Bending piezoelectric nanowires: application to force-displacement sensors based on individually contacted vertical ZnO piezoelectric nanowires

Edgar LEON PEREZ [1,*], **Mireille MOUIS** [2,3], **Emmanuelle PAULIAC-VAUJOUR** [1]

[1]CEA-Leti, Systems Department, F-38054 Grenoble, France - *edgar.leonperez@cea.fr

[2]CNRS, IMEP-LAHC, F-38000 Grenoble, France

[3]Univ. Grenoble Alpes, IMEP-LAHC, F-38000 Grenoble, France

One dimensional nanostructures are investigated in a large range of potential applications in nano-electronic devices. In particular zinc oxide (ZnO) piezoelectric nanowires (NWs) are suitable as elementary transducing blocks for force-displacement sensor applications[1,2]. Upon bending, a piezoelectric charge density distribution occurs within the NW, yielding a piezoelectric potential (piezopotential). This piezopotential is a function of the applied force or displacement onto the sensor. We intend to develop a force sensor based on piezoelectric NW matrices, where the elementary cell (pixel) is a single vertical-contacted-piezoelectric NW. We focus on force/pressure triggered electronic devices and aim to give in-depth understanding of pixel piezoelectric behavior and related technological considerations.

We report both finite element method (FEM) multi-physics simulations that we used as a tool for the device qualitative characterization and design optimization; and the low-temperature hydrothermal process which was implemented to grow NWs on different microelectronics-industry-compatible polycrystalline seed-layers, both template-free and patterned.

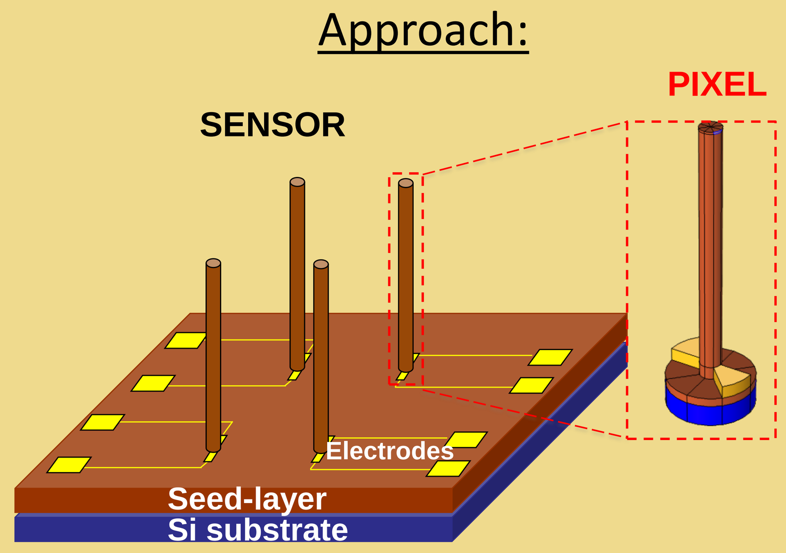
Individually contacted vertical NWs sensor approach

Nanowires → High Sensitivity

µm-sized pixels → High spatial resolution

High performance sensor.

Approach:



Stack and layout architecture for individually contacted NWs

Considerations prior to heterogeneous integration

- i) Understanding of pixel piezoelectric behavior via multiphysics models
- ii) Develop specific microfabrication processes
- iii) Implement controlled NW growth on processed chips

Results shown below:

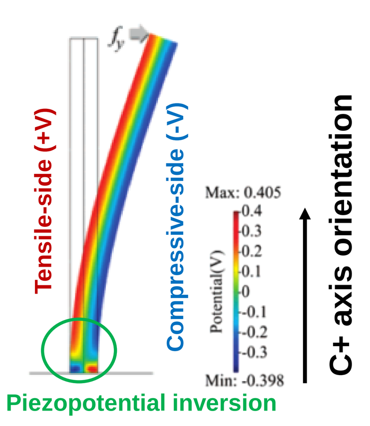
Static simulations of one pixel | Implement controlled nanowire growth

Simulation of one pixel

Existing results in simulation do not satisfyingly take into account the surrounding environment of the NW or the device feasibility:

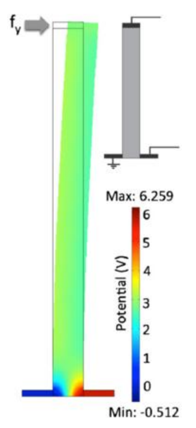
Single bent piezoelectric nanowire[3]

R=50nm and L=600nm



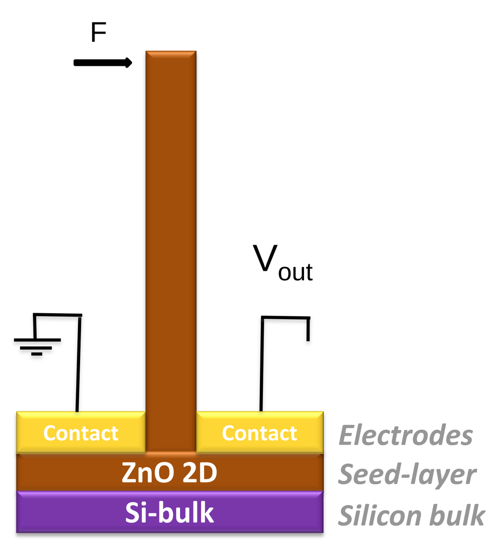
Electrical contacts position[4]

R=50nm and L=600nm



Our work[5]

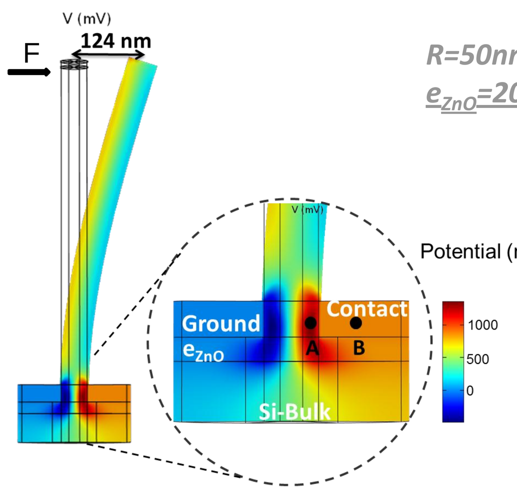
R=50nm and L=600nm



Piezopotential distribution within the pixel middle section

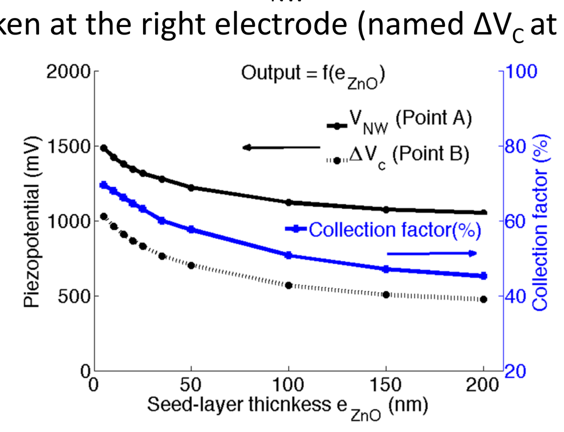
- Piezopotential seed-layer thickness dependence

R=50nm ,L=600nm, F=80nN
e_{ZnO}=20nm and e_{Si}=50nm



$V_{NW} \approx 1340$ mV
$\Delta V_c \approx 860$ mV

The maximum piezopotential value is generated within the NW's base (named V_{NW} at point A). The output potential is taken at the right electrode (named ΔV_c at point B)



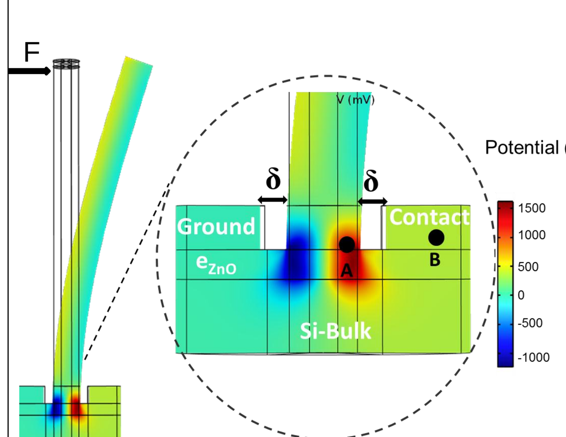
Collection factor= $V_{NW}/\Delta V_c$

V_{NW} and ΔV_c are following the same trend (black plots). The collection factor yields 69% for a value of the seed-layer thickness of 5 nm.

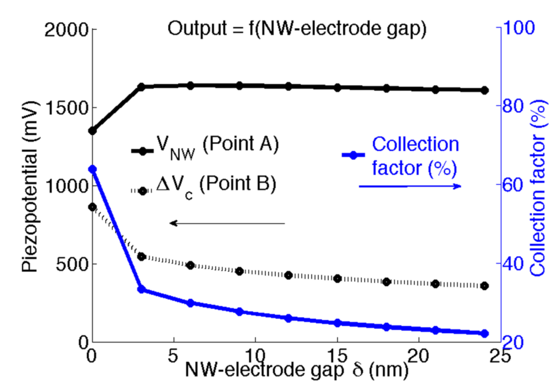
Thinner seed-layers provide a larger pixel response

- Piezopotential NW-electrode gap (δ) dependence

R=50nm ,L=600nm, F=80nN, δ=18nm, e_{ZnO}=20nm and e_{Si}=50nm



$V_{NW} \approx 1600$ mV
$\Delta V_c \approx 380$ mV



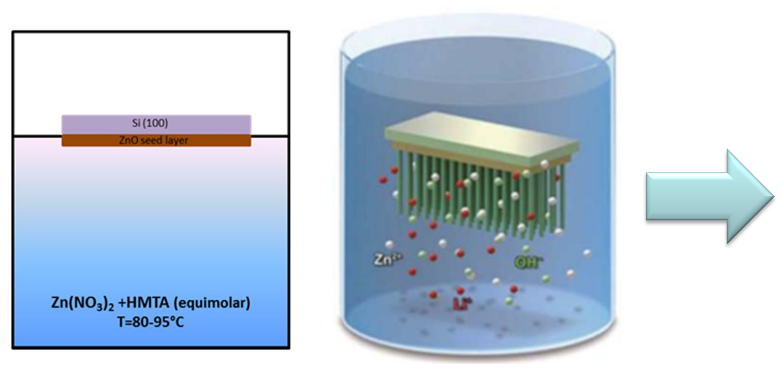
Evolution of piezopotential taking into account a symmetrical NW-electrode gap (parameter δ).

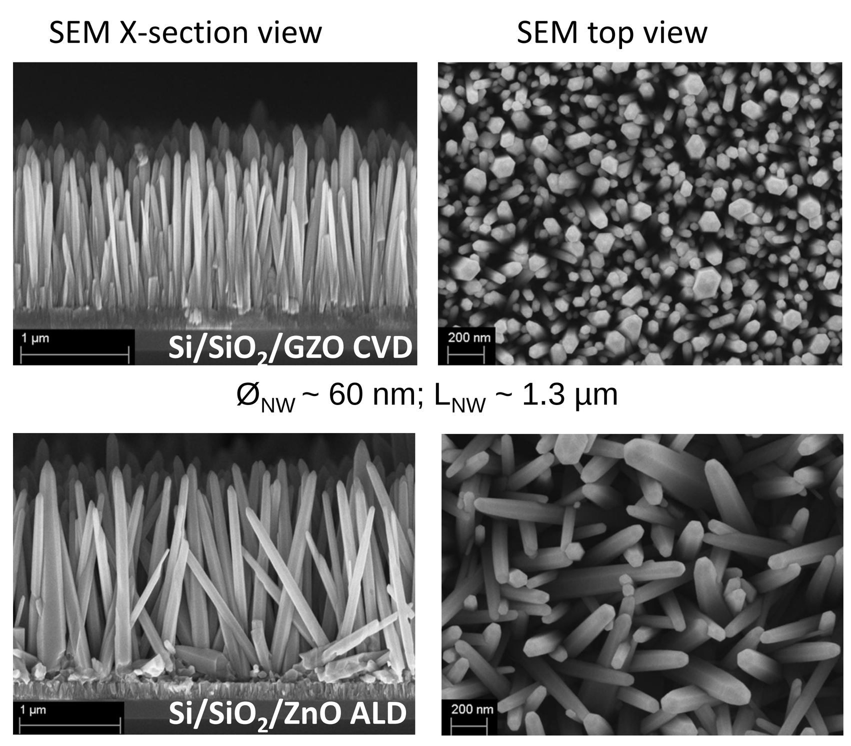
Physical contact loss does not imply complete piezopotential loss : although the collected signal drops, it quickly stabilizes as δ goes on increasing.

NW growth

We carried out NW hydrothermal growth[6] on different clean-room processed polycrystalline seed-layers.

ZnO nanowire growth on template-free layers





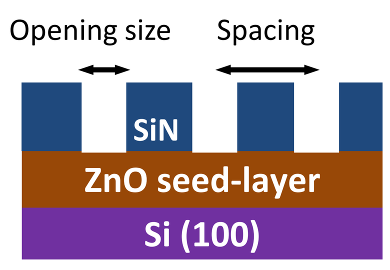
$\varnothing_{NW}$ ~ 60 nm; L_{NW} ~ 1.3 µm

$\varnothing_{NW}$ ~ 78 nm; L_{NW} ~ 2 µm

Growth was carried out on ZnO layers with different doping deposited by CVD, PLD or ALD

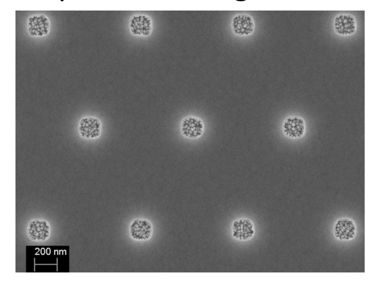
NW growth on pre-patterned seed-layer: control of NW density

The results below were obtained for a gallium-doped ZnO seed-layer.



Micro-fabrication of patterns by electron-beam lithography and dry etching using a SiN hard-mask

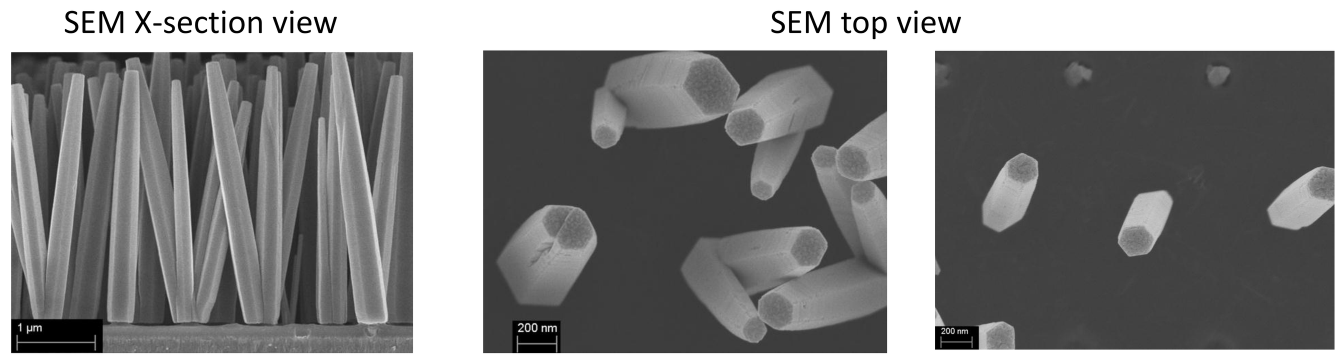
SEM top view of patterns prior to NW growth



Spacing = 750 nm and opening size = 150 nm

After NW growth:

SEM X-section view | SEM top view



$\varnothing_{NW}$ ~ 120 - 200 nm
L_{NW} ~ 2.9 - 3.4 µm

Multiple and single NWs were obtained on the patterns, showing that it is possible to obtain isolated NWs suitable for our applications.

Simulation results give an insight of the tolerance regarding process variability associated with device microfabrication and a tendency of what can be expected in terms of pixel piezoelectric response. NW growth was implemented on different polycrystalline seed-layers, yielding a controlled density of NWs on pre-patterned substrates. These elements provide valuable information for device design and fabrication. Based on these elements, the complete microfabrication process is under development at CEA

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