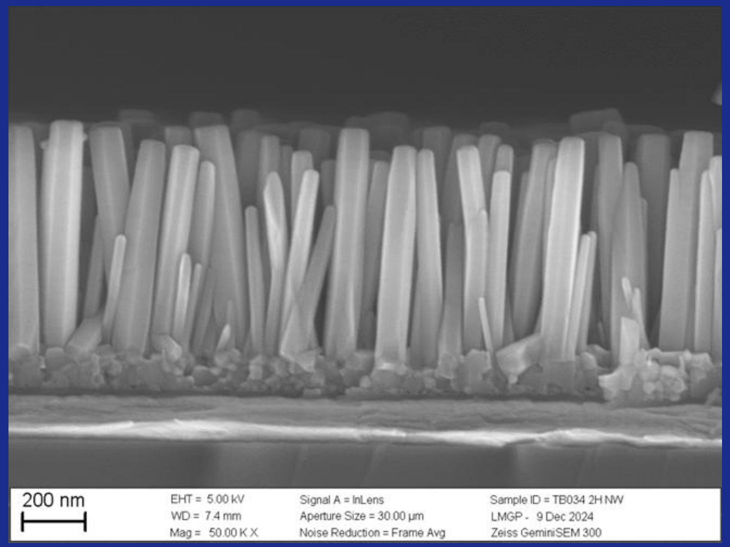


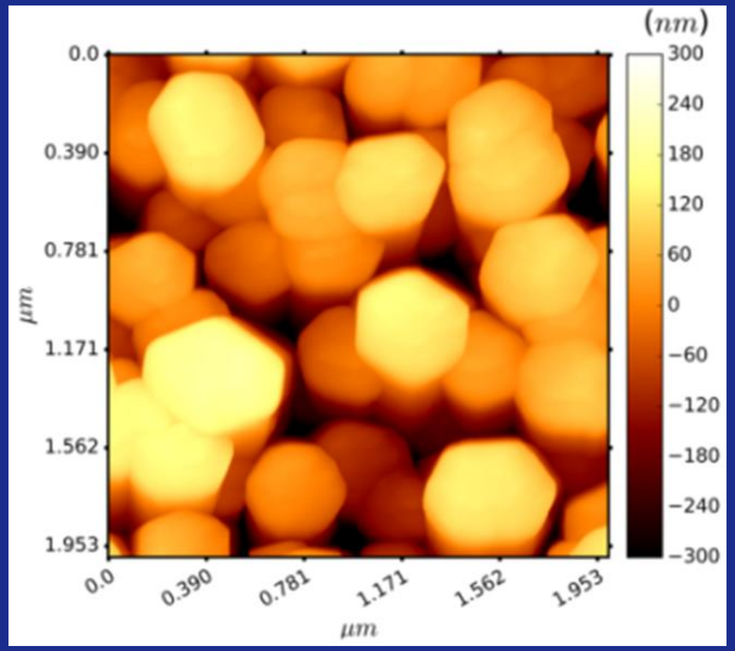


n-doped semiconductor



Results show n-doped profile and reduction of doping concentration after post-growth treatment





Outline

3 Conclusions and perspectives

Conclusions

- ZnO NWs and thin films are promising for piezoelectric transducer applications.
- Study the interaction between piezo and semiconductor properties : provide guidelines :
  - Reduce doping concentration, increase surface traps
  - Reduce radius

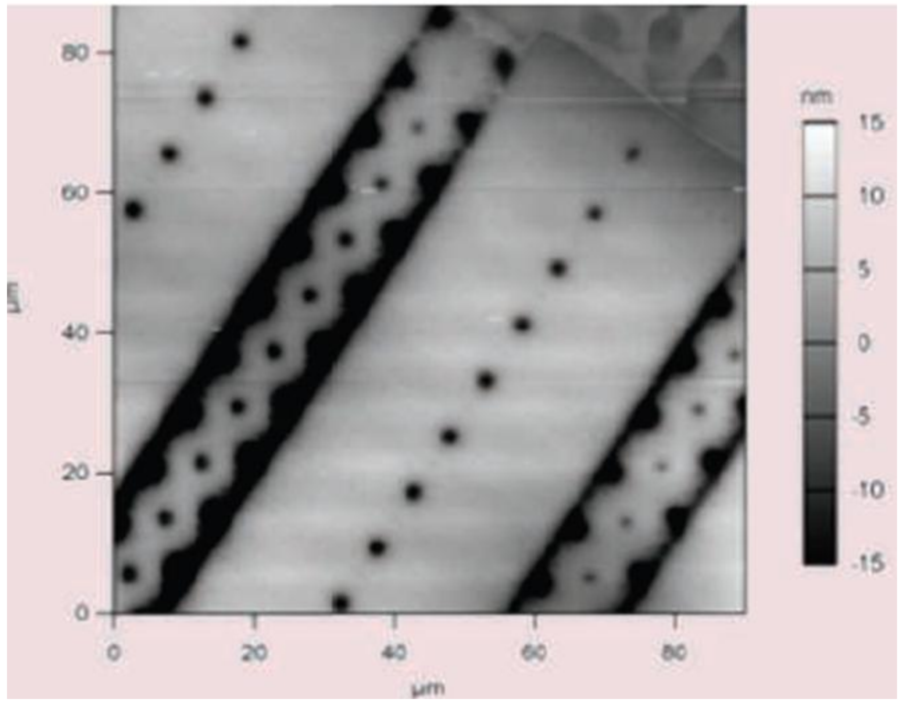
  } Improve piezo performance
- Different electromechanical AFM techniques (PFM, SMIM) combined with Data Cube to characterize piezoelectric nanostructures and thin films

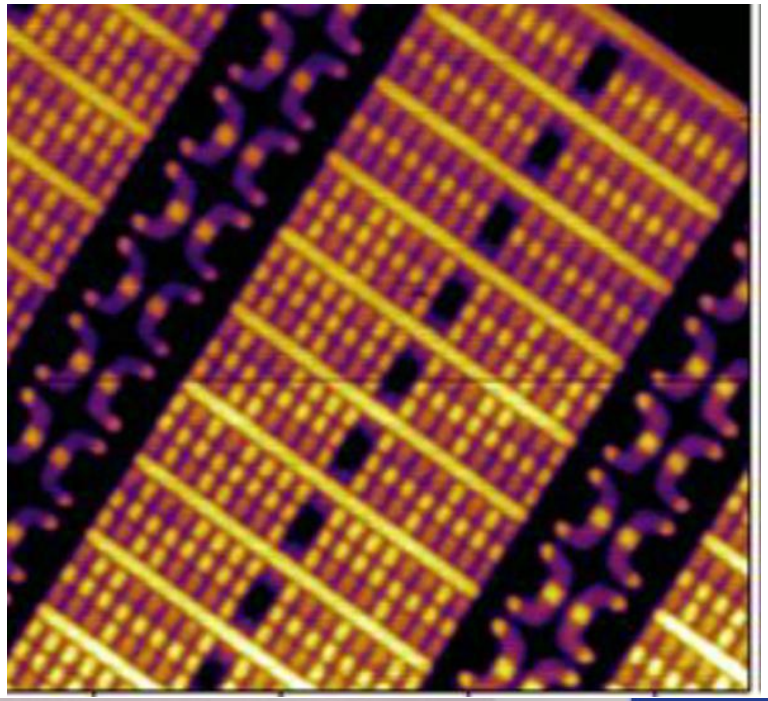
Perspectives

- ➢ Correlate PFM, C-AFM, KPFM to SMIM (same samples)
- ➢ Quantitative SMIM (doping would require reference samples)
- ➢ Beyond piezoelectric materials:

SMIM for studying other kind of samples: defects in semiconductor devices, buried structures. conductivity/resistivity, biology.

Topography





sMIM-C image of an non-volatile memory array. Cells with and without charge [1]

[1] N. Antoniou et al., Proc. Of SPIE 2021

THANK YOU FOR YOUR ATTENTION!

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