PiezoMAT Workshop

Piezo-electro-mechanical characterization of NW sensor structures

V. Lebedev, Fraunhofer IAF

EUROSENSORS 2016

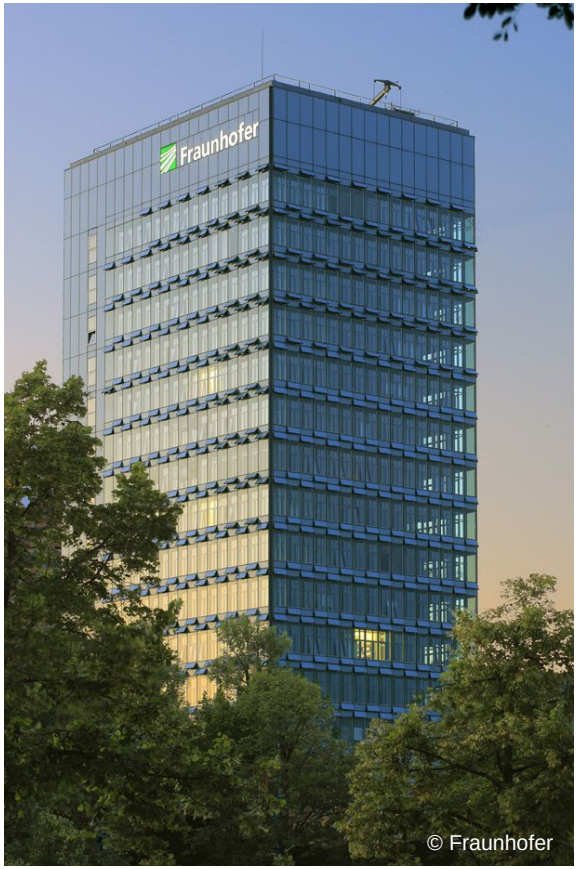
September 7th, 2016, Budapest

SEVENTH FRAMEWORK PROGRAMME

EU Project No. 611019

The Fraunhofer-Gesellschaft

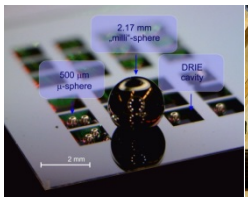
- Europe's largest application-oriented research organization
- 67 Fraunhofer institutes and research units
- More than 23,000 staff, mostly scientists and engineers
- € 2 billion annual research budget (approx. 70 % industry contracts and public funding, 30 % base funding)
- International affiliations through subsidiaries in Europe, USA, Asia

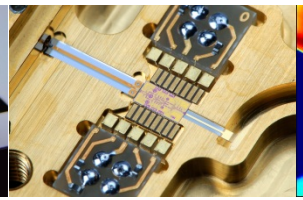
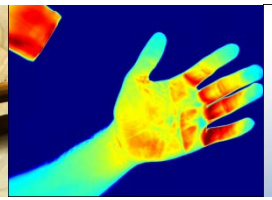


Fraunhofer IAF

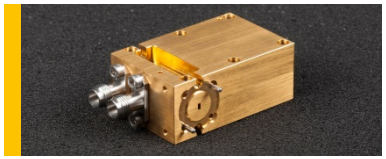
location	Freiburg
foundation	1957
staff	290
total budget	33.2 Mio €
investments	7.7 Mio €
research topics	electronic and optical components based on III-V semiconductors and synthetic diamond
cooperation	~170 partners in industry and research

Fraunhofer Institute for Applied Solid State Physics



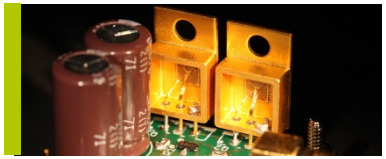



Business units



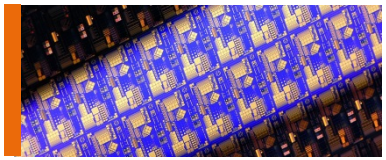
High Frequency Electronics

Electronic integrated circuits and modules for high frequencies



Power Electronics

High performance transistors and circuits based on gallium nitride

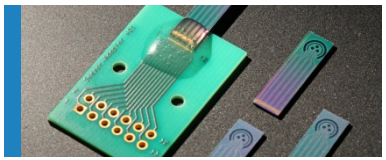


Photodetectors

High resolution detectors in the infrared and UV range

Semiconductor Lasers

Infrared semiconductor lasers, laser systems, LEDs and diode lasers



Semiconductor Sensors

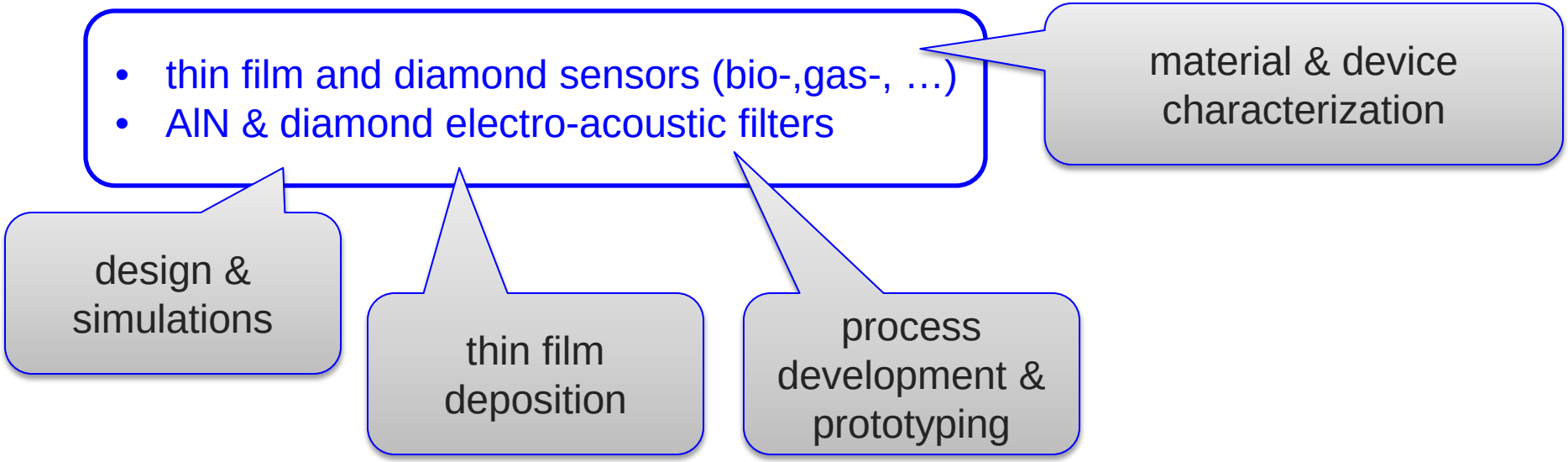
Micromechanics and sensors based on III-V semiconductors and diamond

Semiconductor Sensors

Focus of Department “Semiconductor Sensors”:

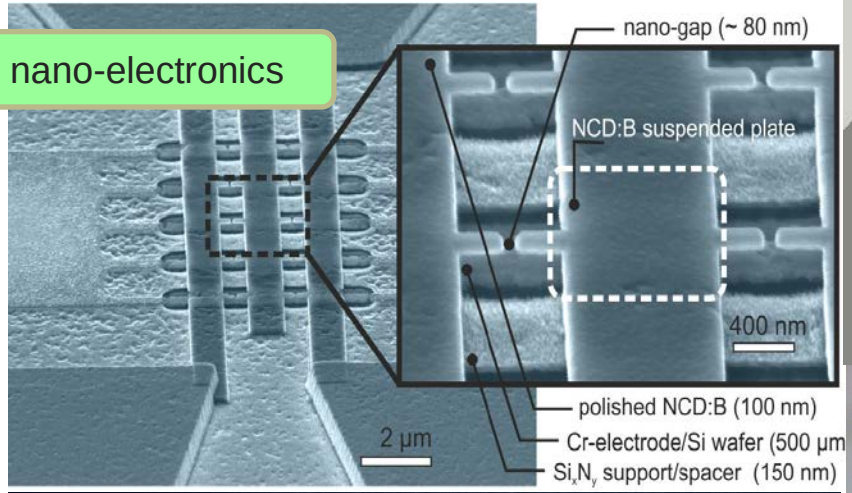
prospective piezoelectric & acoustic materials, e.g. Al(Sc)N, ZnO, synthetic diamond …

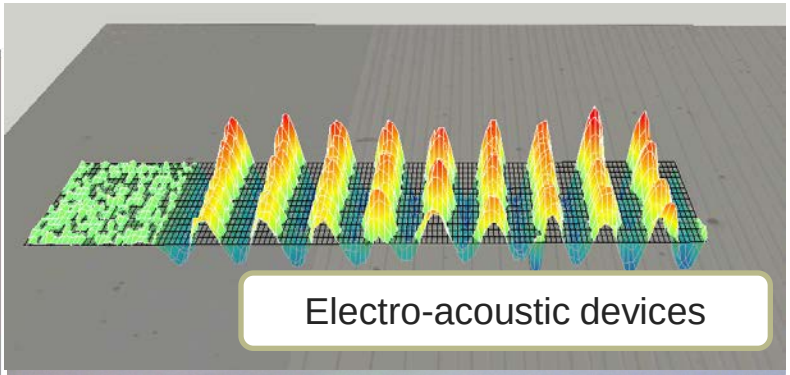
Full chain of development & fabrication steps:



NEMS/MEMS technologies

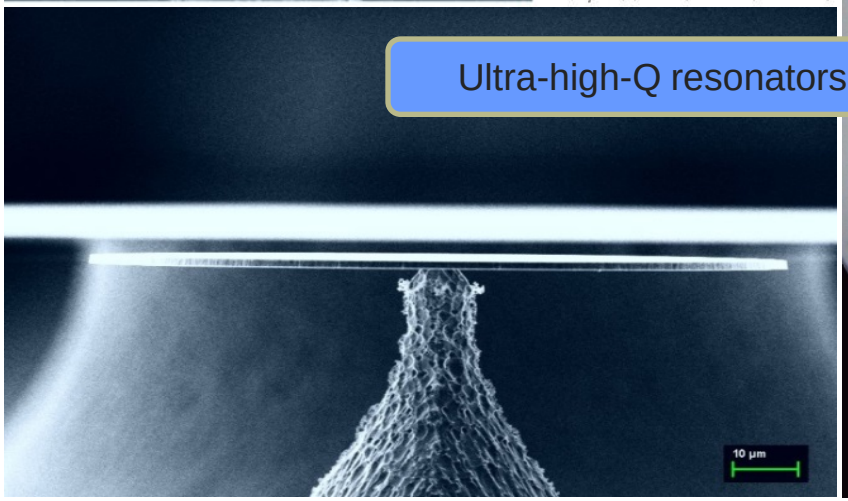
Vacuum nano-electronics

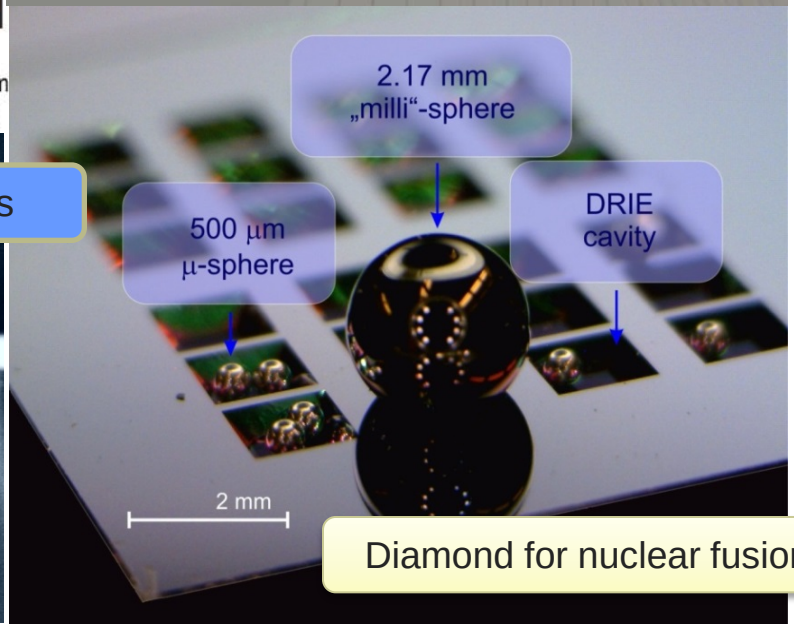




Electro-acoustic devices

Ultra-high-Q resonators





Diamond for nuclear fusion

Fraunhofer IAF: characterization

Main growth techniques

- MBE & MOCVD of III-V
- Plasma CVD of Diamond
- ALD + RTA of Oxides
- Sputter Deposition of Al(Sc)N

Processing

- Front- & Back-End
- Metallization/Passivation
- UV (400 nm) & e.beam lithography
- ICP/ECR dry etch of III-N & Si & Me
- DRIE (Bosch) of Si

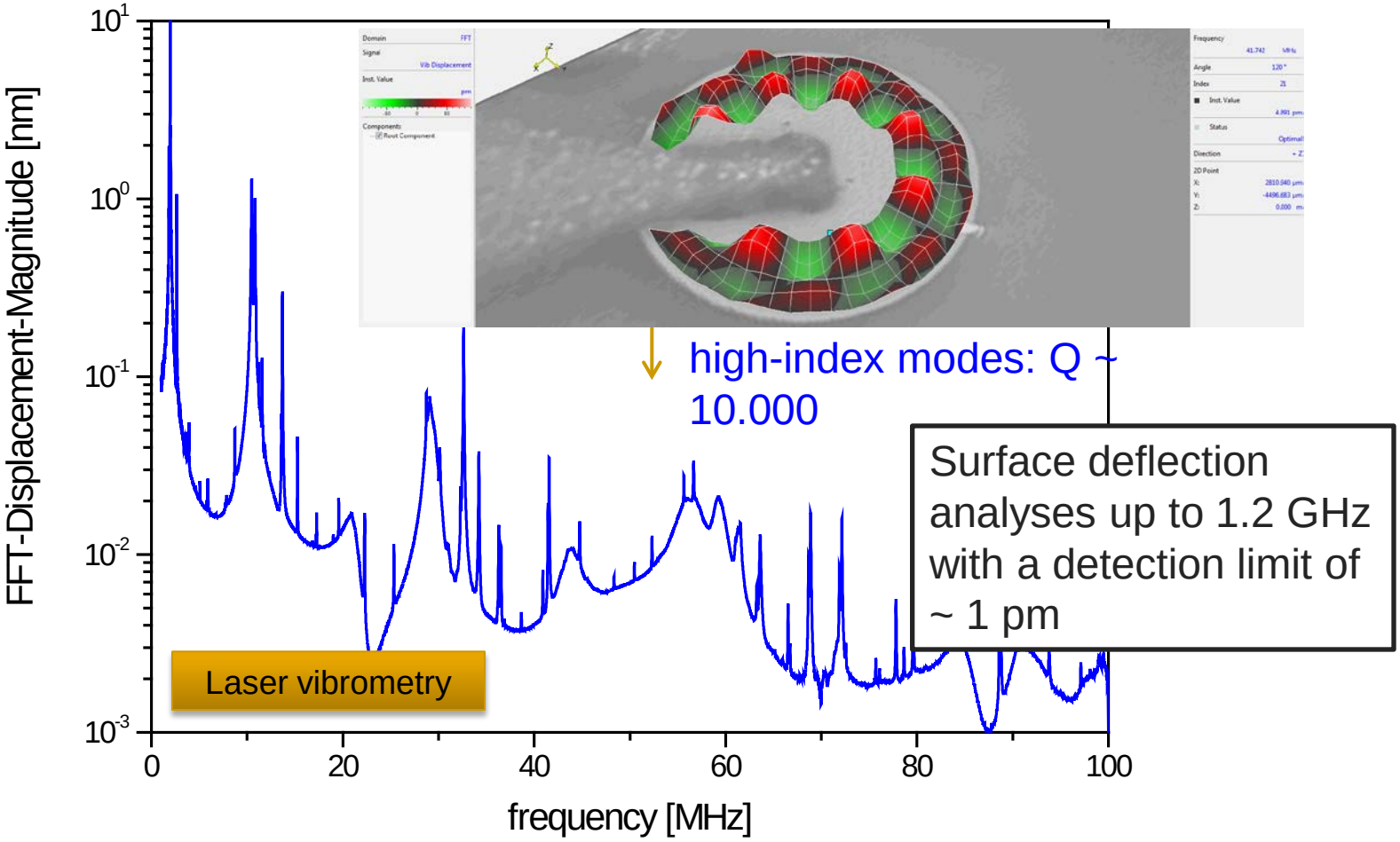
Material characterization in house

- **Scanning Probe Piezo-AFM**
- SEM/AFM/PFM/Kelvin-Probe
- XRD & XRR, SIMS
- Confocal µ-Raman, S-Ellipsometry
- VF-, VT-Hall (up to 2T/800K)
- **Indentation by nano-positioning**

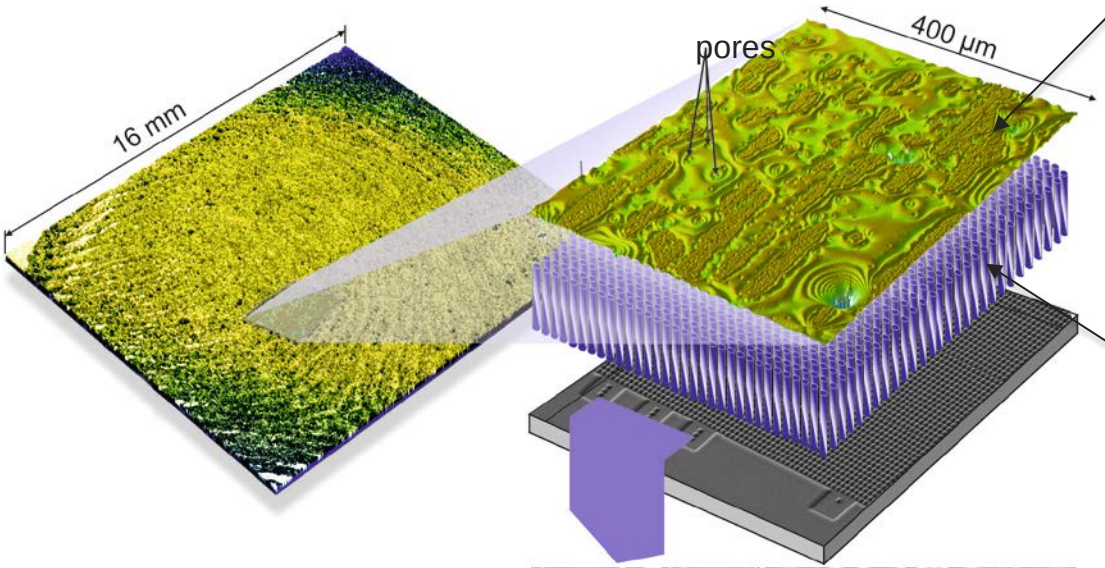
MEMS characterization

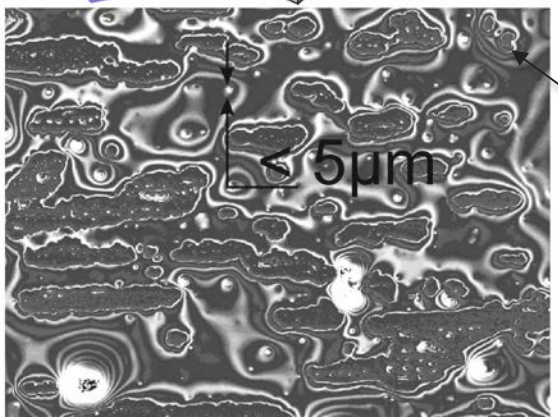
- White light interferometry (static)
- **Laser Doppler Vibrometry**
- S-Parameter Analyses (up to 400 GHz)
- Measurements from vacuum to liquids
- Dedicated Bio-& Gas-Sensor Labs
- Powered by COMSOL (FEM) simulations

Example: laser vibrometry



PiezoMAT fingerprint sensor





PiezoMAT challenge:

fingerprint main features >100 µm

for small features 1-10 µm the resolution > 1000 dpi is essential!

PiezoMAT approach:

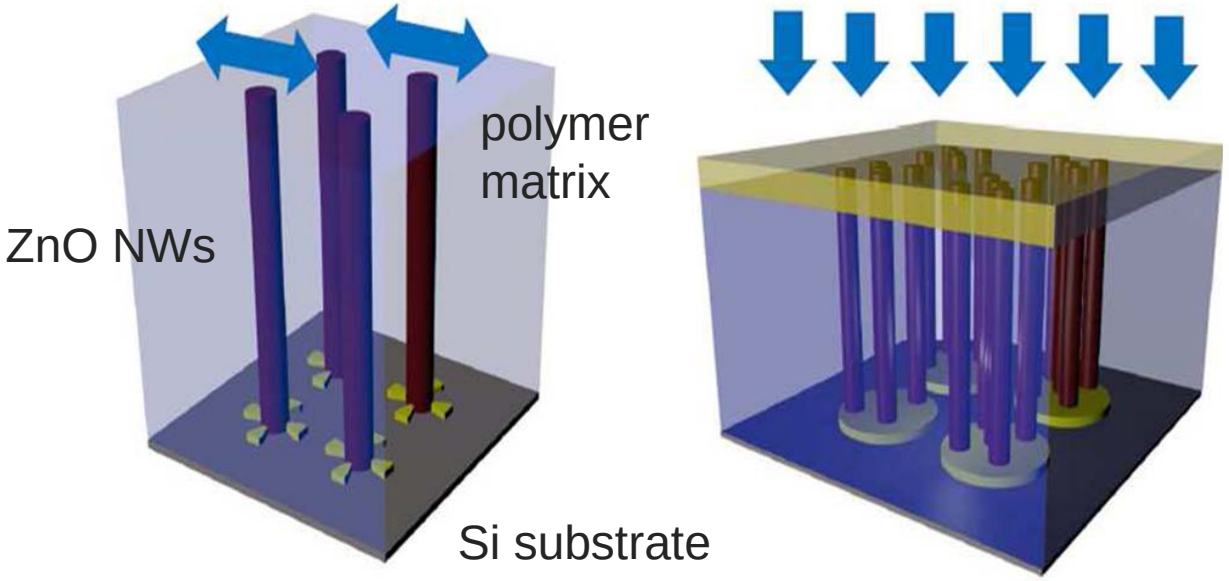
piezoelectric ZnO NWs directly grown on patterned electronic circuits

PiezoMAT aim:

8-bit read-out of NW electric response (256 grey-levels) with detection of level 3 minutiae of fingerprints (pores, ridge edges, …)

PiezoMAT PoC2 & PoC3 chips

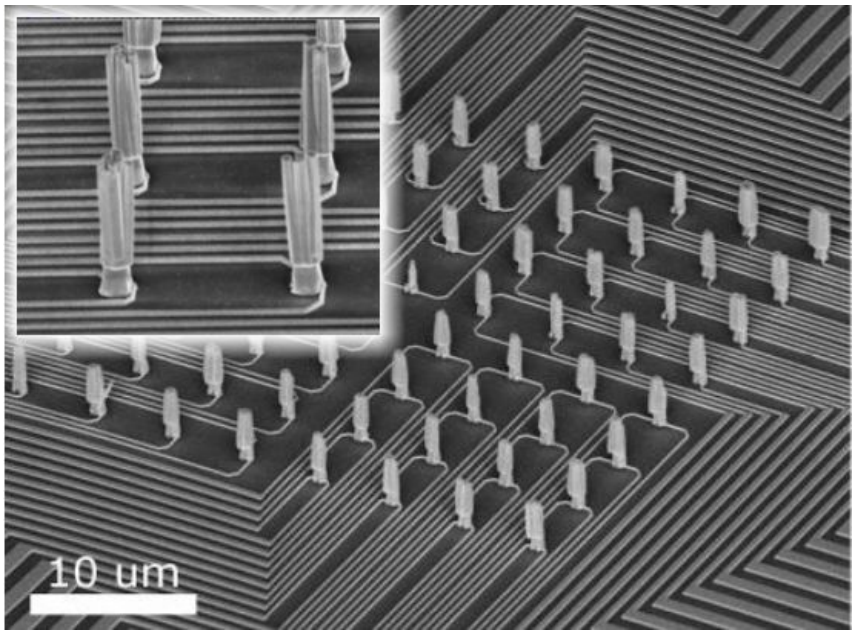
PiezoMAT proof-of-concept sensors to be characterized at Fraunhofer



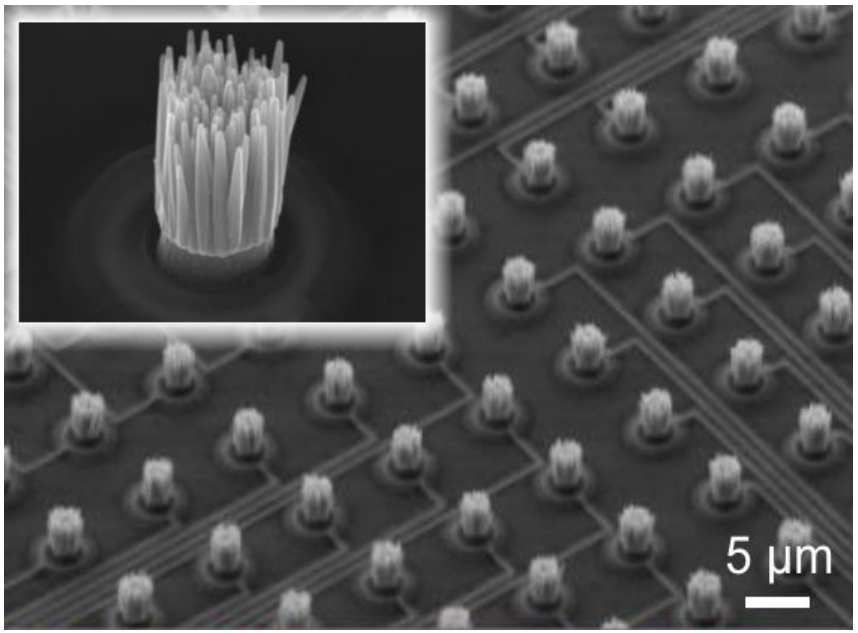
Option 2
compression &
bending forces

Option 3
compression
forces

PoC2 & PoC3 fabrication

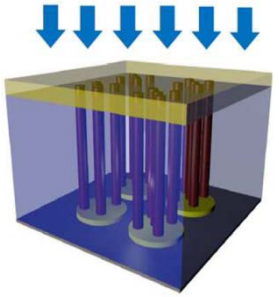


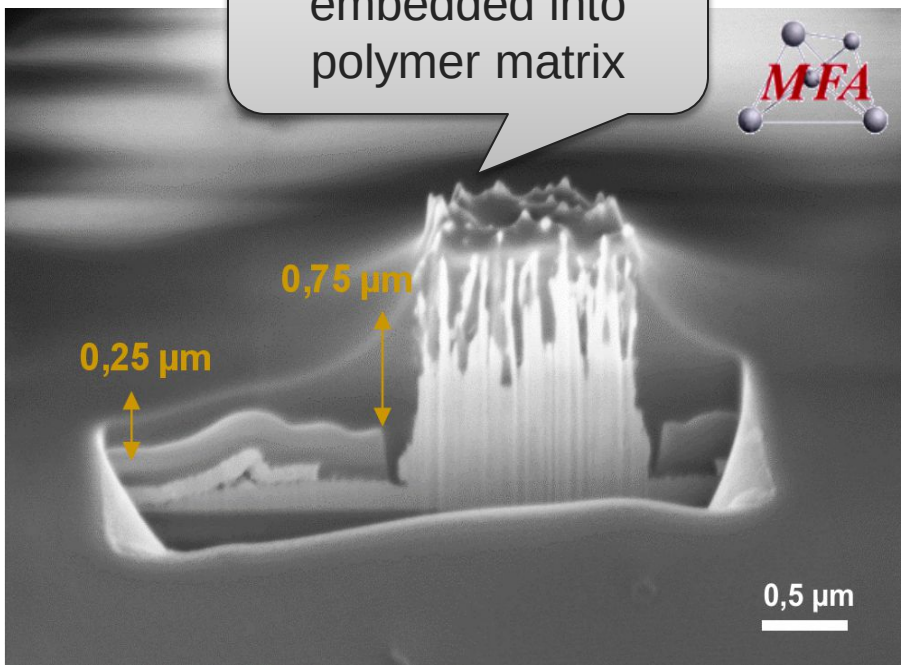
- 8×8 PoC2A fabrication & main characterization by MTA EK MFA

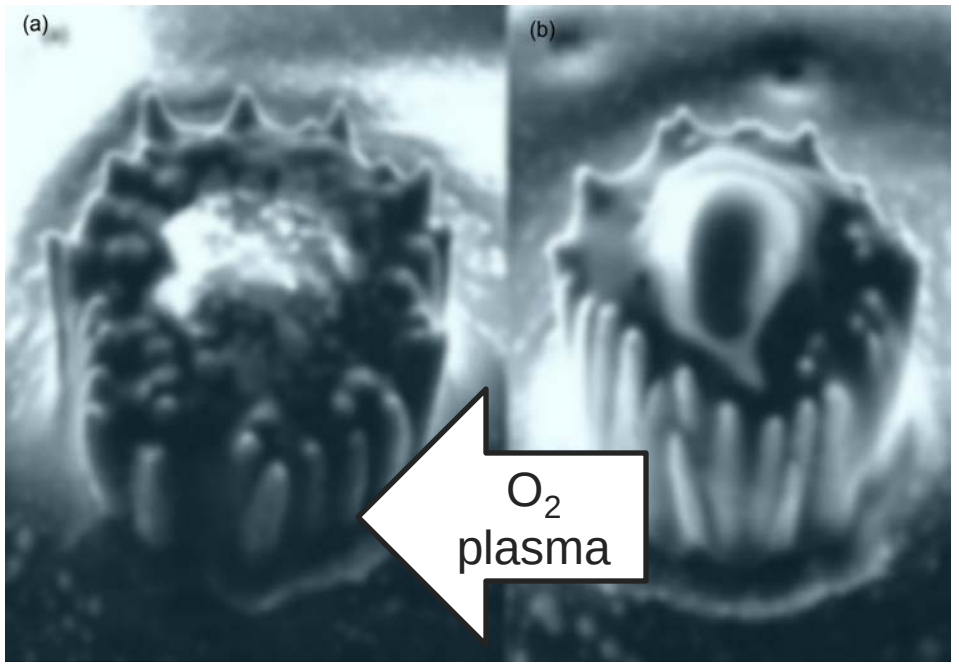


- 10×10 PoC3 by CEA/MTA EK MFA; characterization by Fraunhofer

PoC3 encapuslation

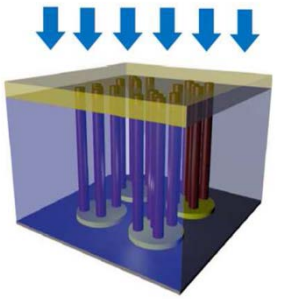




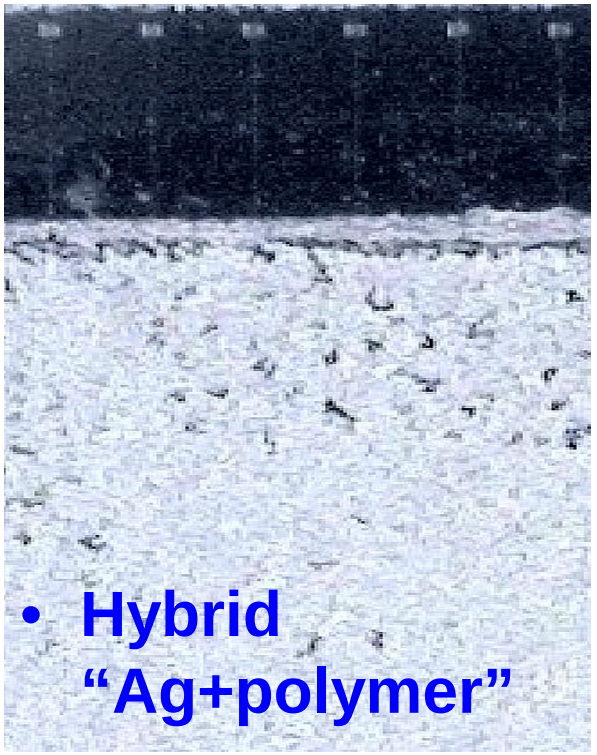


- PoC3 encapsulated by polymer layer at SP (SEM at MFA)
- Encapsulated PoC3: preparation for top-electrode processing

PoC3 top-electrode



Ti/Au
top-electrode layer
evaporated onto
PoC3 sensor



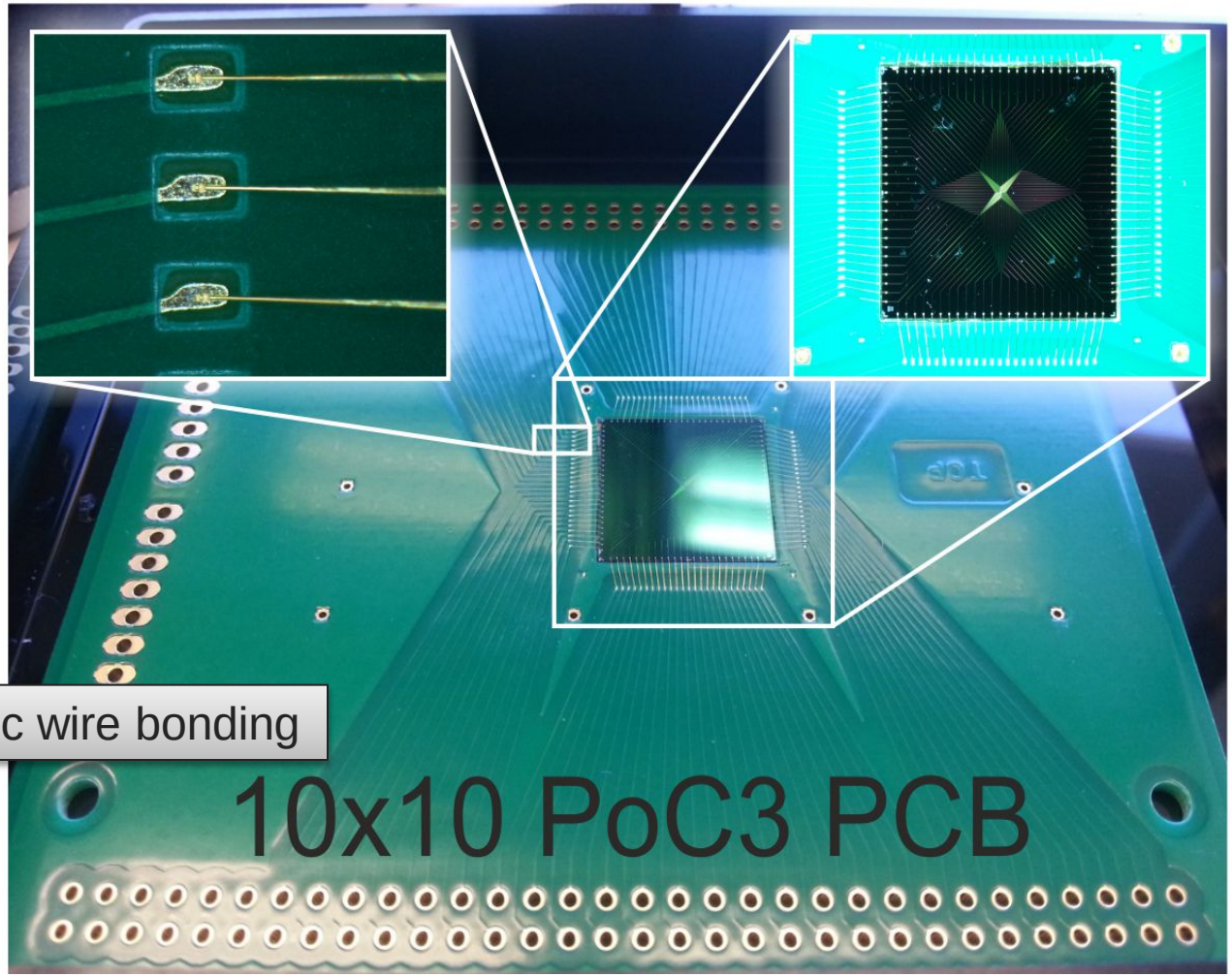
- **Hybrid “Ag+polymer”**

- Standard: 100 nm Au layer

New approach by Specific Polymers

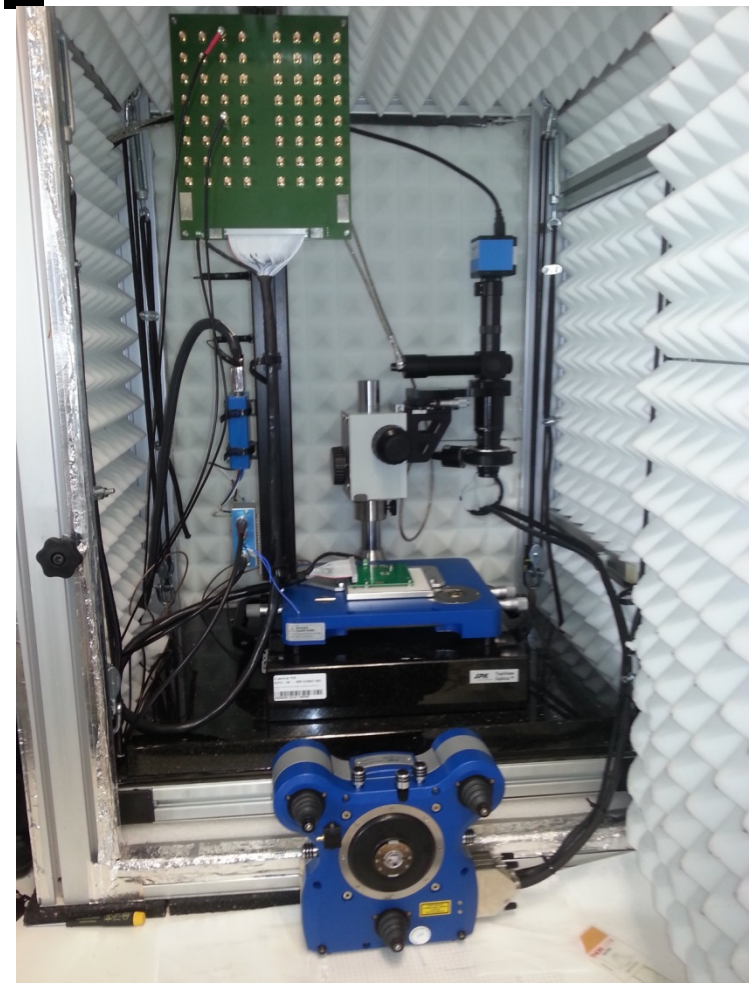
PoC3 montage/bonding

- 100 channel low-noise PCB design
- automatic Au wedge-wedge wire bonding

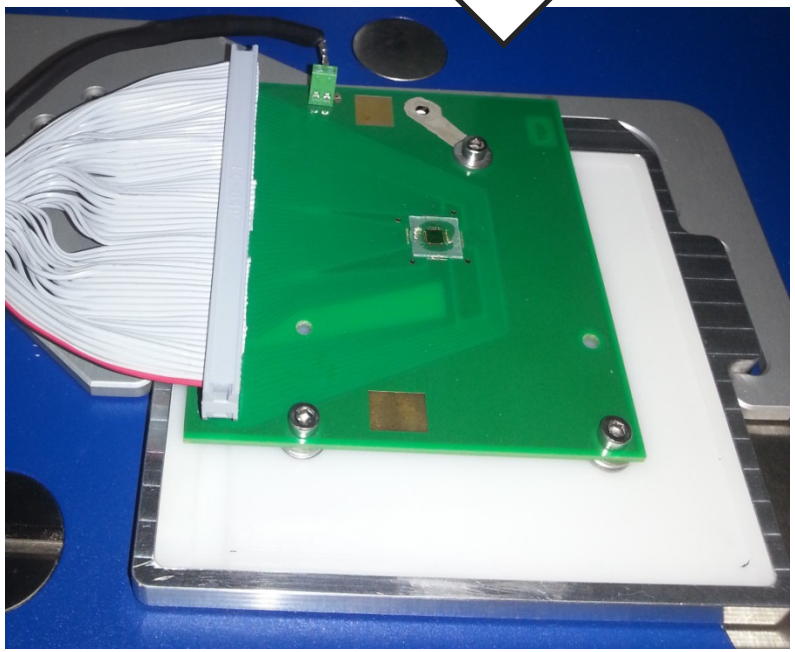


- 10×10 PoC3: automatic wire bonding

AFM based setup

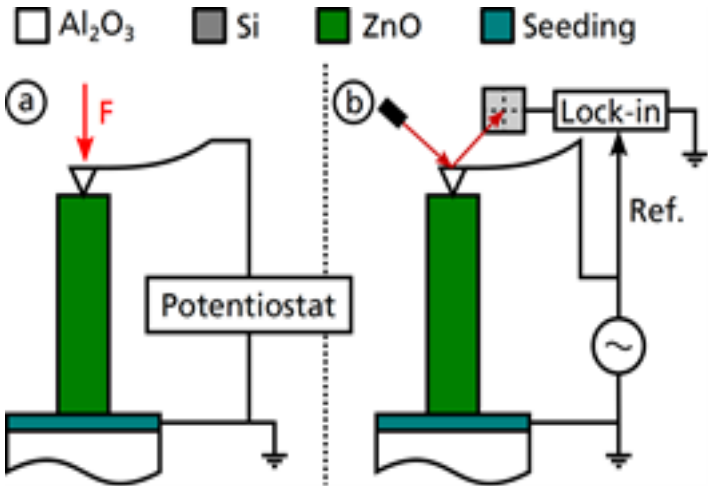


- high acoustic & electrical insulation
- single-NW & array characterization

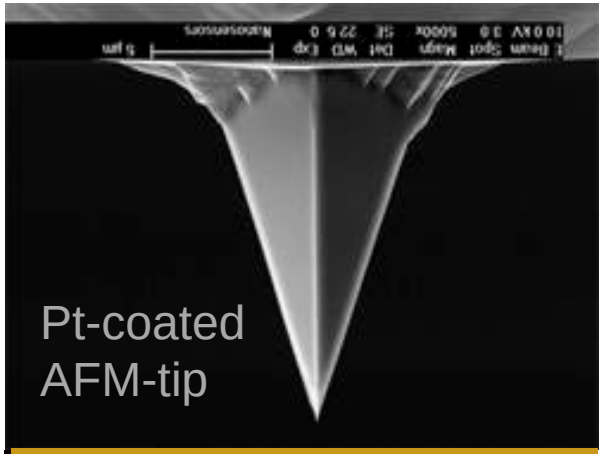


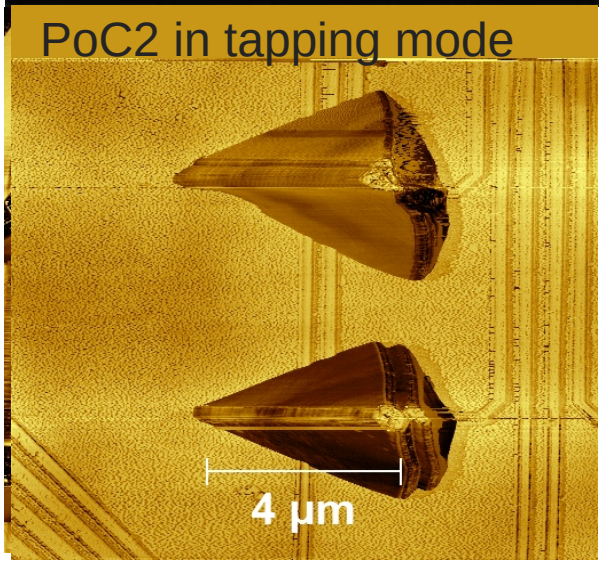
AFM-based analyses

- two main methodologies:



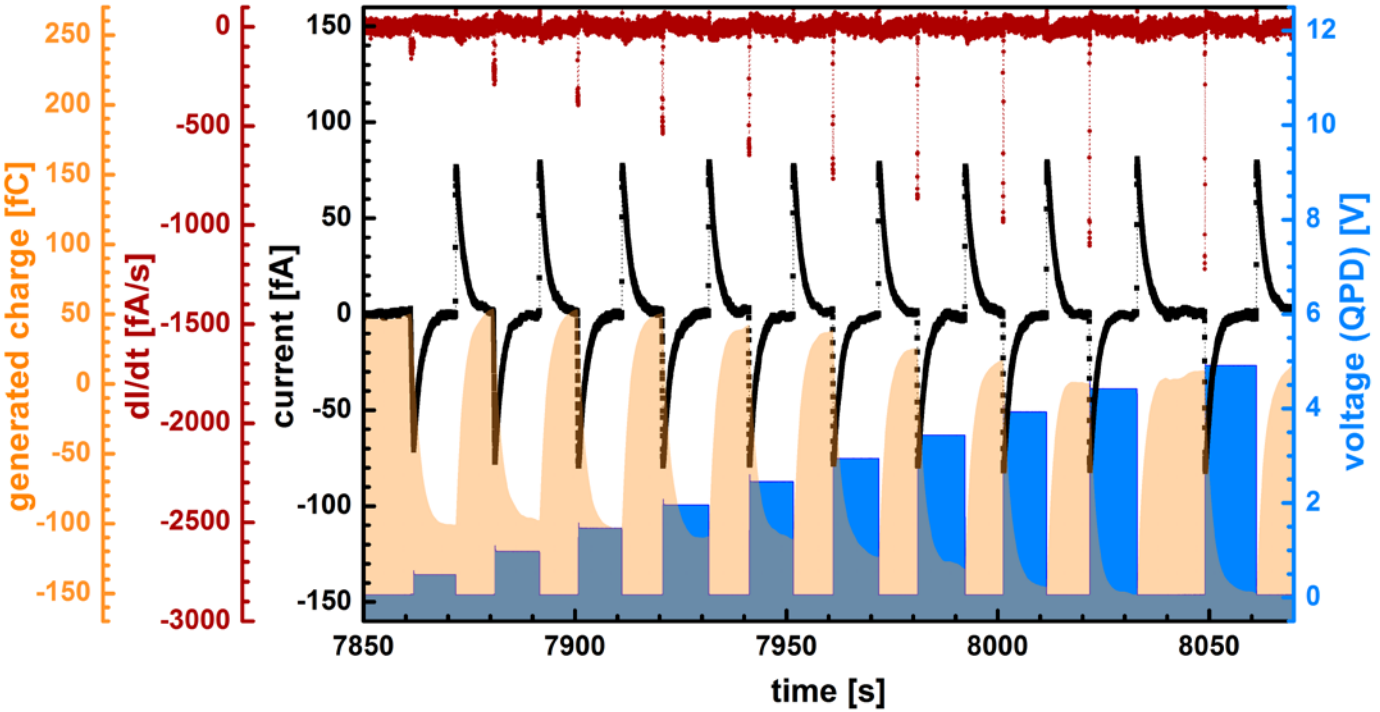
a) force-response *(AFM-FR, up to 1 μN);*
b) piezoelectric coefficient *(AFM-d_{33}) measurement configurations.*





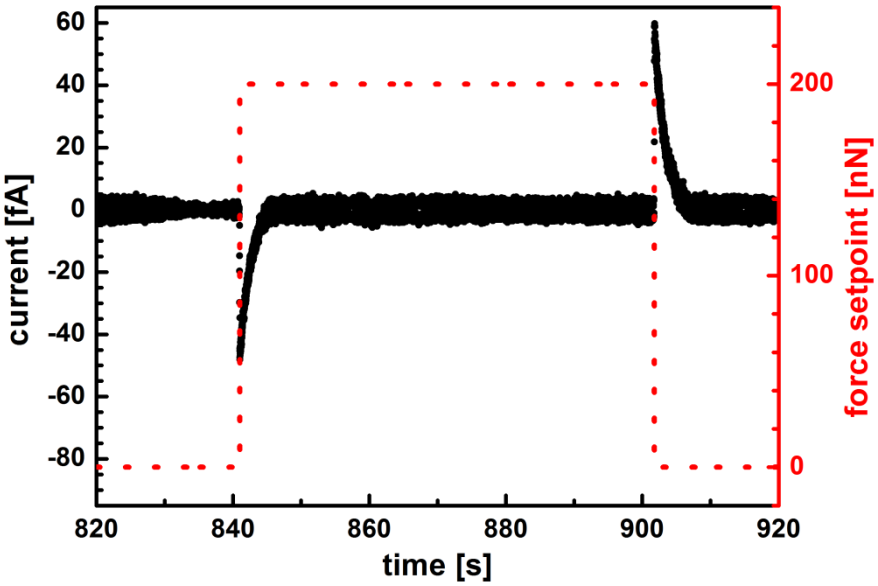
AFM-FR time analyses

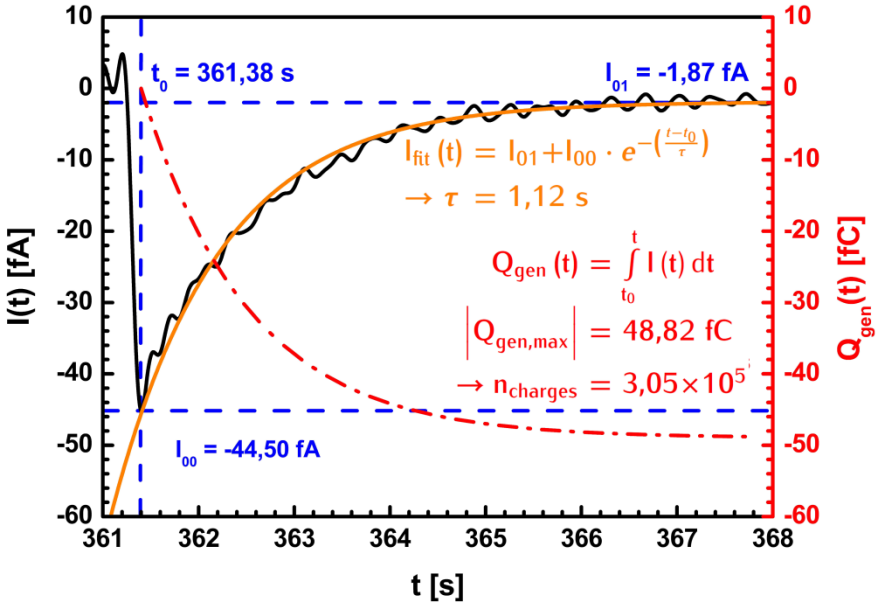
- Example of typical FR-measurement protocol (time-chart):
  -> record of electromechanical NW response to different force magnitudes.



- Recording current (black) & z-position (blue) vs. time;
- Calculating force, dI/dt (red) & generated charge (orange);

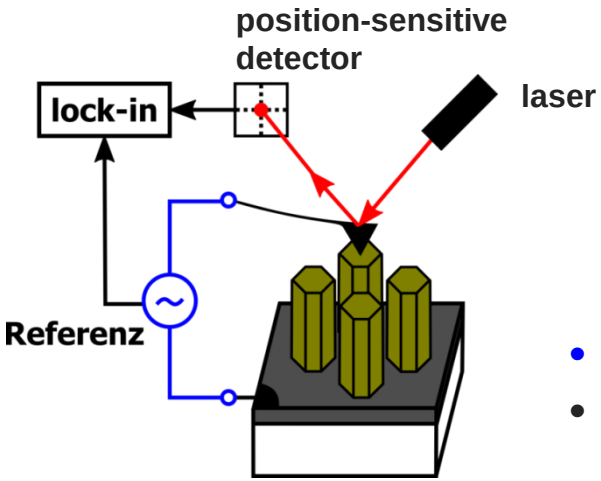
AFM-FR: data treatment





- peak piezo-response of ZnO NW at **200 nN** compressive force, recorded by potentiostat;
- total generated charge of **~ 50 fC** is estimated by means of a time-domain analysis of the decay time constant.

AFM-d_{33} : piezo-coefficient

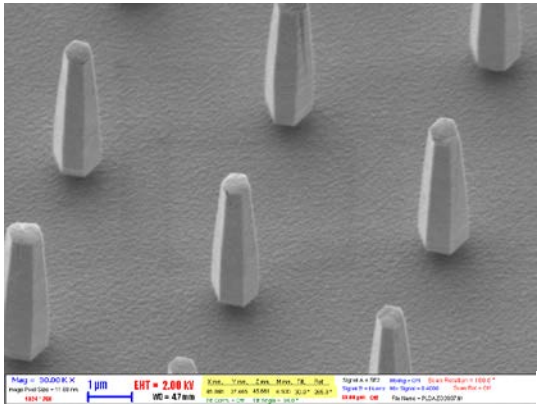


applying ac voltages → measuring z-axis movement d[33]

- **lock-in** technique for the low-noise conditions;
- measured cantilever sensitivity and reference piezo-response of AlN micro-pillars (d_{33} = -5.8 pm/V);
- ZnO NW d_{33} value of **~ 15 pC/N** in a good agreement with the literature data
- high crystal quality ZnO NWs!

$$d_{33} = \frac{\text{signal} * \text{sensitivity} * \text{prop.factor}}{\text{input signal}} = \frac{220 \cdot 10^{-6}\ \text{V} * 34.2 \cdot 10^{3}\ \frac{\text{pm}}{\text{V}}}{5\ \text{V}} * 10 = \mathbf{15.1}\ \frac{pm}{V}$$

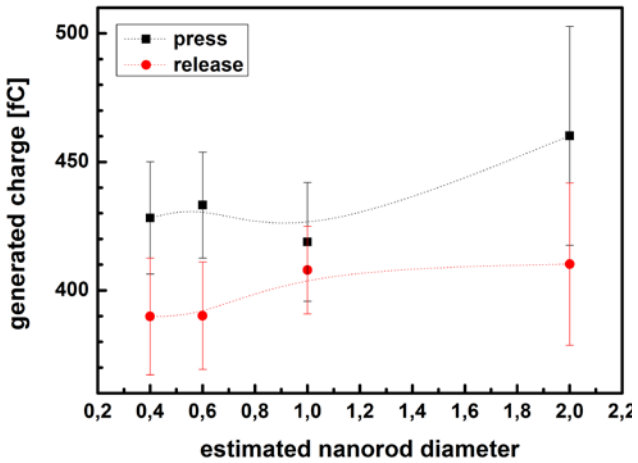
AFM-FR: sensitivity

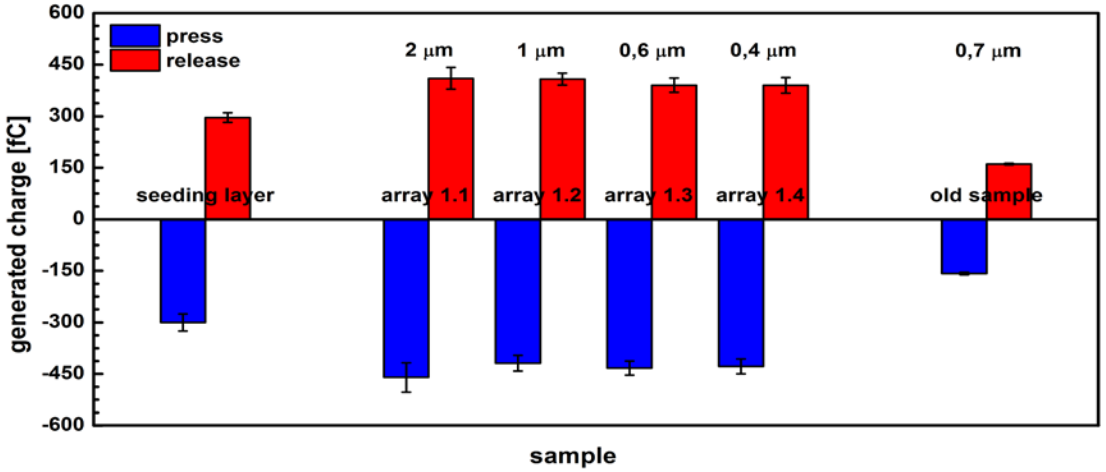


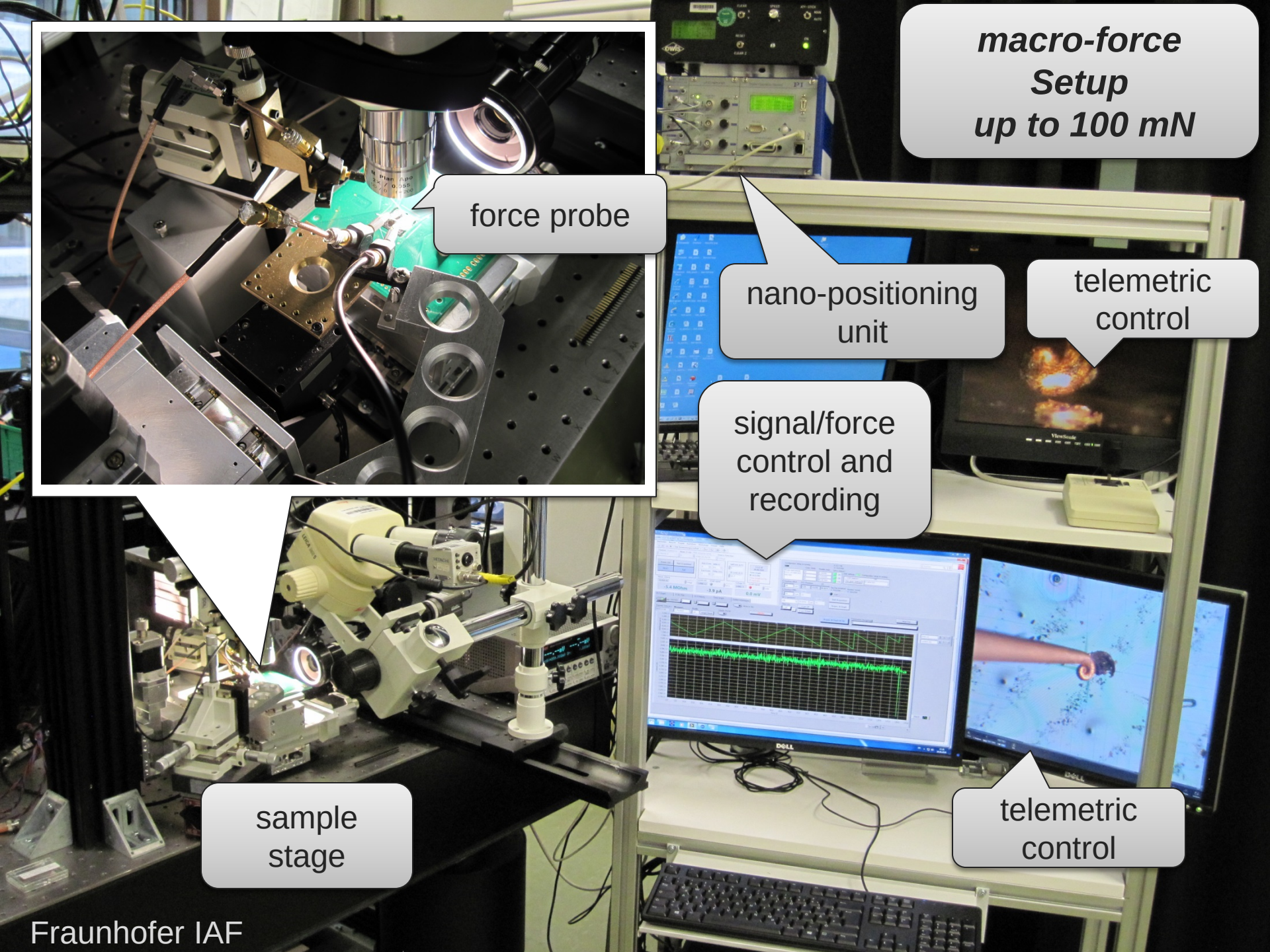
AFM-FR is an extremely sensitive method

… even a week response dependence on the varying NW diameter can be detected …

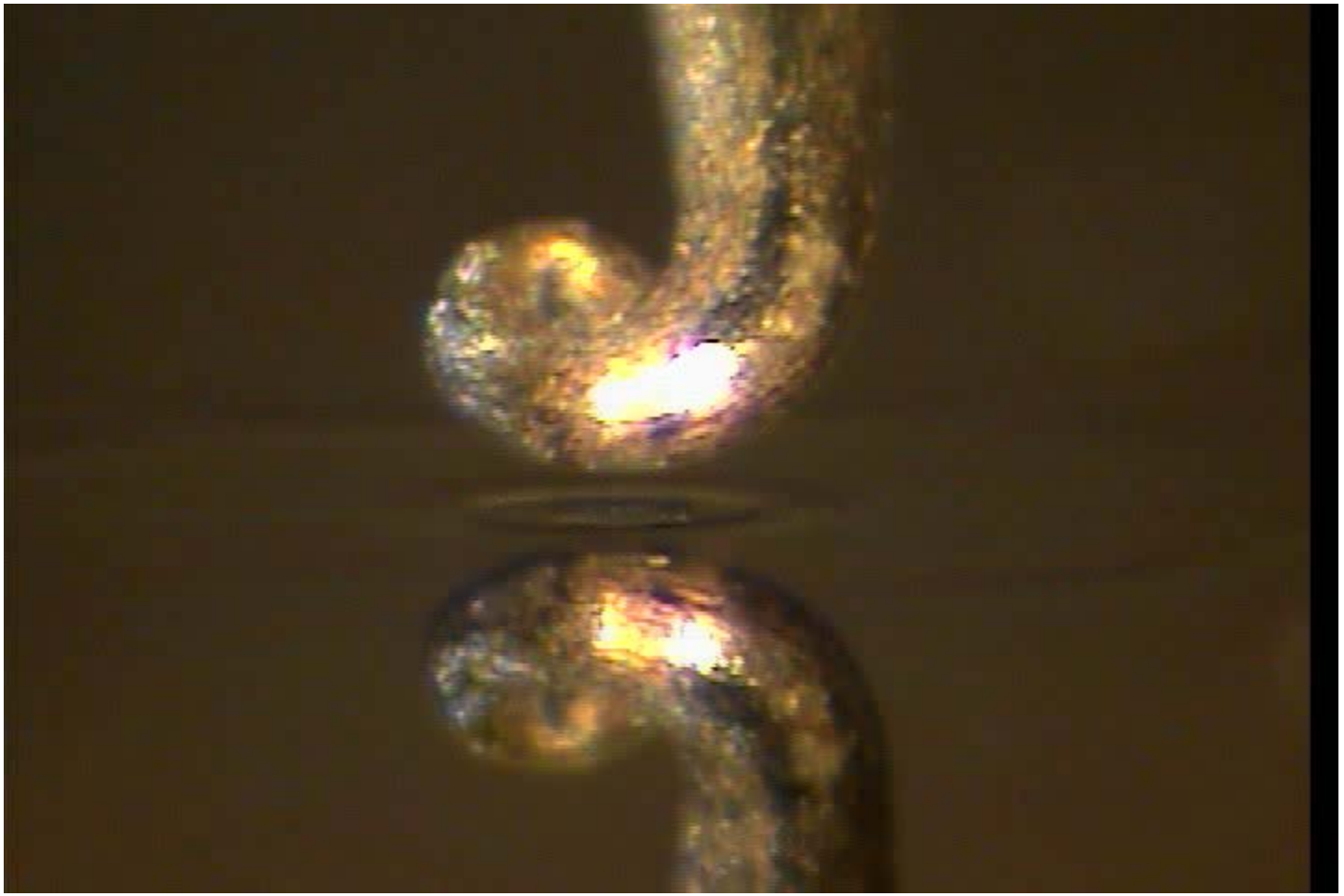
but limited to the force range < 1 µN.





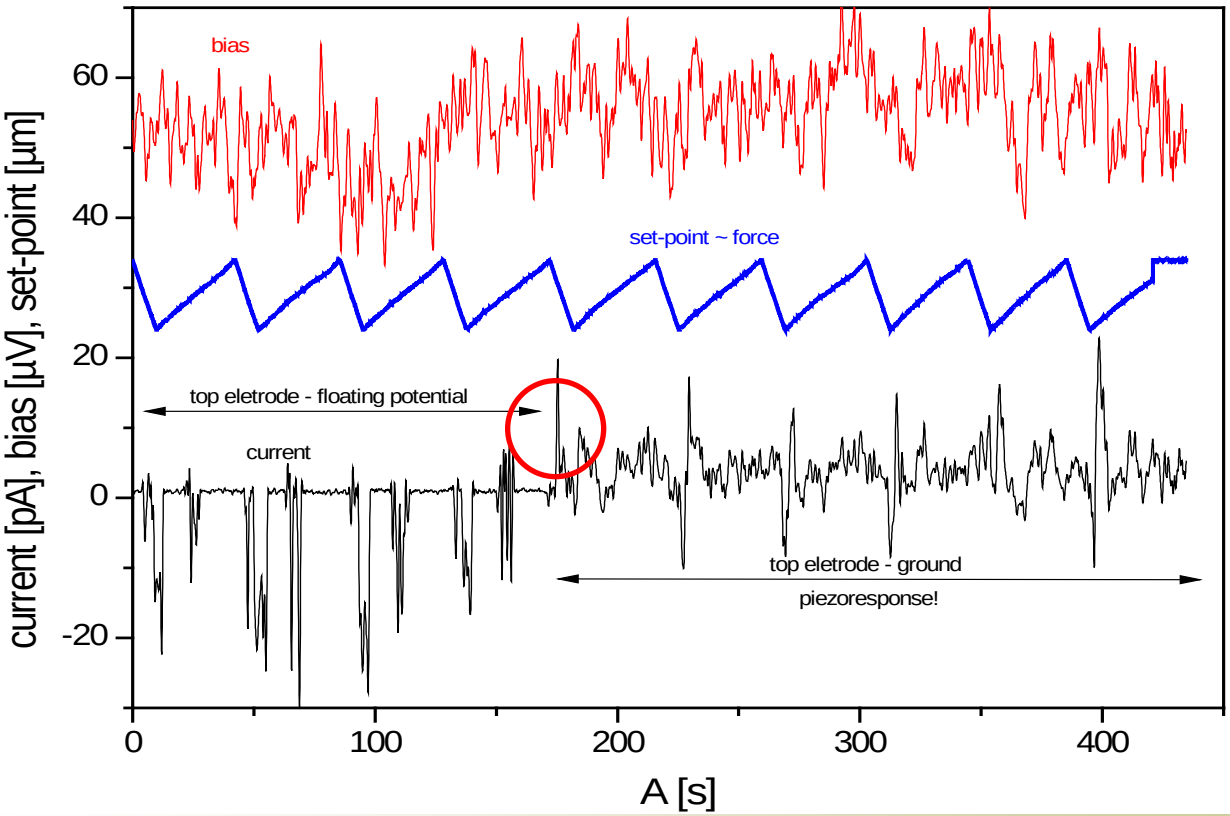

macro-force
Setup
up to 100 mN
force probe
nano-positioning
unit
telemetric
control
signal/force
control and
recording
sample
stage
telemetric
control
Fraunhofer IAF

Macro-FR: PoC3



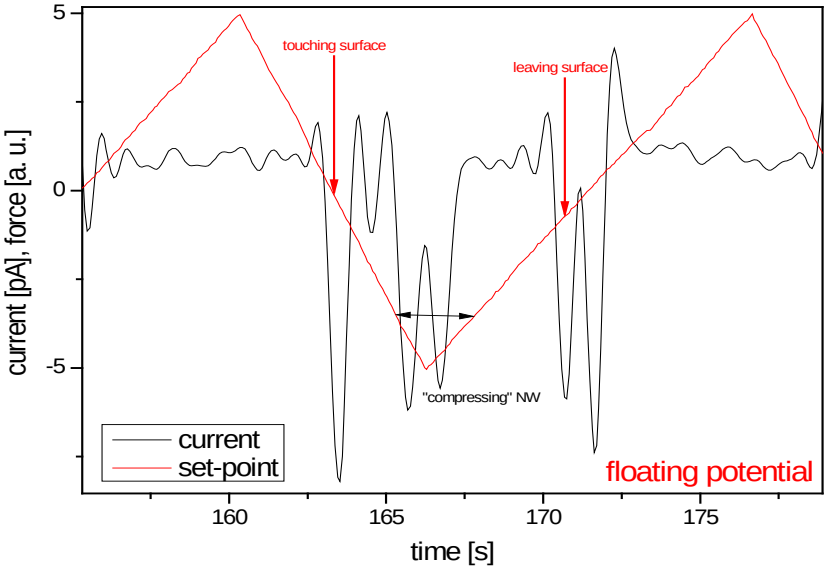
Macro-FR: PoC3

- Typical force-response protocol:
  with transition from “surface contact detection” to NW response regime

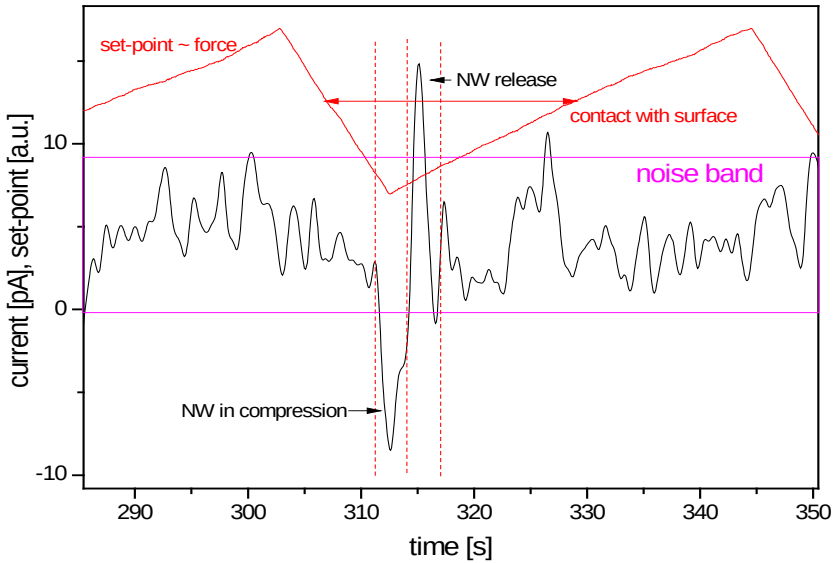


Macro-FR: PoC3 at FhG

- "surface contact detection"



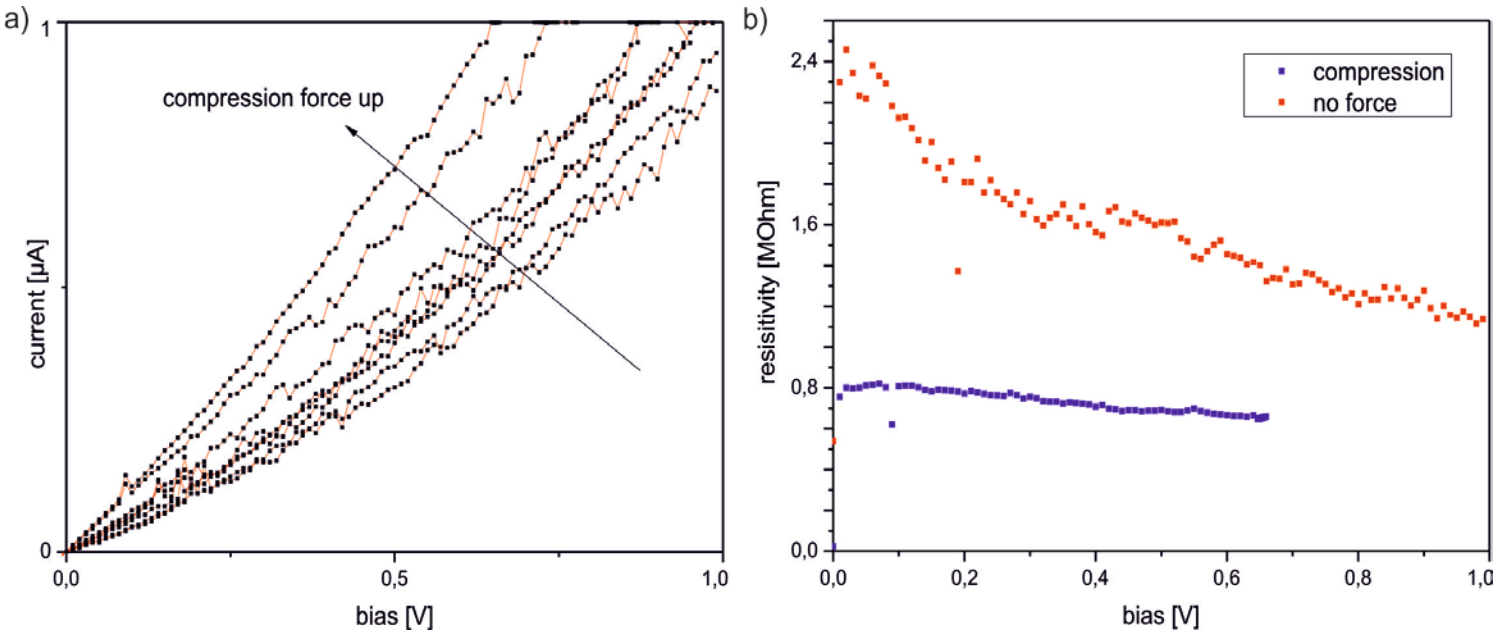
- NW response at "0"-bias



$\langle |Q_{px}| \rangle = 13.2 \div 19.1$ pC

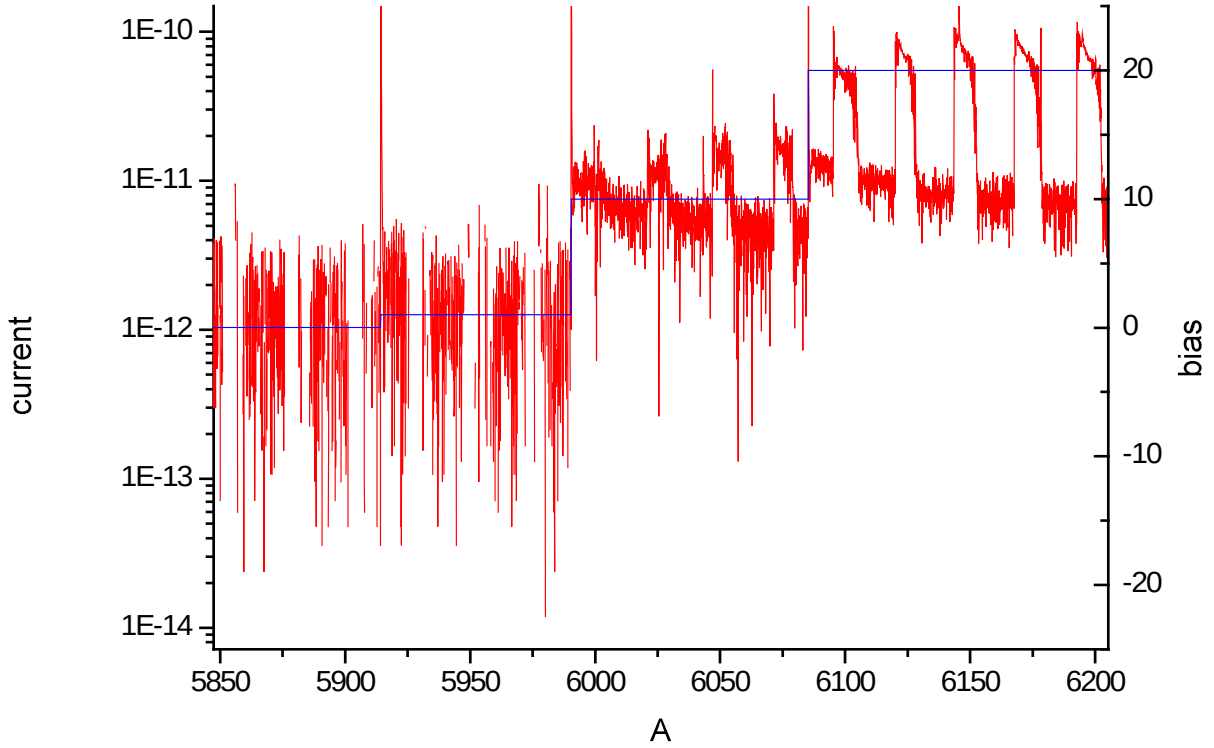
PoC3: piezo-tronic?

- $\langle |Q_{px}| \rangle$ > 10 pC is huge number!
- good for the detection, but what is additional mechanisms?



ZnO is “piezo-tronic” material -> resistance is a function of applied force!

PoC3: piezo-tronic?



- additional confirmation of “piezo-tronic” behavior is an enhanced response of ZnO NW at applied bias
- modeling by PiezoMAT partners is in progress …

Summary

- Three main methodologies for the PiezoMAT sensor characterization:

  - AFM-based force-response measurements up to 1 µN;
  - AFM-based vibration analyses: d_{33} coefficient measurements;
  - Macro-force probing up to 100 mN using nano-positioning;

- Sensitivity of AFM-based setup: ~1 fA (potentiostat) × 10 nN;

- Sensitivity of MACRO setup: ~ 100 fA (source-meter) × 10 µN;

- force-dependent multi-channel respon se has been detected on proof-of-concept PiezoMATchips;

- the decisive role of the **piezotronic effect** has been confirmed;

WP6: Summary