

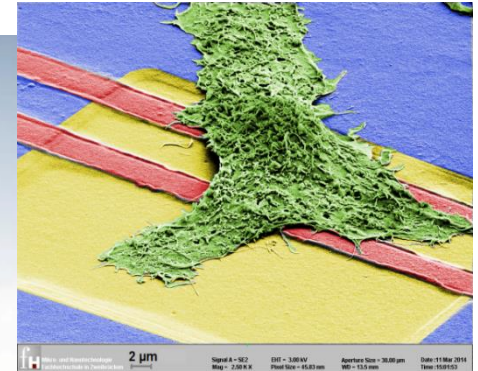
# Micro- and nanoelectronics sensors: from technologies to applications

**Dr. Xuan Thang Vu**

Institute of Materials in Electrical Engineering 1

Chair of Micro- and Nanosystems

**RWTH Aachen University**



# Personal background

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- 2001: Bachelor of Science - Physics and materials science at Vietnam National University, Hanoi.
- 2003: Master of Science - Materials Science, International Training Institute for Materials Sciences (ITIMS), Vietnam.
- 2010: Ph.D student at Research Center Juelich and RWTH-Aachen University, Germany
  - [Silicon nanowire transistor for biomolecular detection](#)
- 2010 - 2013: Postdoc at University of Applied Sciences Kaiserslautern, Germany
  - [Micro-nanoelectronics devices for biomedical applications](#)
- 2014 - 2018: Postdoc at Physics Institute (1A), RWTH – Aachen, Germany
  - [Phase change memory devices – Dynamics of amorphous materials](#)
- 2015 - 2016 : RAM Group DE GmbH, Germany
  - [Sensors development and fabrication management](#)
- 7. 2018 : Permanent research staff at the Chair of Micro and Nanosystems, Faculty of Electrical Engineering and Information Technology, RWTH Aachen University, Germany
  - [Lecturer](#)
  - [Micro- and Nano-electronic sensors](#)
- 7. 2021 : Faculty member (Akademischer Rat), Faculty of Electrical Engineering and Information Technology, RWTH Aachen University, Germany

# Personal background

## Research Center Jülich (2006-2011)



## RWTH Aachen University (2014-...)



## University of Applied Sciences Kaiserslautern (2011-2013)



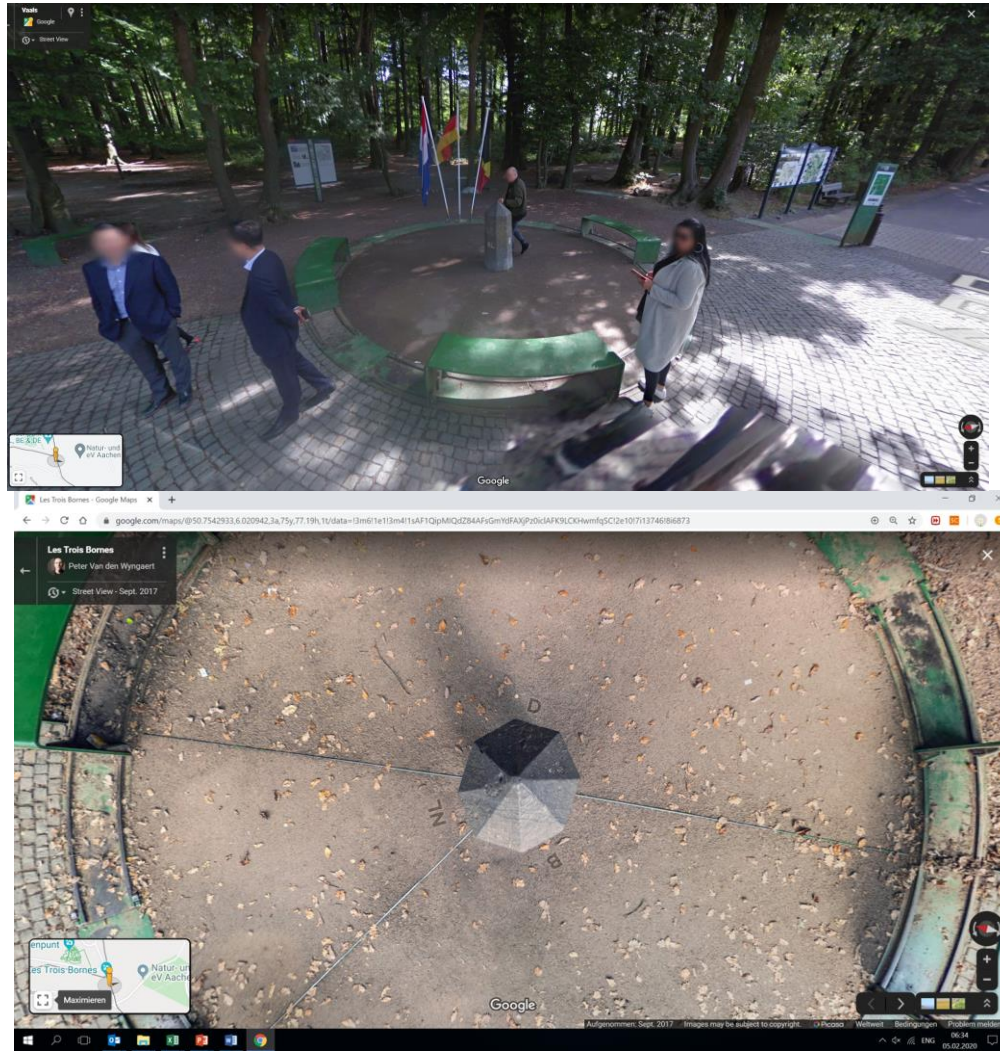


# Aachen city



**Aachen Cathedral** ([German](#): *Aachener Dom*) is a [Roman Catholic](#) church in [Aachen](#), [Germany](#) and the [see](#) of the [Roman Catholic Diocese of Aachen](#). One of the oldest [cathedrals](#) in [Europe](#), it was constructed by order of the [emperor Charlemagne](#), who was buried there in 814. From 936 to 1531, the [Palatine Chapel](#) saw the [coronation](#) of thirty-one [German kings](#) and twelve queens. The church has been the [mother church](#) of the Diocese of Aachen since 1802

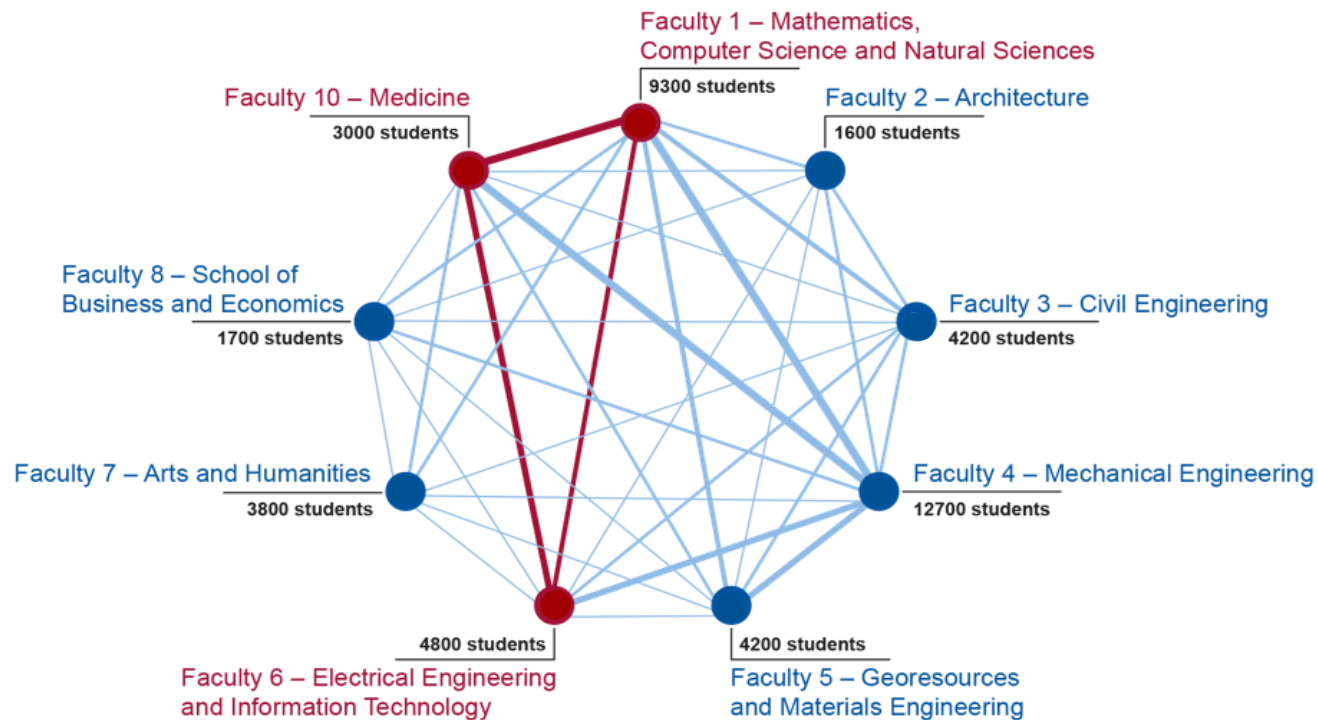
Source- Wikipedia 2020



# RWTH Aachen University: Current Facts & Figures

## Germany's largest technical university

Students	>45,000
Bachelor and Master Degree Programs	152
Overall Budget	>1000 million €



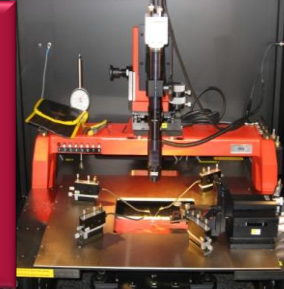
## Research Profile

### Energy and Environment



**6 Chairs/Institutes**  
**E.ON Energy Research Center**

### Micro- and Nanoelectronics



**9 Chairs/Professors**  
**7 Institutes**  
**1 Research Group**  
**Advanced Microelectronic**  
**Center Aachen (AMICA)**

### Medical Engineering



**2 Chairs/Institutes**  
**1 Affiliated Helmholtz-Institute for**  
**Biomedical Engineering**

### Information Technology and Mobile Systems



**10 Chairs/Institutes**  
**UMIC-Research Cluster**



# Institute of Materials in Electrical Engineering I

**Prof. Dr. Sven Ingebrandt**

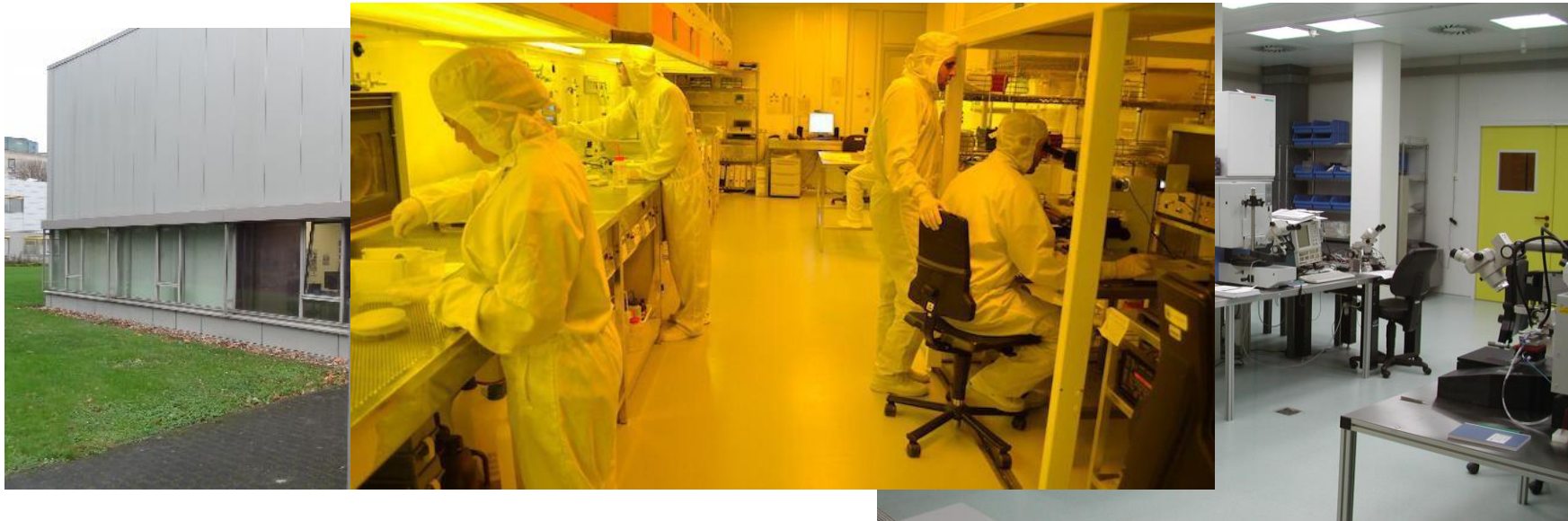
<http://www.iwe1.rwth-aachen.de/>

Chair of Micro- and Nanosystems

(successor of Prof. Dr. Wilfried Mokwa)

**IWE1** Institut für  
Werkstoffe der  
Elektrotechnik 1

**RWTHAACHEN**  
UNIVERSITY

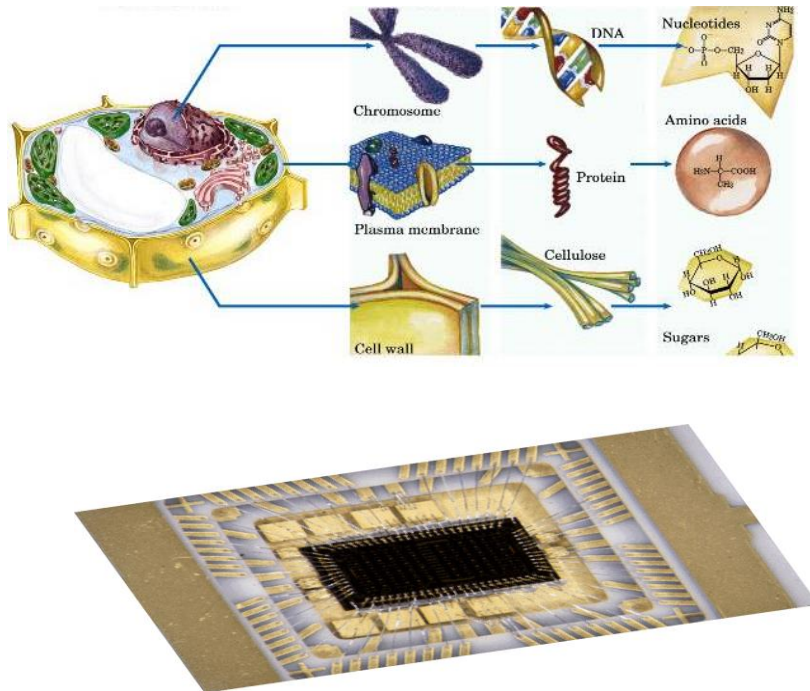


**Central clean room facility**

<http://cmnt.rwth-aachen.de/>

**Microsystem packaging facility**

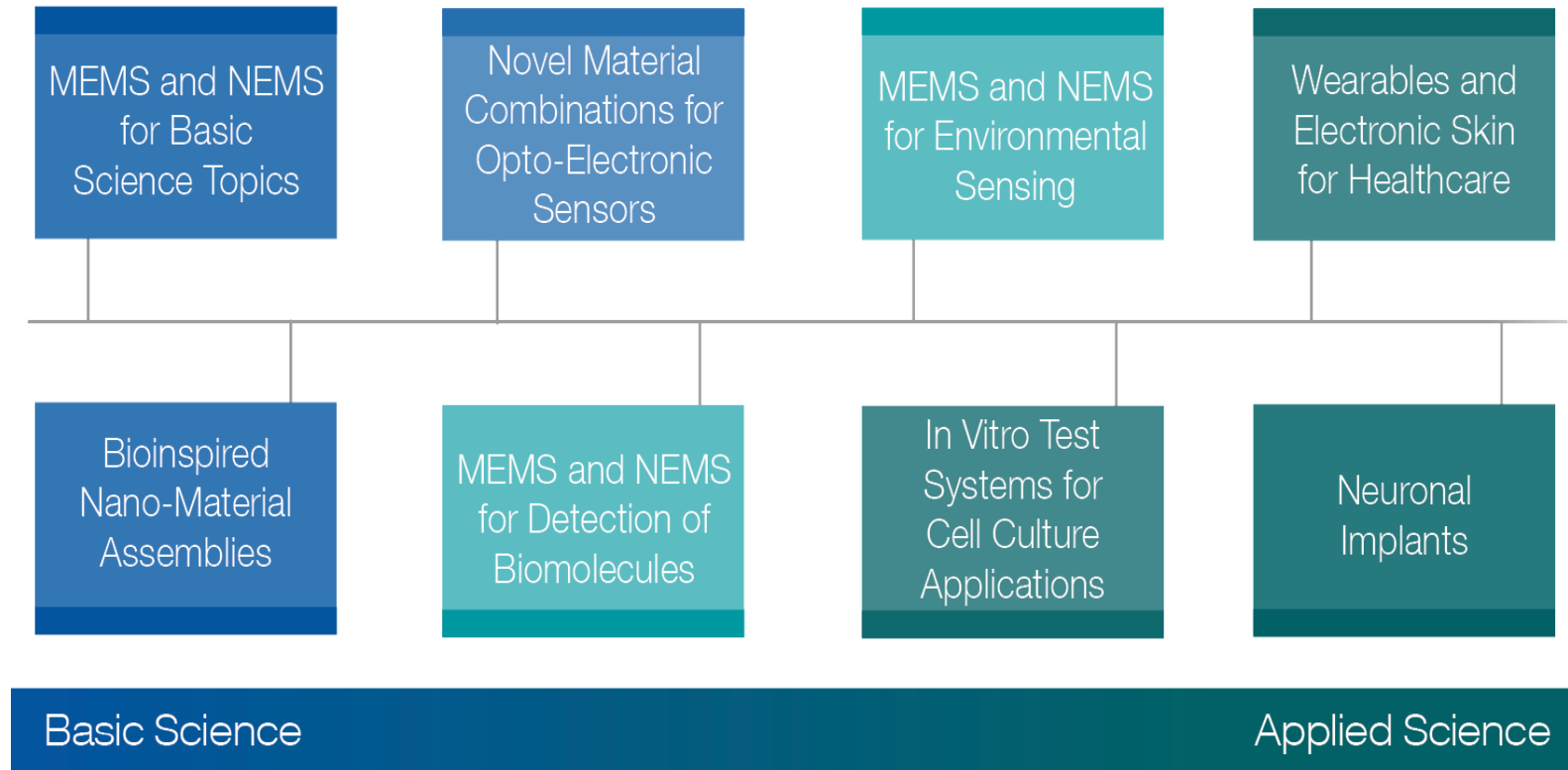
## Biosensors and Bioelectronics



## Environmental Sensing in Industry 4.0







# IWE1 – Research Groups

Prof. Dr. Sven Ingebrandt  
Director,  
Institute of Materials in Electrical Engineering 1  
(IWE1)



Dr. Vivek  
Pachauri



Dr. Xuan Thang Vu



Prof. Uwe  
Schnakenberg

Prof. Sven  
Ingebrandt

Group Leader  
Dr. Vivek Pachauri

Nanomaterials  
and Bio-Nano  
Interfaces

Group Leader  
Dr. Xuan-Thang Vu

Micro- and  
Nanoelectronic  
Sensors

Group Leader  
Apl.-Prof. Dr.-Ing.  
Uwe Schnakenberg

Microfluidics  
and  
Lab on a Chip

Group Leader  
Univ.-Prof. Dr.  
Sven Ingebrandt

Micro-Nano-  
Systems and  
Bioelectronics

Micro- and Nanosystems for Life Science, Environmental Sensors and Industry 4.0  
Clean Room Technology, Material Characterisation, Assembly and Connection Technology,  
Sensor Development, Wearables, Wireless Sensors, Sensor Characterisation

- 16 PhD students...  
and growing
- 15 masters thesis and  
project students
- Secretariat and  
technical staff

# IWE1 – Infrastructure



Central Laboratory for  
Micro- and  
Nanotechnologies **CMNT**

2 Clean-room modules of  
625 + 450m<sup>2</sup> for  
nanofabrication

Sensor's surface,  
electrical, and optical  
characterization labs



Chip encapsulation  
and packaging

Biolab (S1) for study of  
relevant biological  
systems, cell lines, etc.



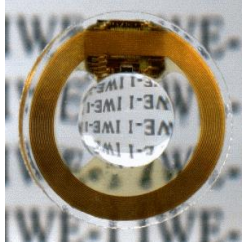
More information: <http://www.zmnt.rwth-aachen.de/>



# Development of intelligent implants

## IWE 1 Telemetric BioMEMS

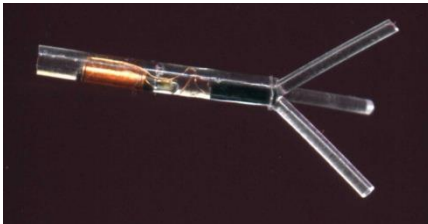
Inner eye pressure



Blood pressure



Blood pressure

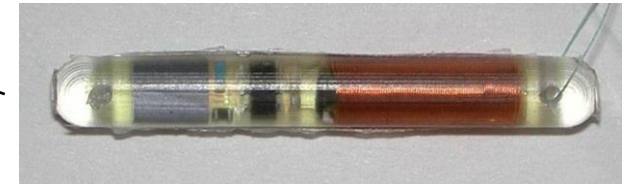


EPI-RET III



Retina eye implant

Bladder pressure



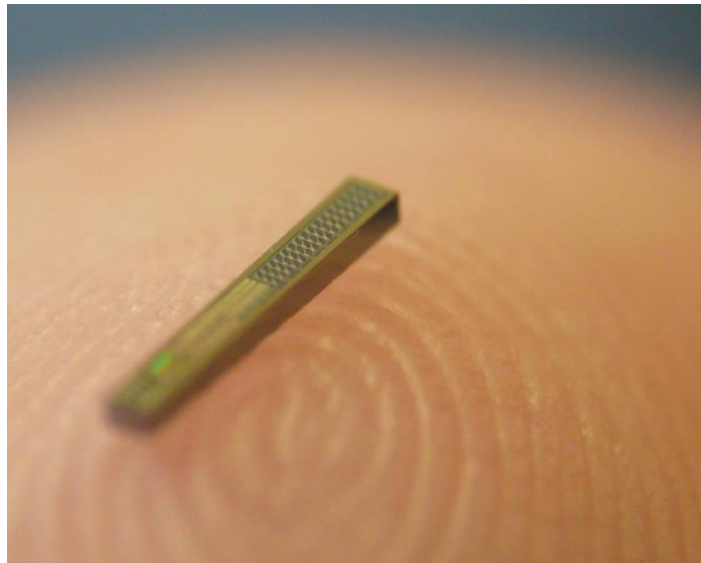
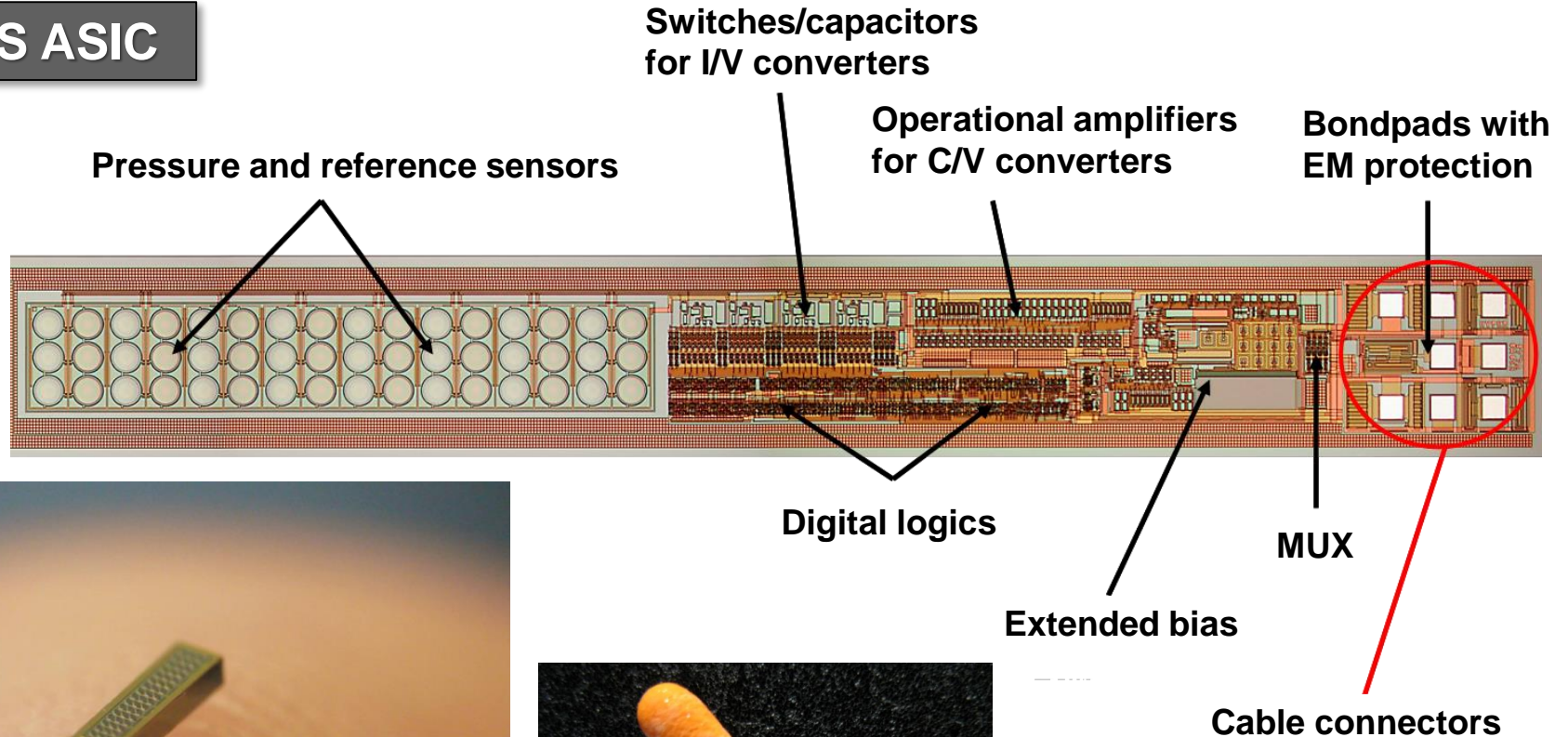
Blood pressure



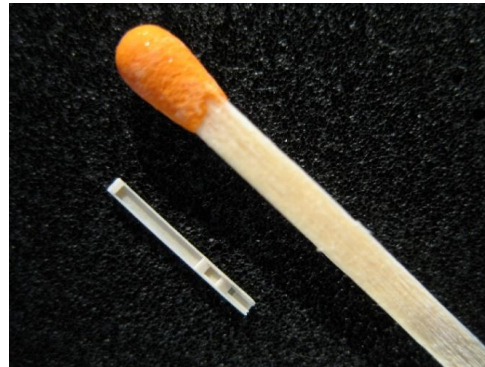
Inside atery

# Implantable system to monitor blood pressure

## MEMS ASIC

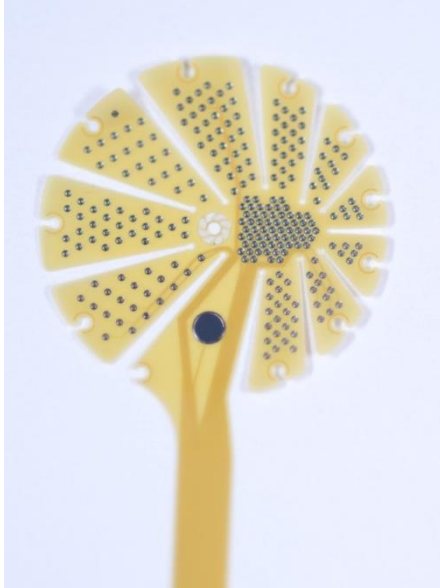


Microsystem on a finger tip



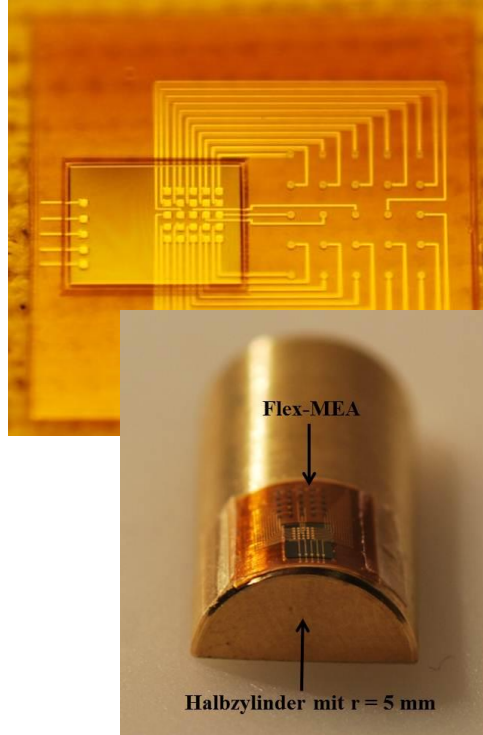
Size comparison - match

## Microelectrodes on stretchable and bendable substrates



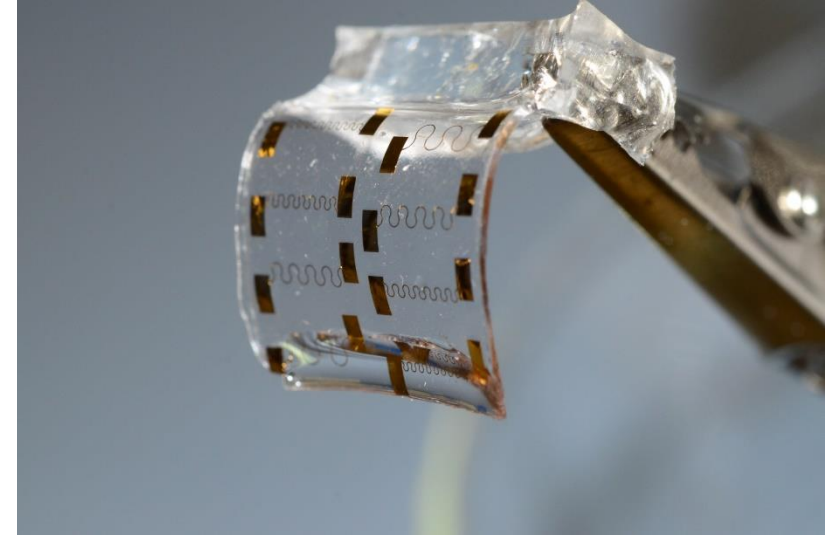
**Polyimide support structures for eye implant**

(foldable during eye implantation)



**Flex-MEA technology**

(nanostructures surfaces, polyimide support, embedded thinned silicon ASIC)



**Stretch-MEA technology**

(microelectrodes and contact lines on stretchable PDMS – stable under relative stretching of 120%)



# Research Projects in IWE1

---

- ❖ Mechanobiology in Epithelial 3D Tissue Constructs - **ME3T-RTG**
- ❖ Characterization of Oocytes for in vitro Fertilization using Electrical Impedance Spectroscopy - **EiCatcher**
- ❖ Single point sensor system for non-invasive, dynamic measurement of heart function - **SINDynamik**
- ❖ Molecular Programs for neurodegenerative diseases markers Biosensing - **MolPro2BioSens**
- ❖ Molecular Programming for early onset detection of Neurodiseases - **MolPron**
- ❖ EIT Health initiative to promote innovation in health sector - **SensUs**
- ❖ Bio-Nanoelectronic based Logic Locking for Secure Systems - **BioNanoLock**
- ❖ Polymer Thermophysical Properties Materials Informatics - **JST-CREST**
- ❖ G-quadruplex enabled Two-dimensional Neuromorphic Bioelectronics - **G4NeuroTec**
- ❖ Peptide evolution platform for biologization of two-dimensional material interfaces - **Pep2D**

## Coming up:

- ❖ Multiplexed point-of-use antibiotics monitoring delivered by system-integrated electrochemical transducers based on metal-organic frameworks - **MOFSENS**
- ❖ Innovative Retinal Interfaces for Optimized Artificial Vision - **InnoRetVision**
- ❖ Technology development and prototyping of a fully functional new-generation flexible SPR Biosensor Platform - **FlexiPlas**



 EIT Health is supported by the EIT,  
a body of the European Union



Federal Ministry  
of Education  
and Research

**DFG**  
Deutsche  
Forschungsgemeinschaft

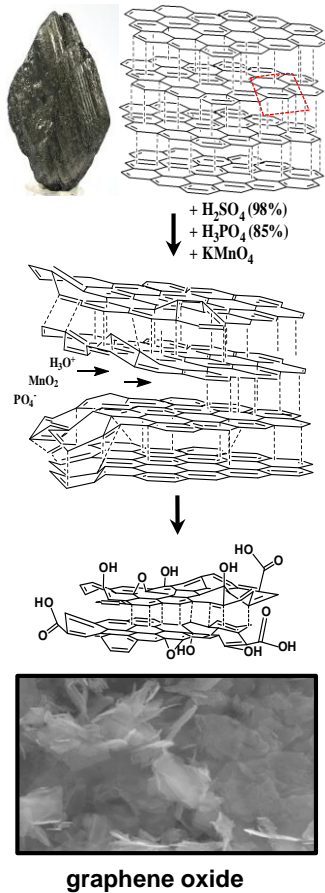
**DAAD**  
Deutscher Akademischer Austauschdienst  
German Academic Exchange Service

 **ERS** Exploratory  
Research Space

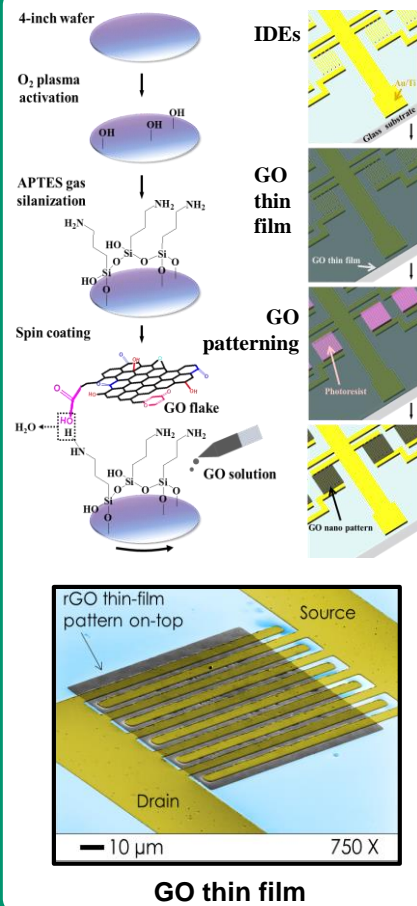
**RWTHAACHEN**  
UNIVERSITY

# Reduced graphene oxide and its applications

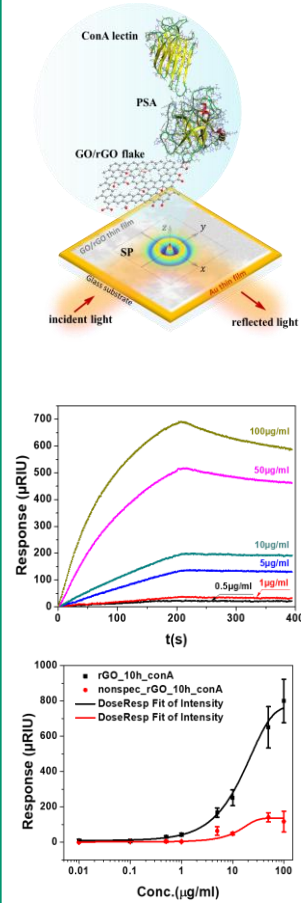
## GO flake synthesis



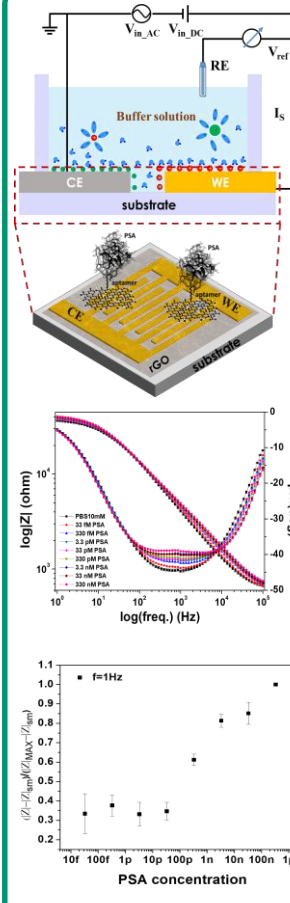
## GO device fabrication



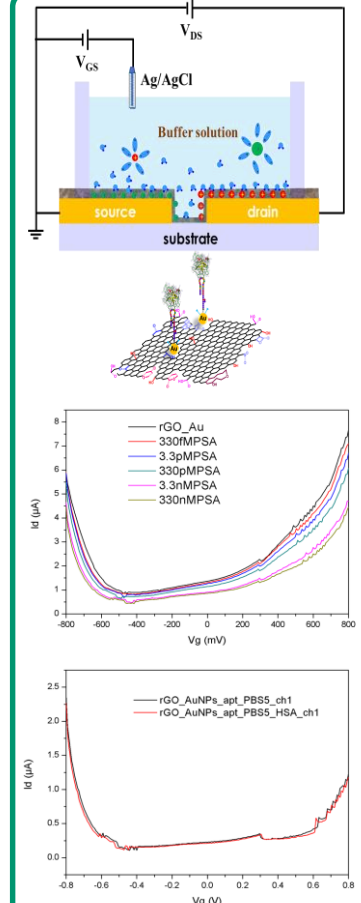
## SPR biosensor



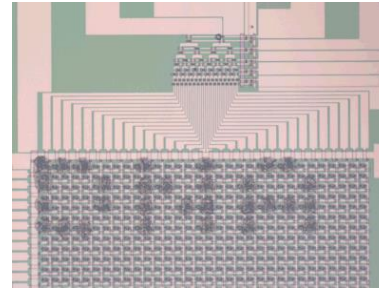
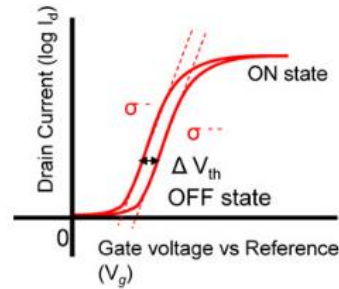
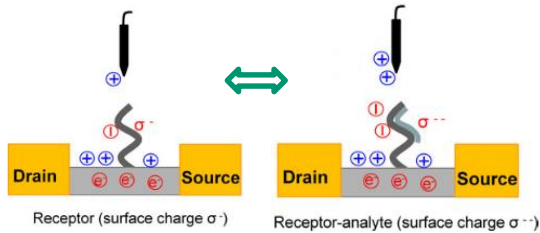
## EIS biosensor



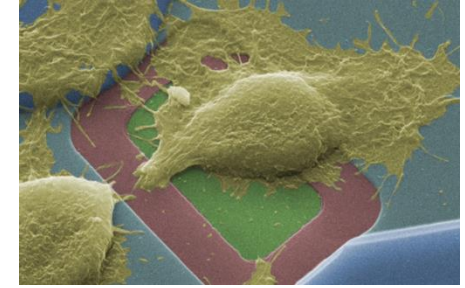
## ISFET biosensor



# Biologically modified nanoscale field-effect transistors

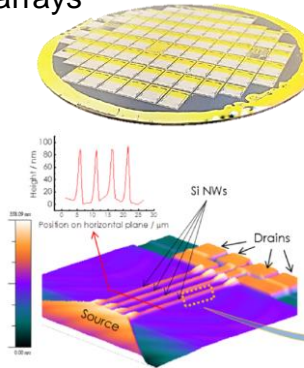


DNA on an FET biosensor device

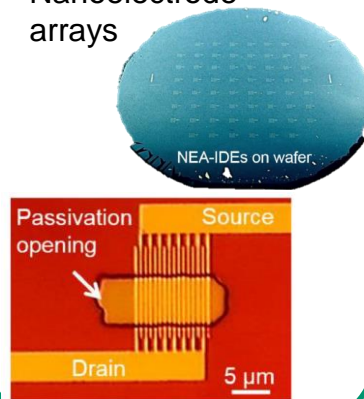


Tumor cell on an FET biosensor

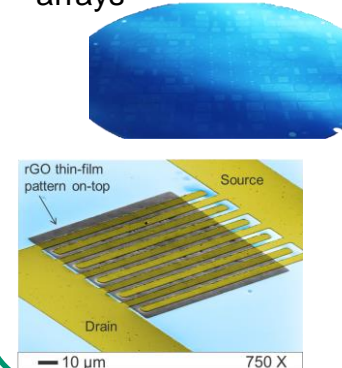
Si nanowire FET arrays



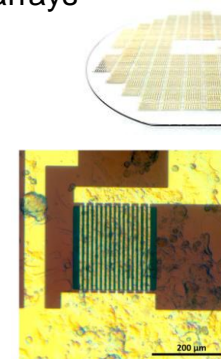
Nanoelectrode arrays



Graphene FET arrays

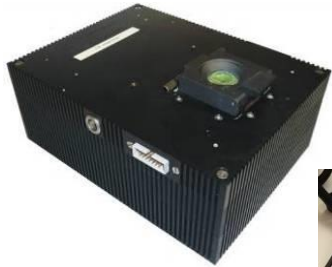


Organic polymer FET arrays





## Integrated systems for electronic recording and actuation of micro- and nanosensors and devices



FET amplifier system  
©2007 - FZJ



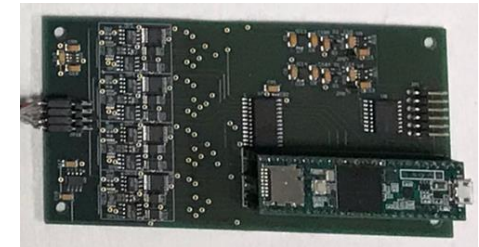
Portable 8 channel amplifier made in Zw  
©2015 - RAM Group DE GmbH  
Temperature, pH, DC and high- frequency AC recording



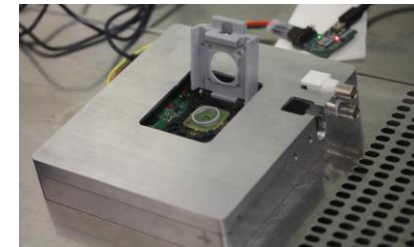
Versatile desktop recording system  
©2017 - FZJ



Portable electrowetting system  
©2020 - IWE1



4-channel FET system battery powered and WiFi enabled ©2020 - IWE1



16-channel MEA system for stimulation and recording based on a microcontroller circuit including sample and hold function ©2020 - IWE1

Most systems include highly sensitive analogue amplifier electronics

# Tools and techniques

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- Fabrication and modelling of Graphene/2D materials based electronic transducers
- Studying bimolecular interactions on 2D electrical transducer surfaces

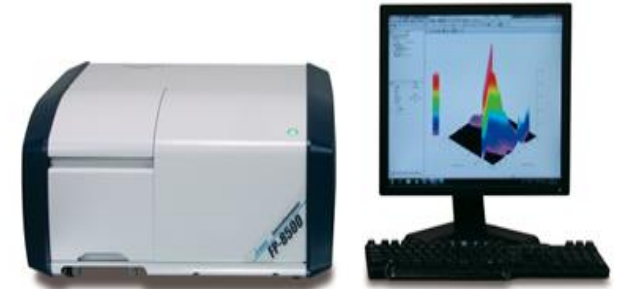
## Major tools and techniques



Microspotter, SPR



Cleanroom processes



Spectroscopy techniques

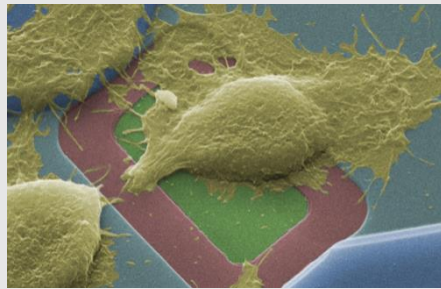
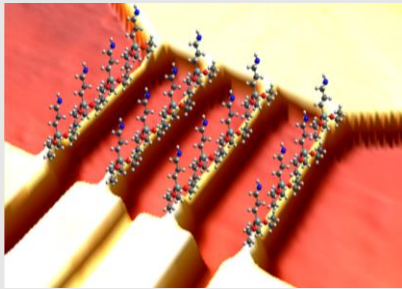
# Micro- and Nanoelectronic Sensors group at IWE1

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- Micro- and Nano-engineering for material research and for bioelectronics
- Ion sensitive field-effect transistor and silicon nanowires (biosensors and bioelectronics)
- Polymer-based devices (PEDOT:PSS) for bioelectronics
- Microelectrode arrays (MEA) and ISFET-MEA combined system
- Electronic and optoelectronic sensors
- Thermocouple for flexible electronics using novel materials
- Gas sensing for health care applications
- Wearable electronics based on new materials
- Environmental sensing
- Energy harvesting for wearable or remote sensing



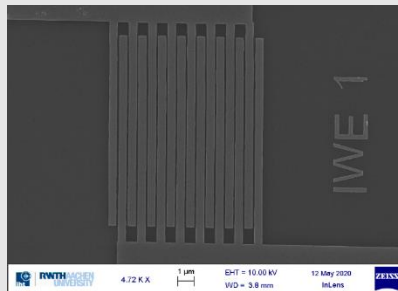
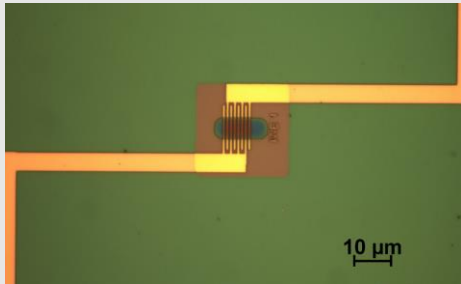
# Micro- and Nanoelectronic Sensors



## Silicon based nanoscale Sensor-arrays

**Electrical** detection of

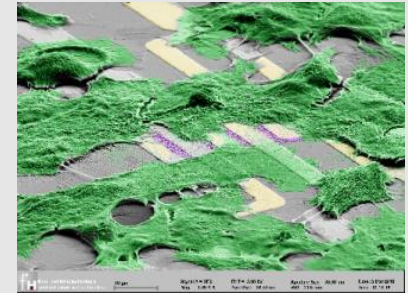
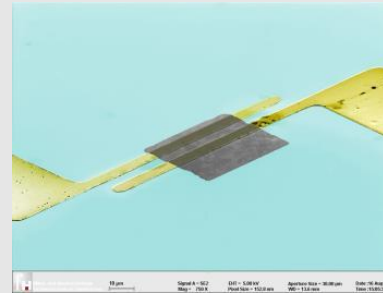
Analytes: pH, Nucleic acid, Proteins, Cells etc.



## Nanoscale Electrode arrays

**Electrical** and **optical** detection of

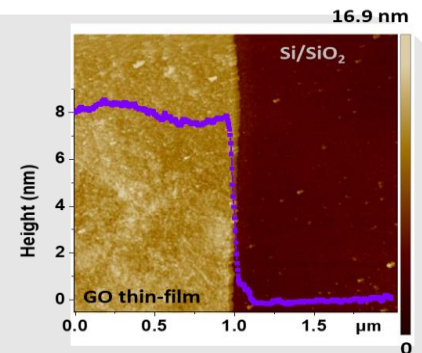
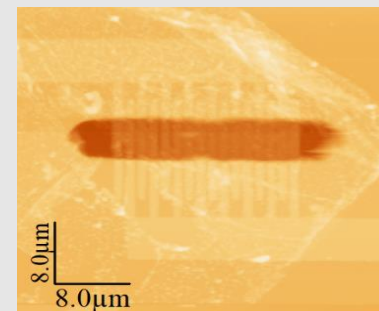
Nucleic acid, Cells; sub-micro fluidics



## Two-dimensional Sensor-arrays

Graphene & TMDs, **Electrical** and **Optical** detection

Analytes: pH, Nucleic acid, Proteins, Cells etc.

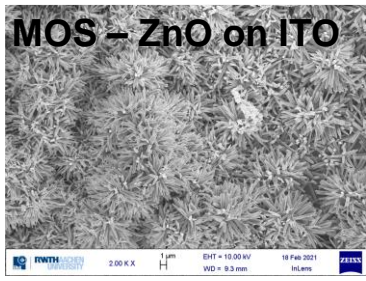


## New materials

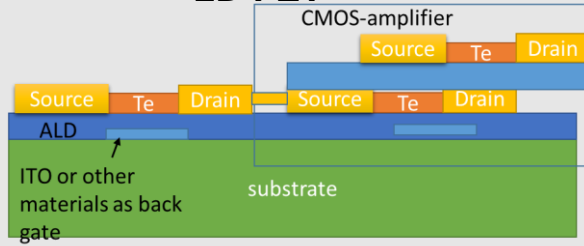
Nanostructured 2D material architectures for multimodal sensing

# Micro- and Nanoelectronic Sensors

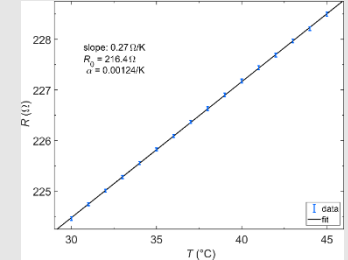
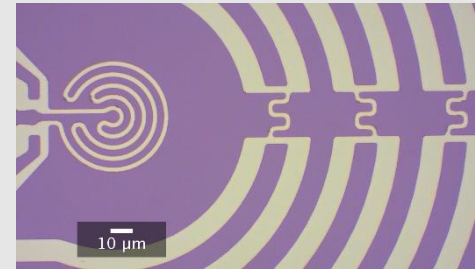
MOS – ZnO on ITO



2D FET



**Gas sensors based on metal oxide semiconductor and 2D materials**



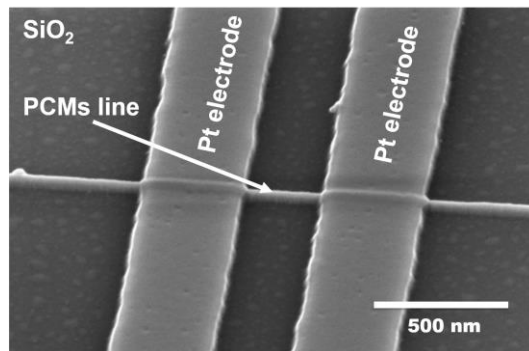
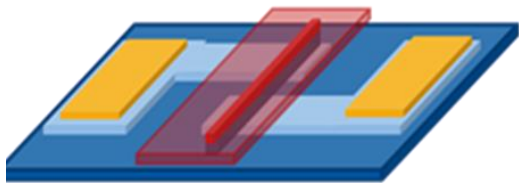
**Micro-nanoscale thermal Sensors**

RTD and thermocouple

# Phase change memory (PCM) for in-memory computing

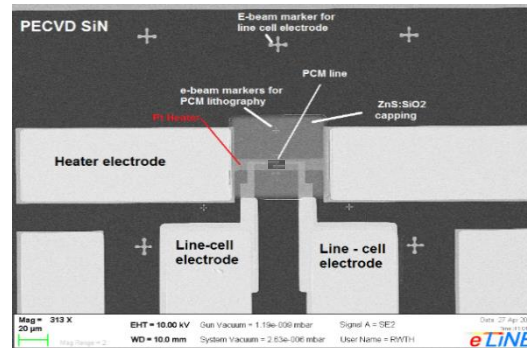
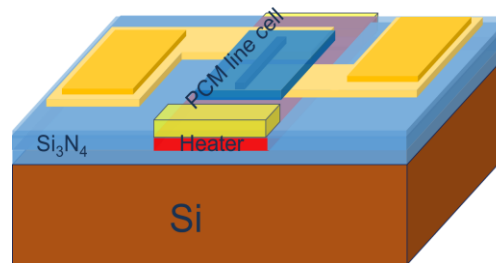
## Line-cell device

Scaling effect, new materials



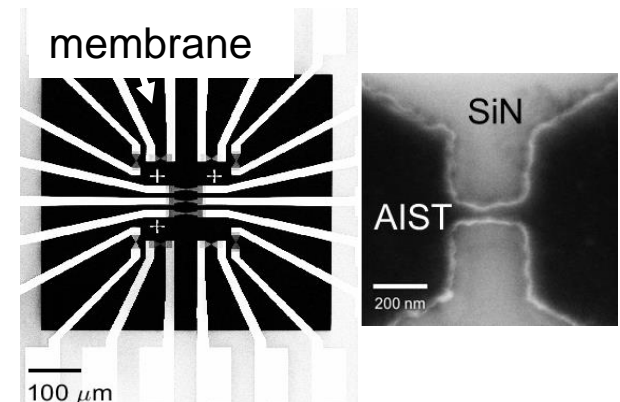
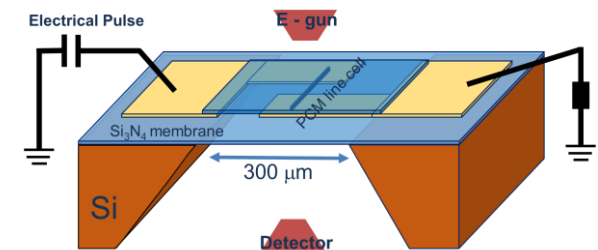
## Micro-heater

Relaxation in glasses of PCM, crystal growth



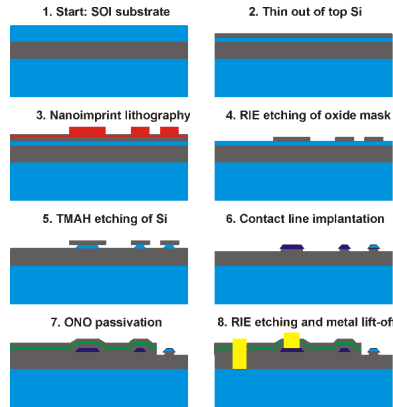
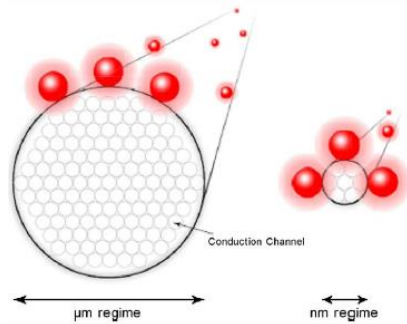
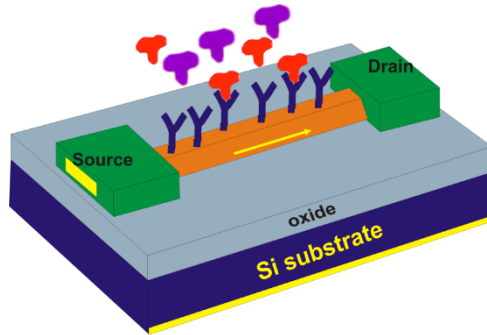
## In-situ TEM

Threshold switching in PCM, microstructure analysis

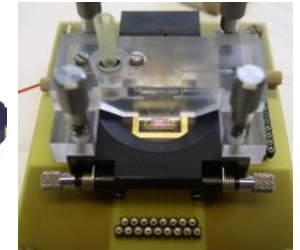
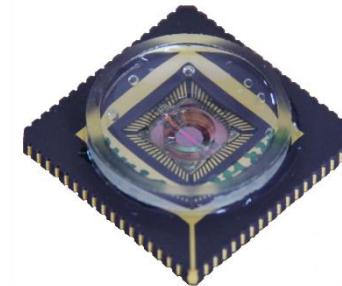
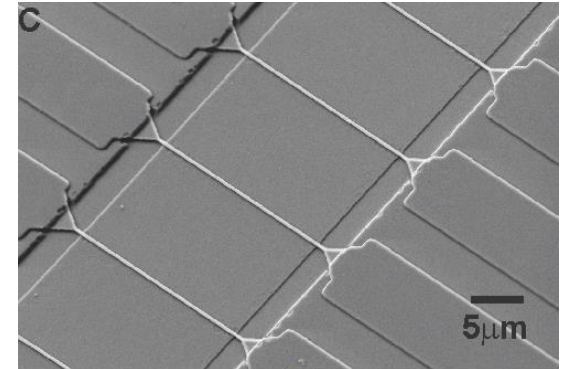




# Top-down processed SiNW transistor for bioelectronics

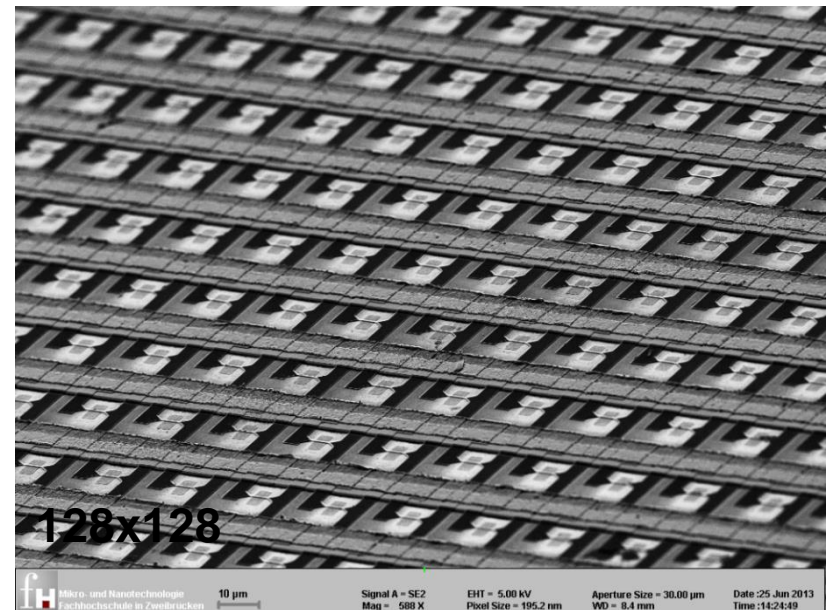
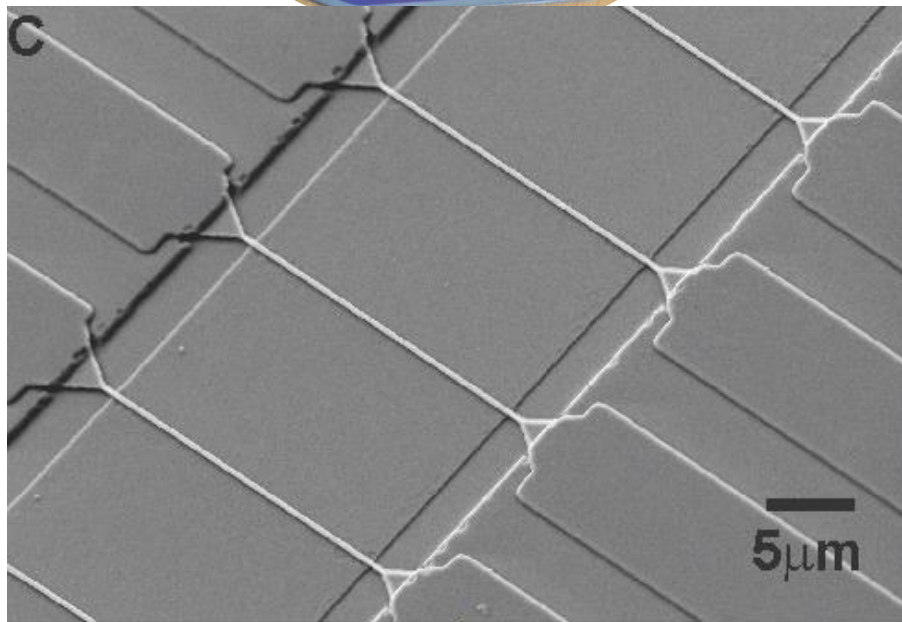
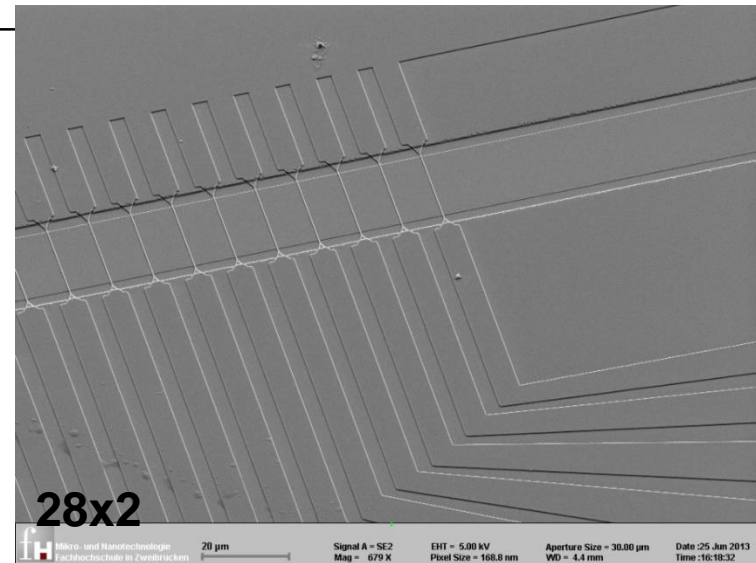
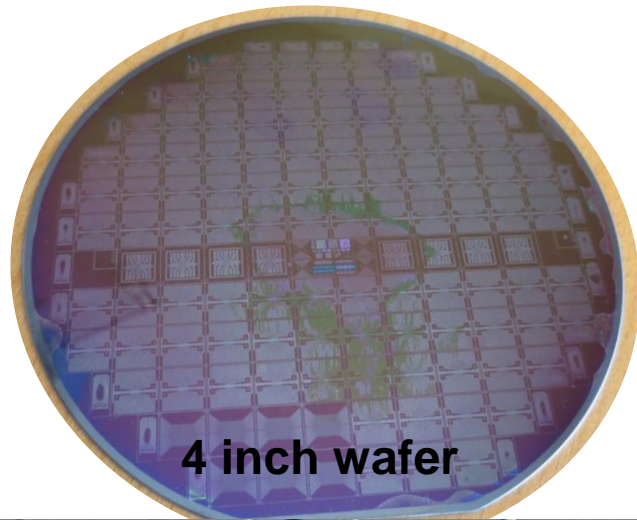


X.T. Vu et al, *Physica Status Solidi*, 206 (2009) 426  
 X.T. Vu et al, *Sensors and Actuators – B Chemical*, 144 (2010) 354



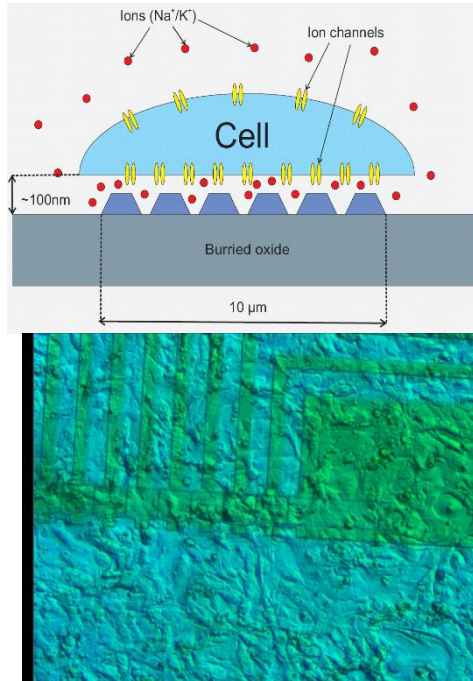
- Ultrahigh surface-to-volume ratio
- Dimensions of the biomolecules are comparable to that of the nanowires
- Strong influence of the surface effects to the electronic properties
- Possibility to create dense arrays
- Wafer-scale, reproducible process
- Size of SiNW: 60 nm at the bottom
- High quality of the gate oxide and smooth surfaces
- High quality of the passivation layer – stable operation in electrolyte solution
- Stable working with electrolyte
- Reusable
- Standard protocol for harsh chemical cleaning

# Silicon nanowire devices

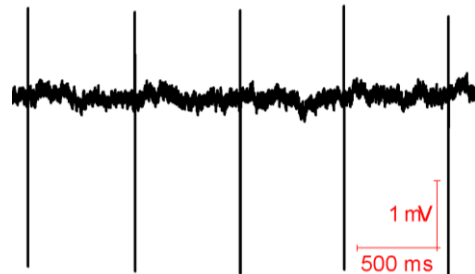


# Biosensors based on SiNW transistor arrays

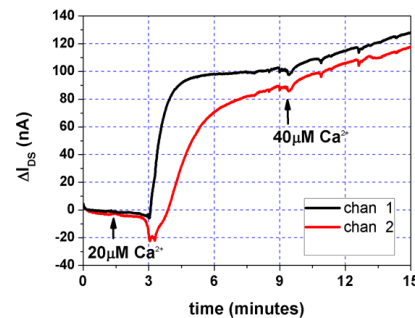
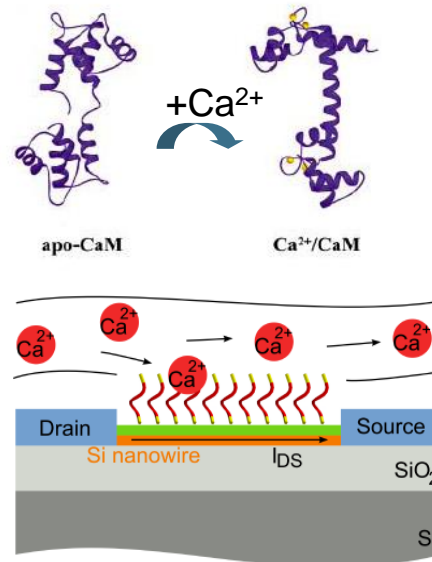
## Cell – transistor coupling



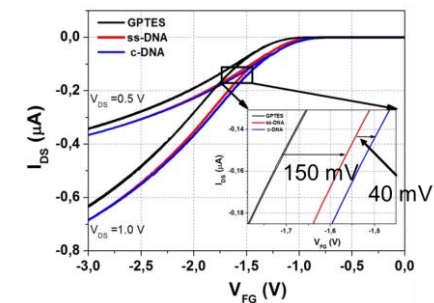
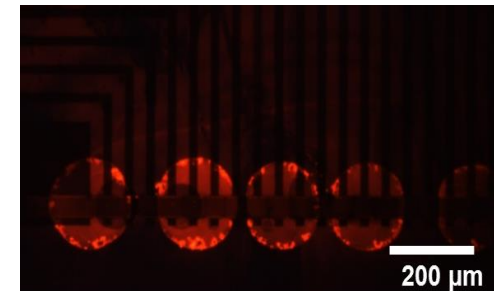
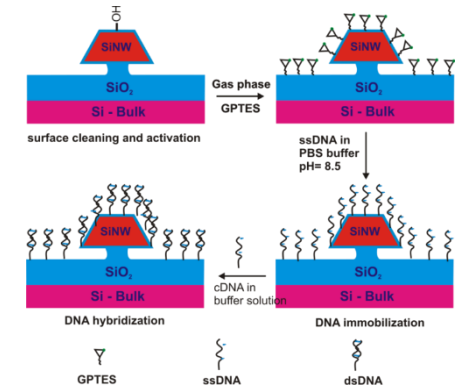
Rat cardiac myocytes at 5 DIV



## Ions or small molecules detection

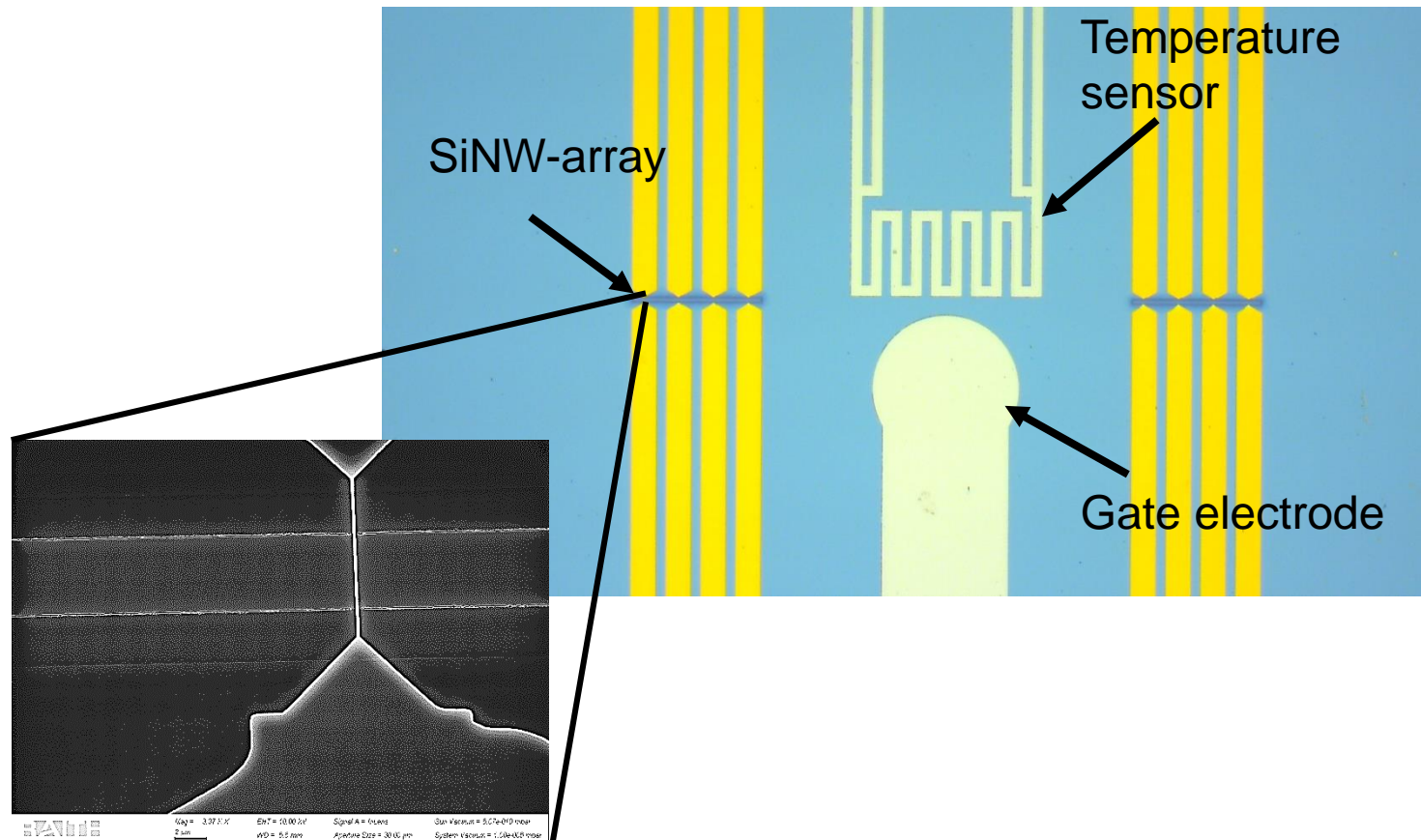


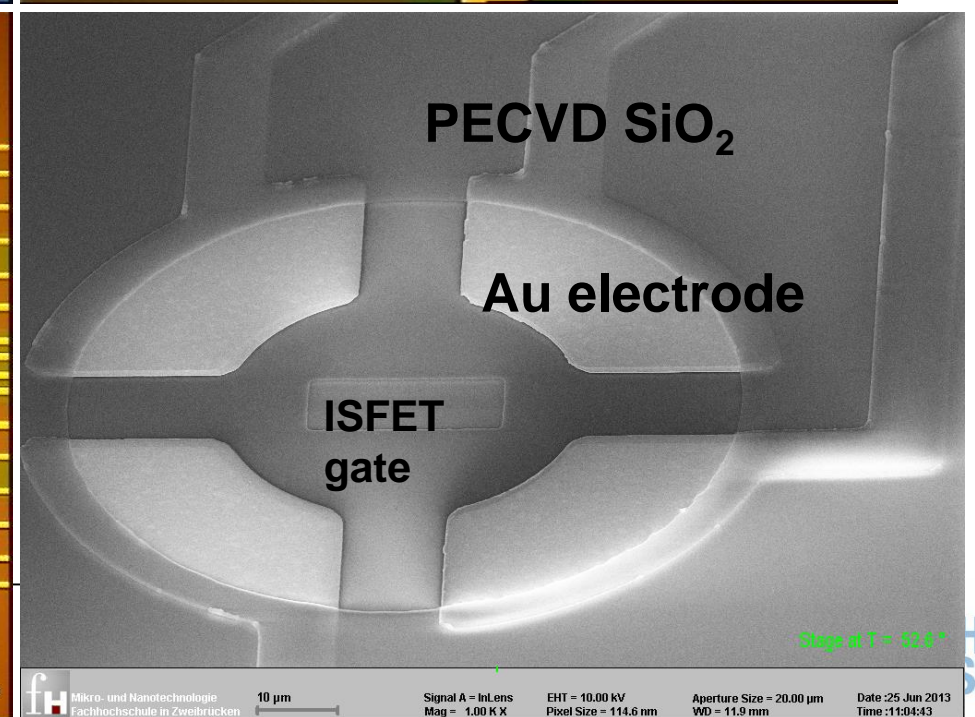
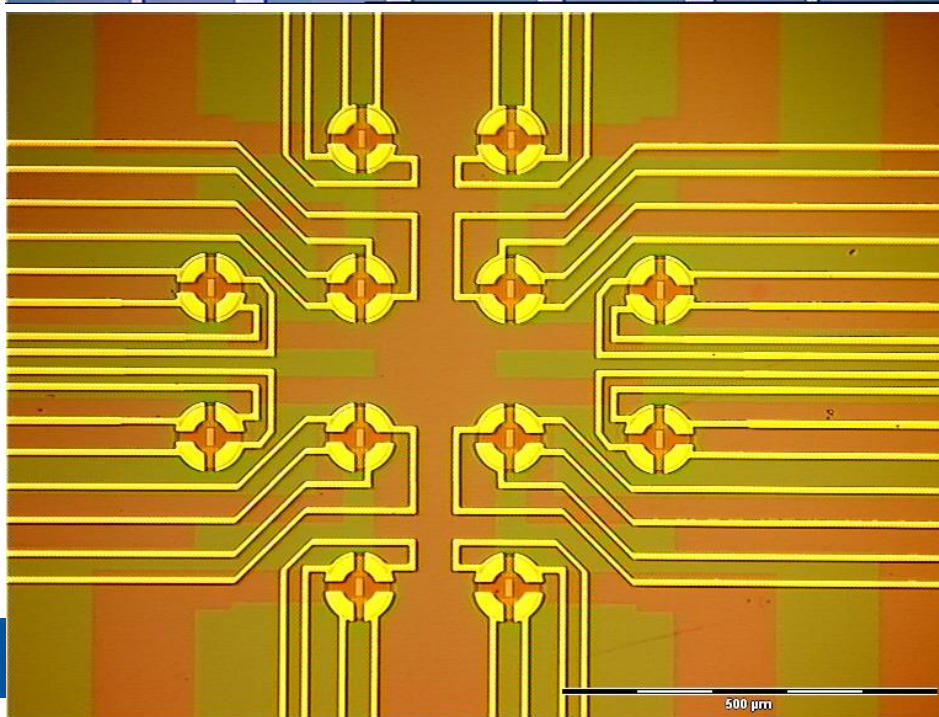
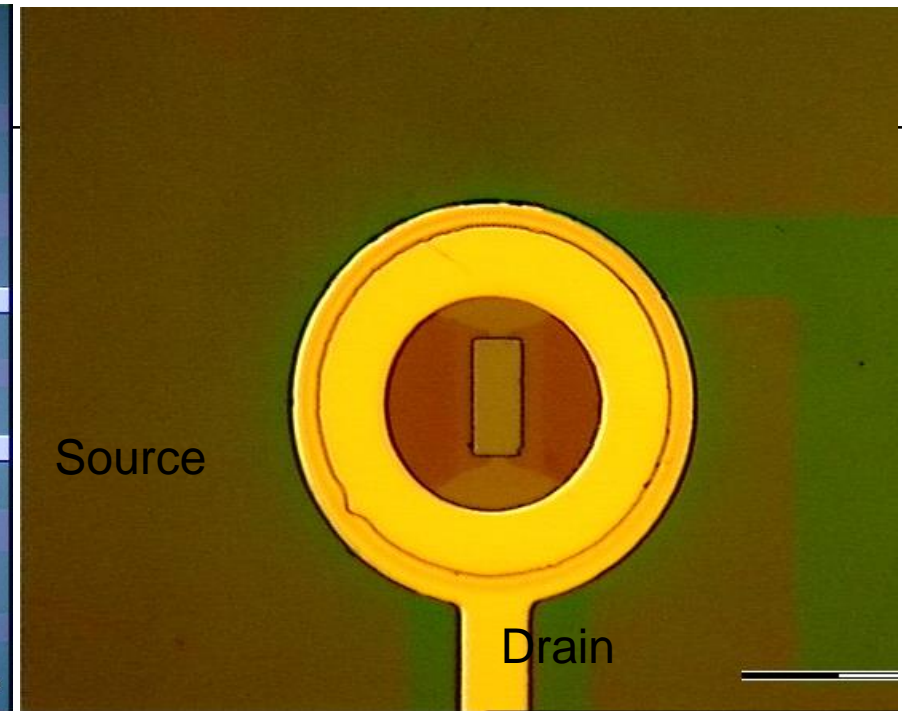
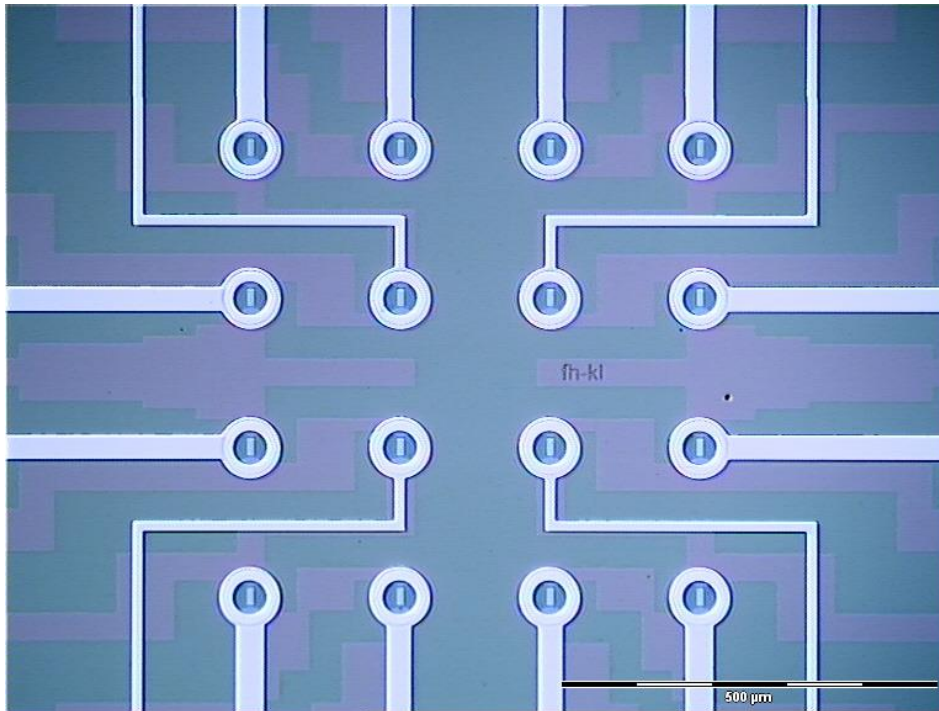
## DNA, proteins detection





# Toward lab-on-a chip with SiNW sensors



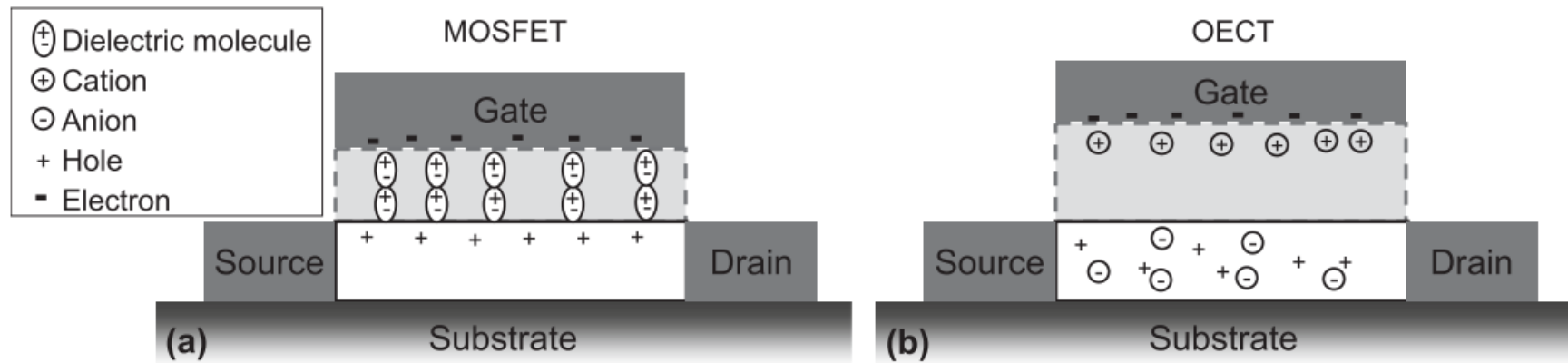


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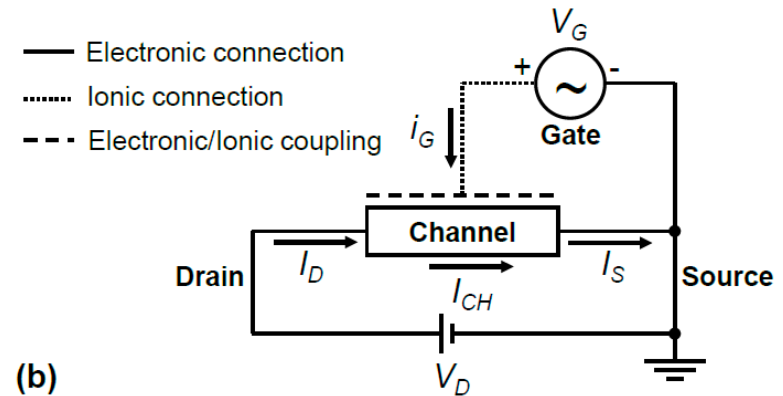
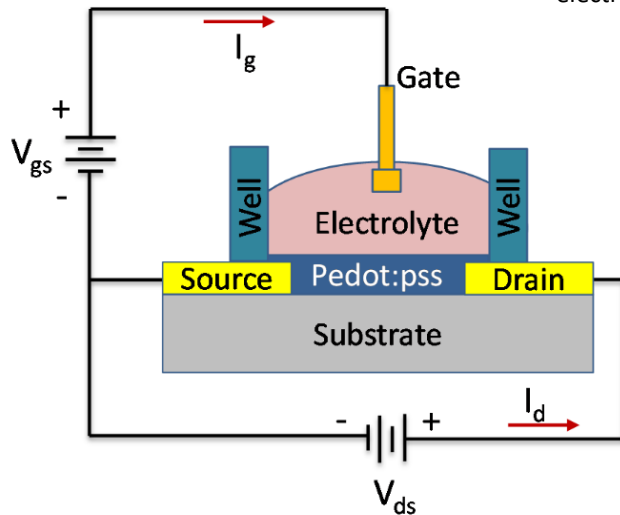
## **PEDOT:PSS organic electrochemical transistor**



# The electrochemical transistor – novel gating mechanism

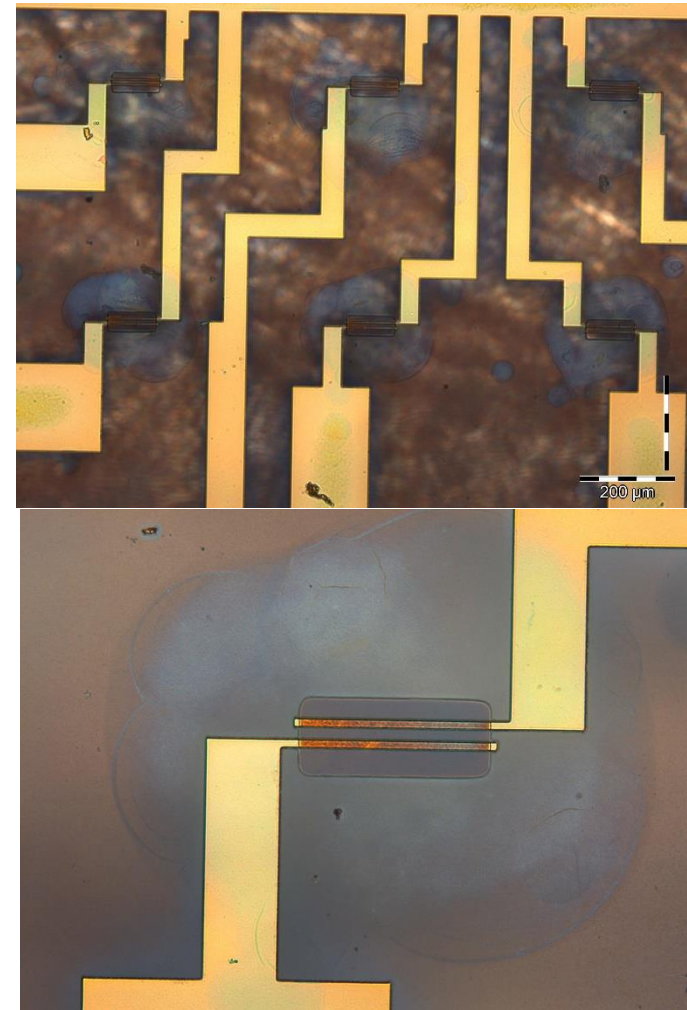
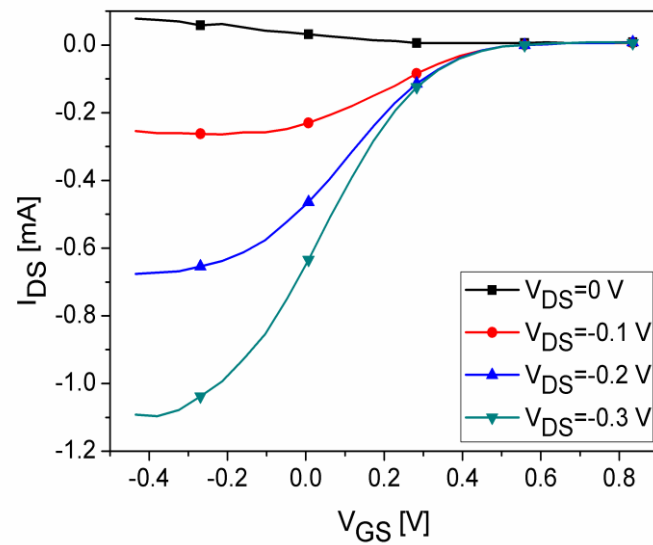


J.T. Friedlein, S.E. Shaheen, R.R. McLeod, Optical method for making spatially and temporally resolved measurements of the hole concentration in organic electrochemical transistors, SPIE Organic Photonics + Electronics, SPIE, 2014, p. 8.



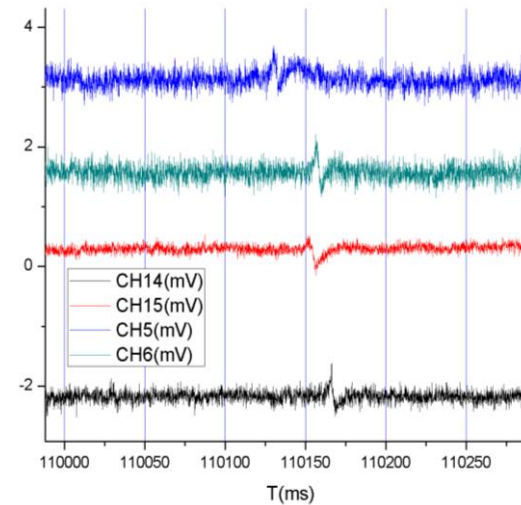
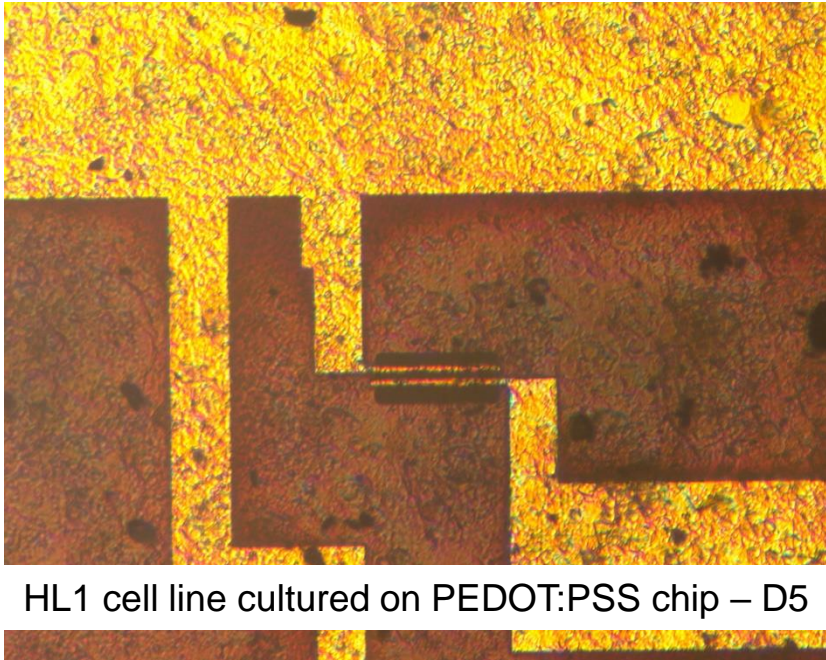
# Polymer devices for bioelectronics

- Pre-defined gold microelectrode structures
- spin coating PEDOT:PSS



Susloparova and Vu 2012

# Recording of extracellular action potentials (HL1)

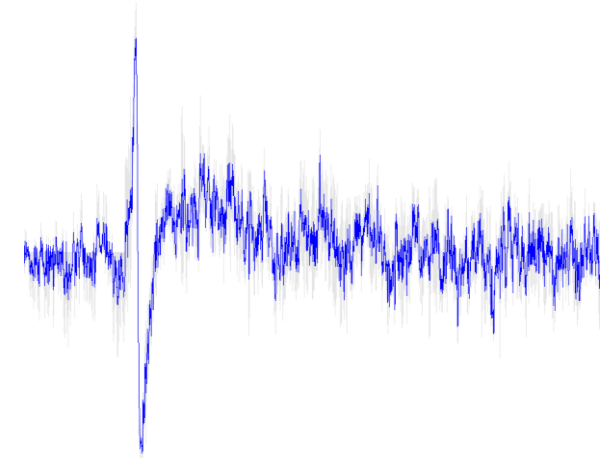


Noise is too high

Characteristics are stable during the cell culture and measurement but change after cleaning for second use

Characteristics depend on the applied voltage

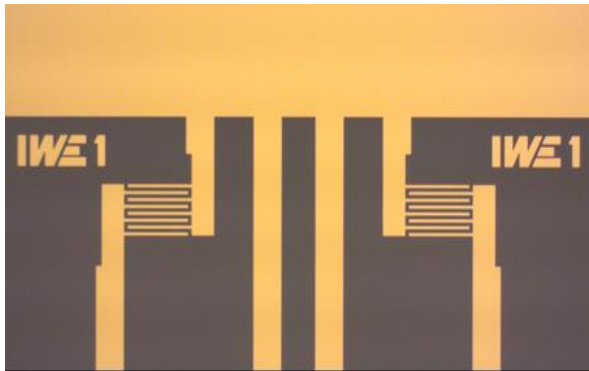
First time demonstrate action potential recorded by polymer FET



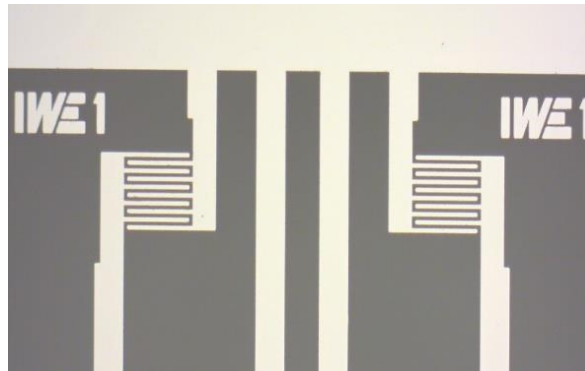
Vu 2013

# Electrode – PEDOT:PSS interface

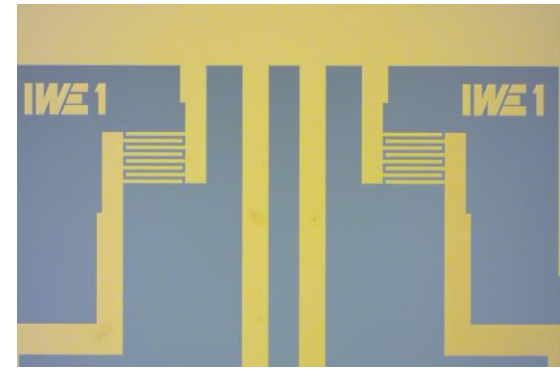
Lithography process for metalizing Au, Pt, TiN, ITO and IrOx electrodes on Glass substrate



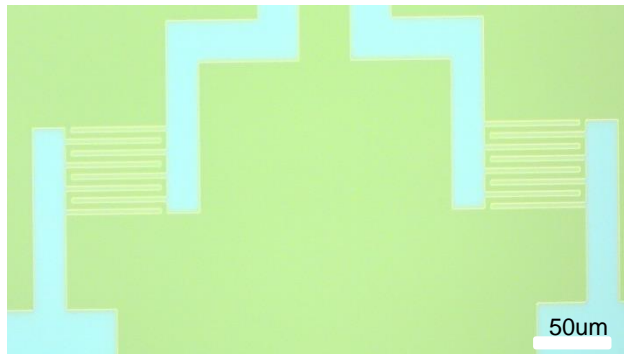
Au-evaporation



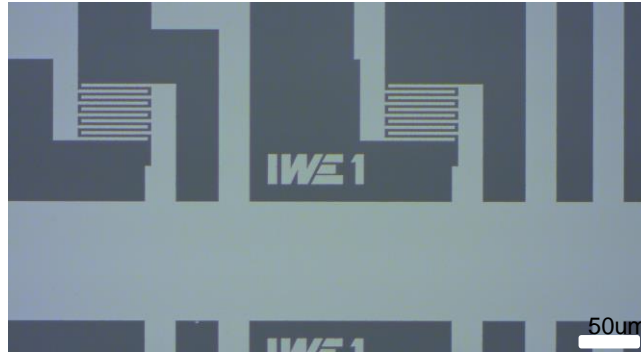
Pt-sputtering



TiN-sputtering



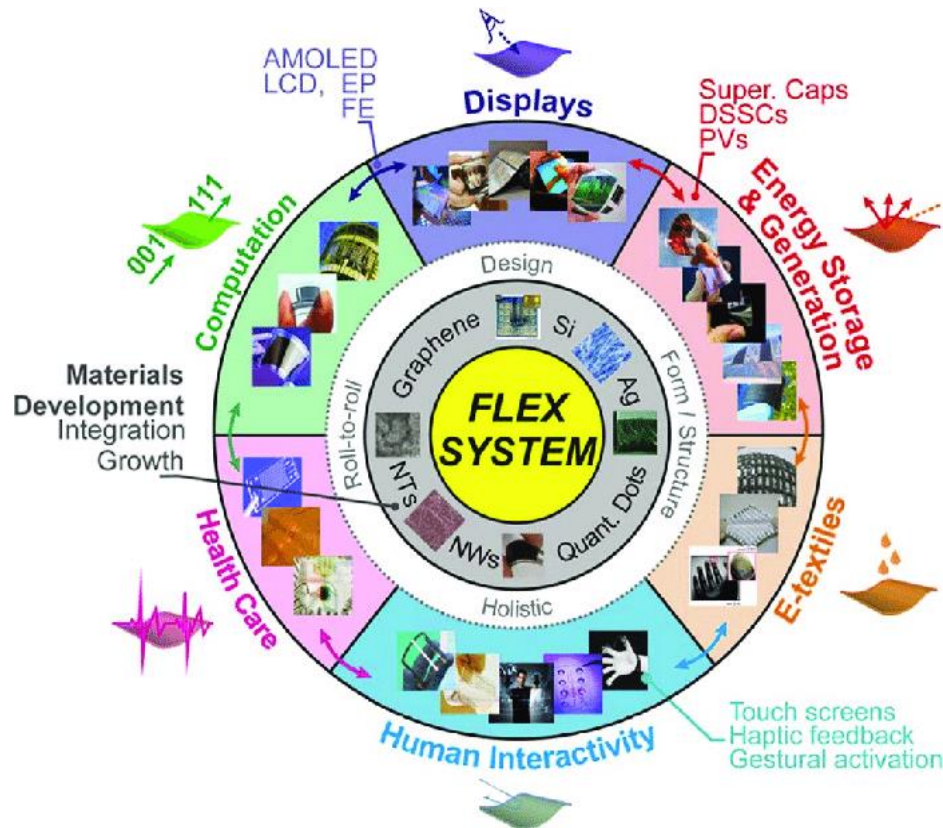
ITO-sputtering



IrOx-sputtering



# Nanomaterial-enabled flexible and stretchable electronics



- **Technology development**

- Fabrications technique on rigid and flexible substrates.
- Materials selection – PEDOT:PSS, SOI, Graphene...
- Transducer principles – OECT, SiNW-FET, Impedance

- **Electronics readout integration**

- Wireless readout (e.g. Mobile phone, NFC, Bluetooth) for OECT, SiNW-FET
- System integration – Microfluidic, multiplexer, multiple sensors

- **Applications (sweat compositions detection and related diseases)**

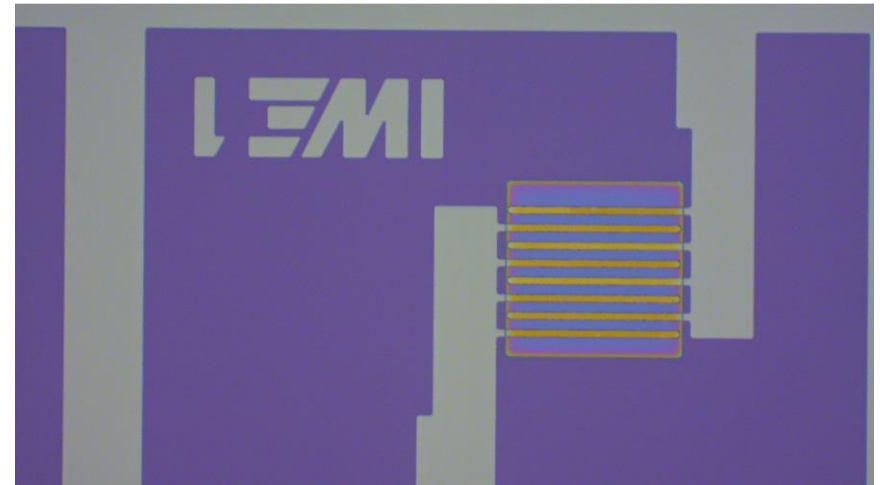
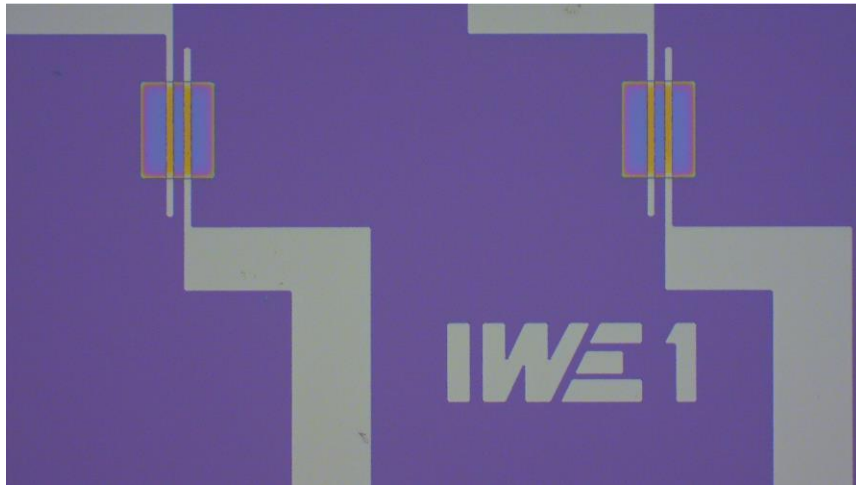
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## Gas sensors for healthcare and environmental sensing

# Gas sensors for healthcare and environmental sensing

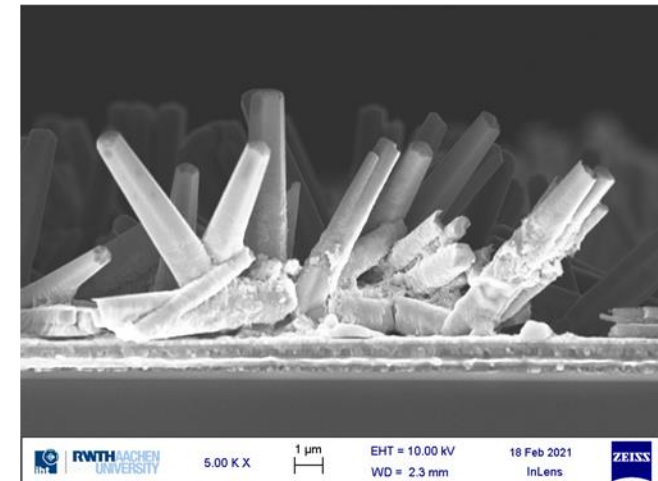
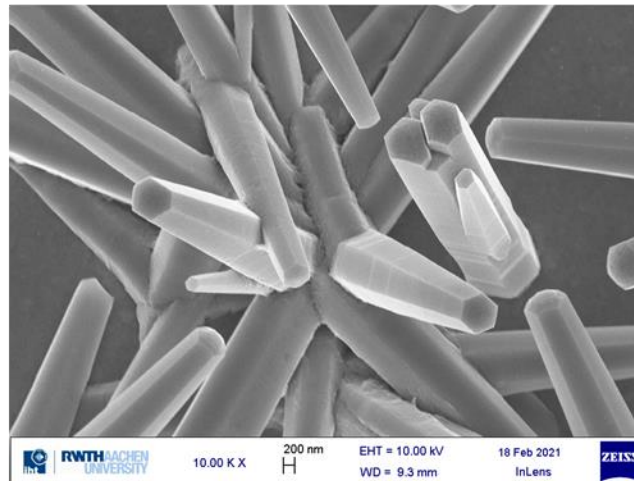
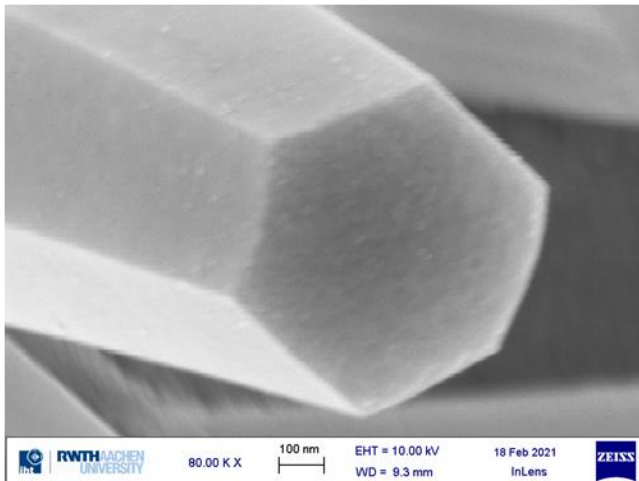
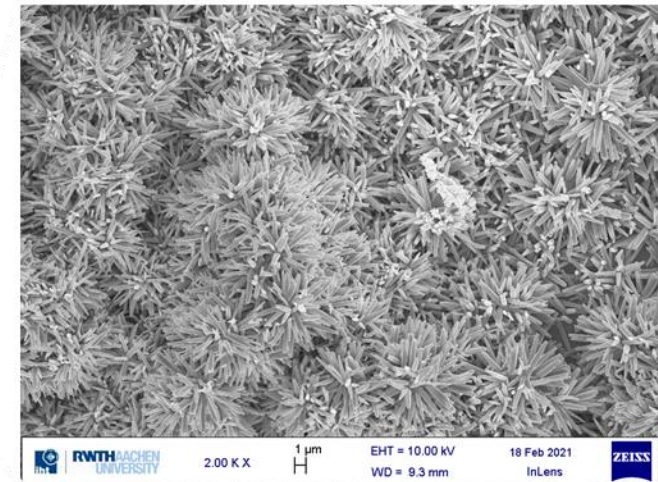
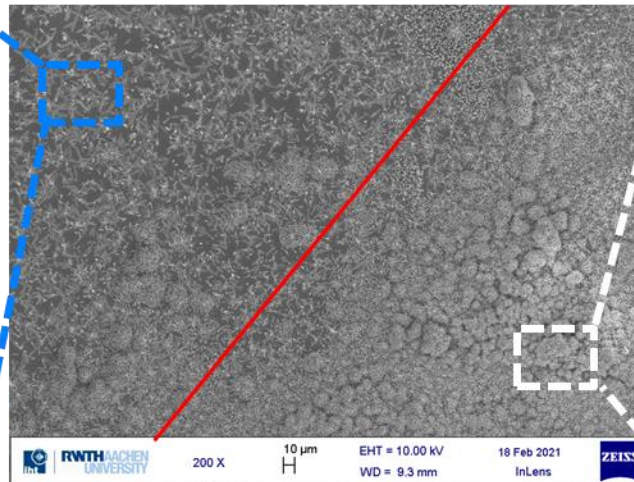
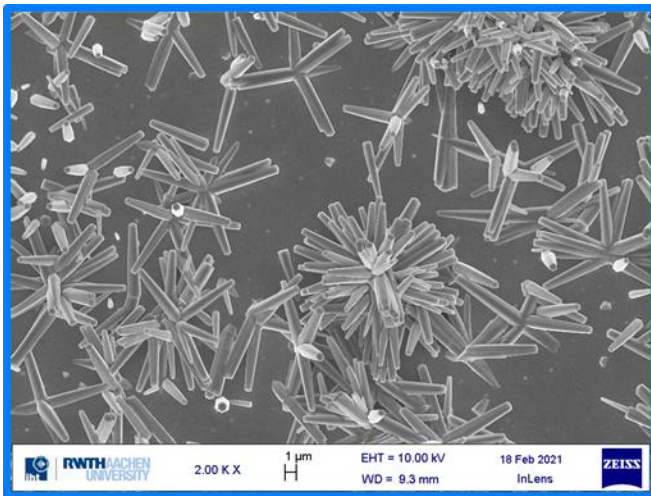
## ZnO nanowire

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Very thin ITO was deposited on the IDE as seed layer for ZnO nanowire

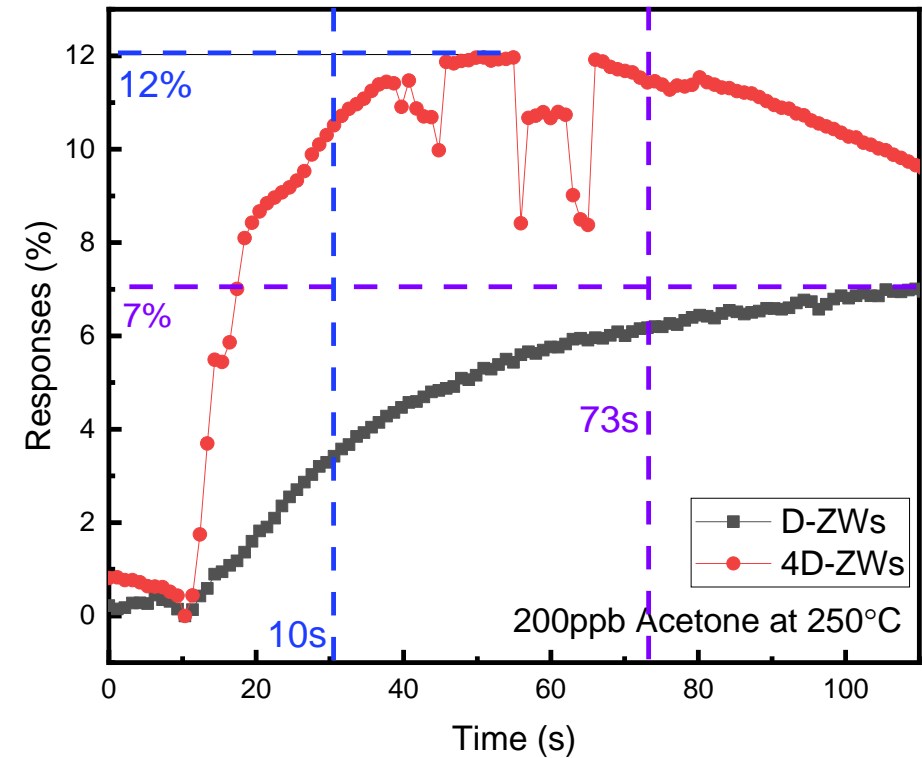
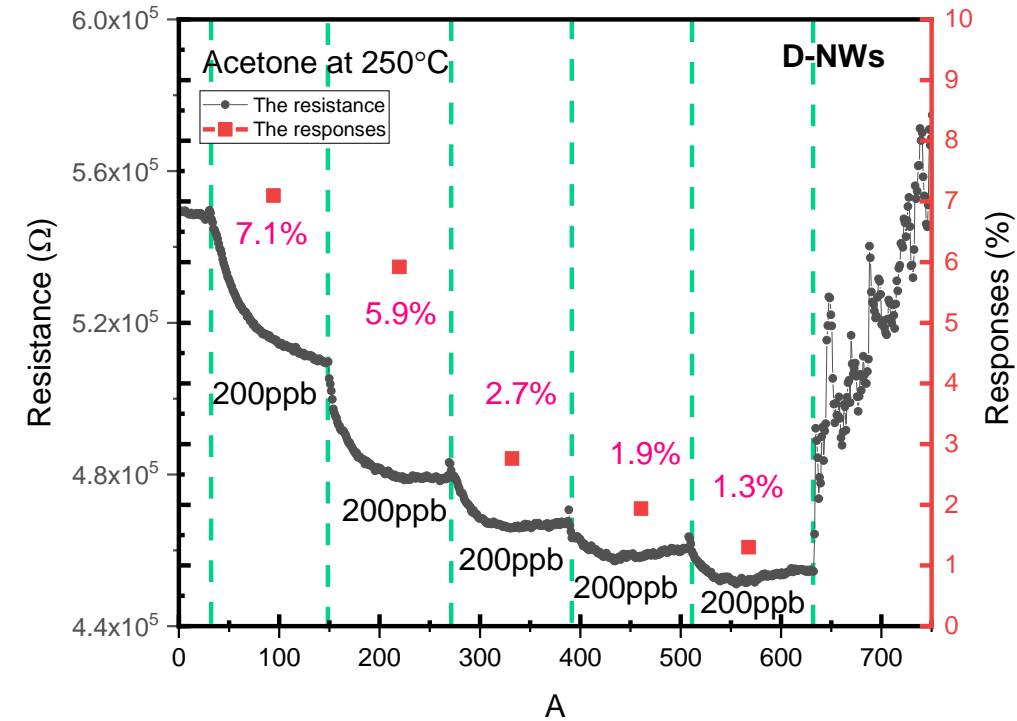
# ZnO nanowire on ITO



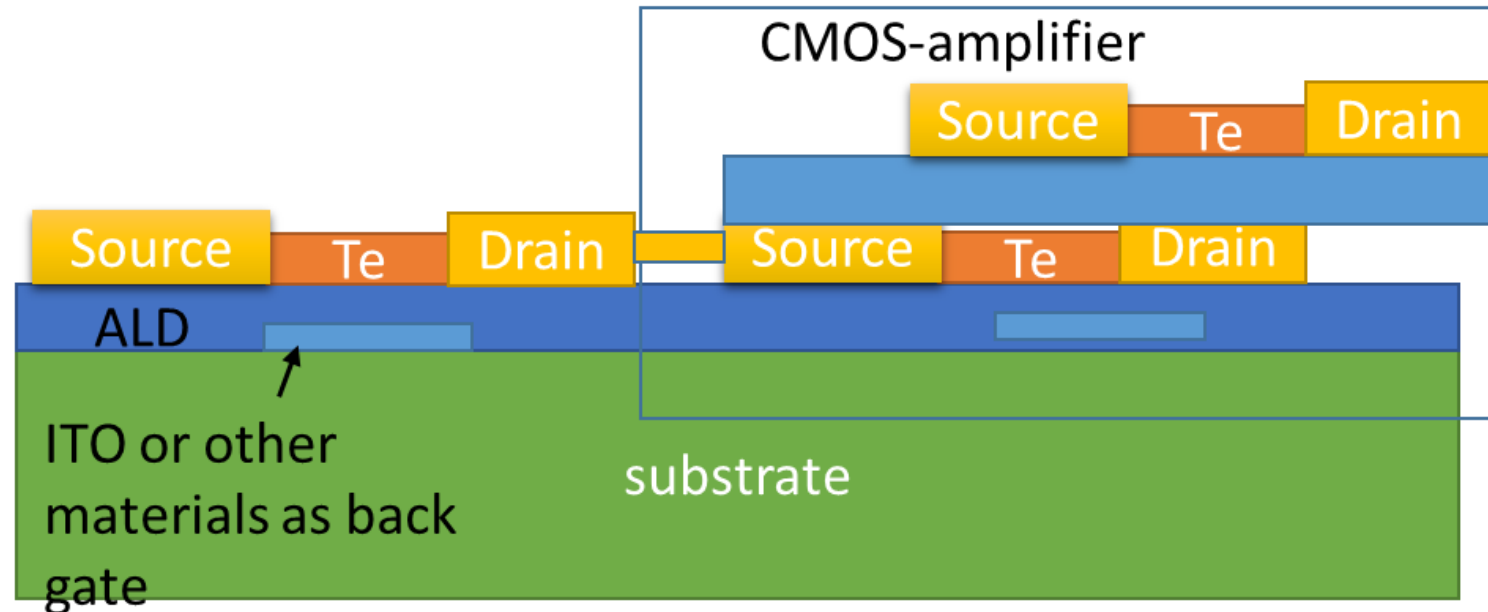
## ZnO nanowire on ITO thin-film



# Gas sensing



## 2D materials based device for gas sensing

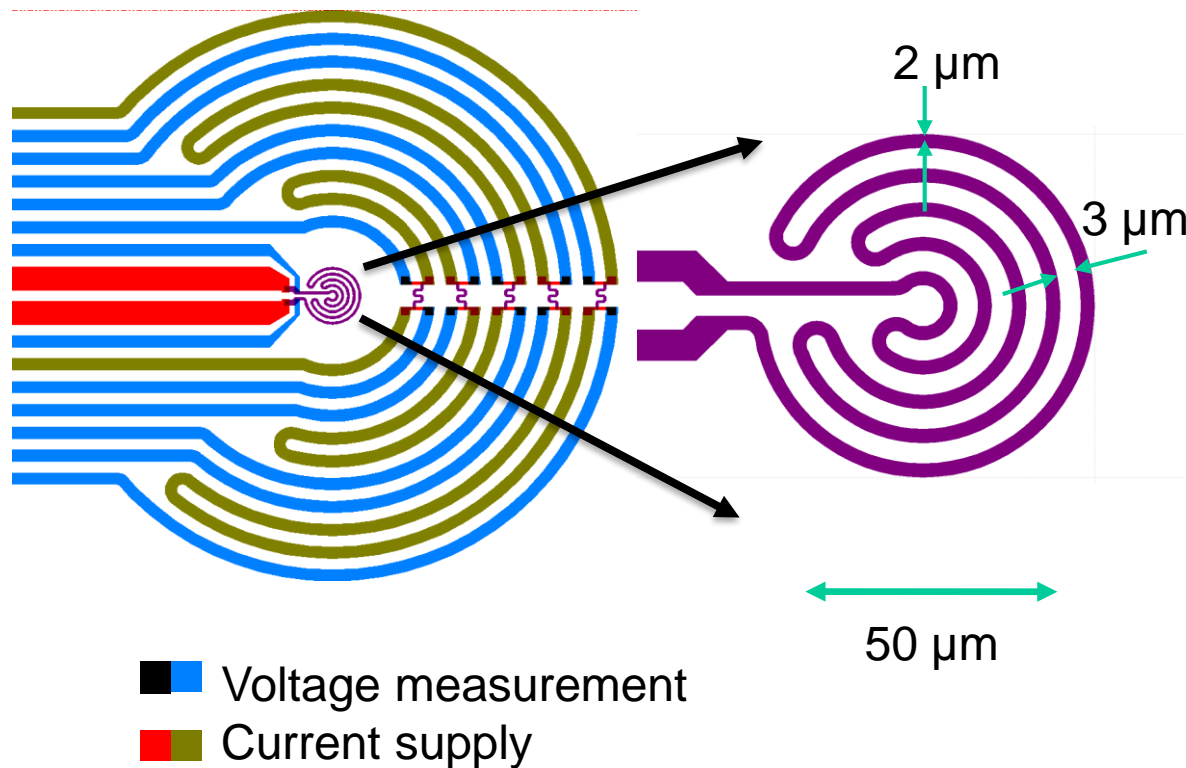


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# MEMS Device for Multi-Scale Thermal Material Characterization



# Micro- and Nano temperature sensors



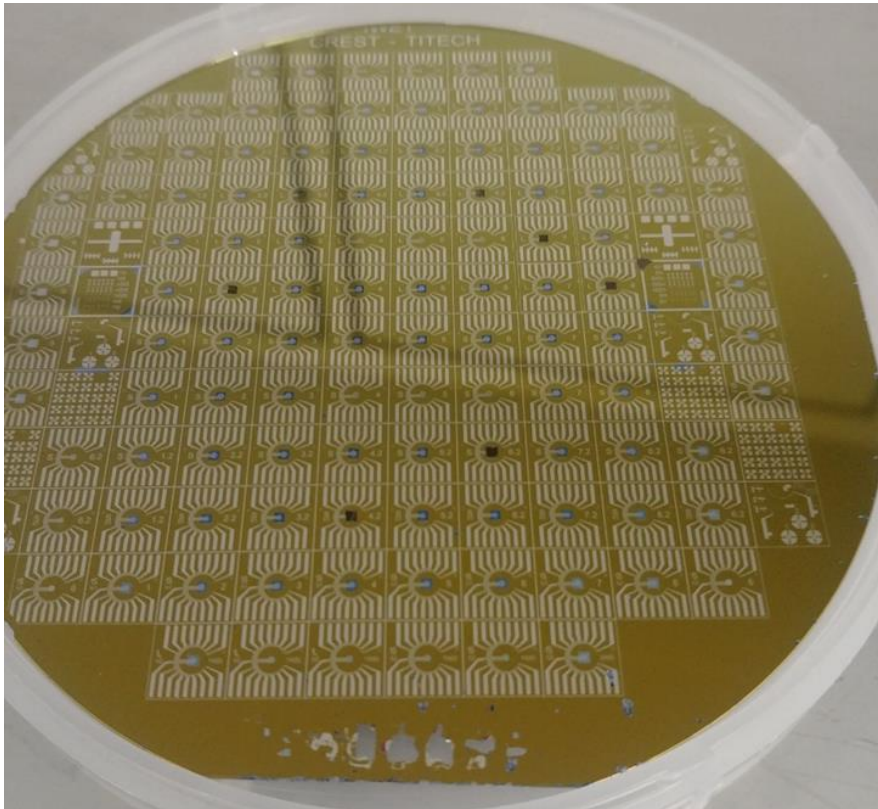
## Measurement principle:

- Applying heat to the center
- Time resolved temperature response in fixed distances to the center is measured
- Currently: spatial resolution down to tenths of microns
- Later: nanoscale characterization

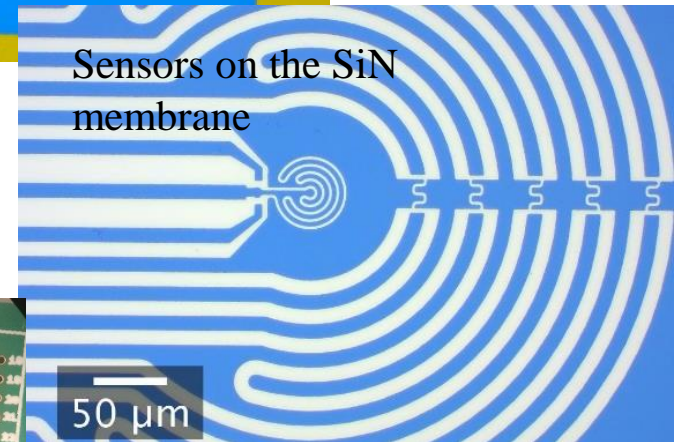
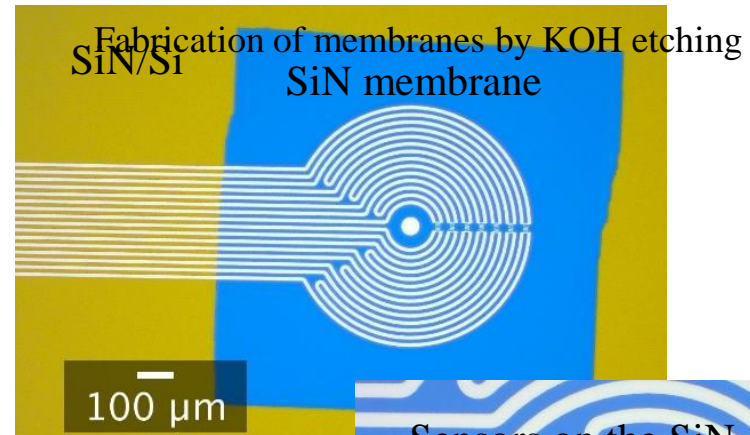
## Measured quantities:

- Thermal properties, heat conductance along the surface and inside thin films
- Changes in thermal response due to material phase transitions

# Micro- and Nano temperature sensors

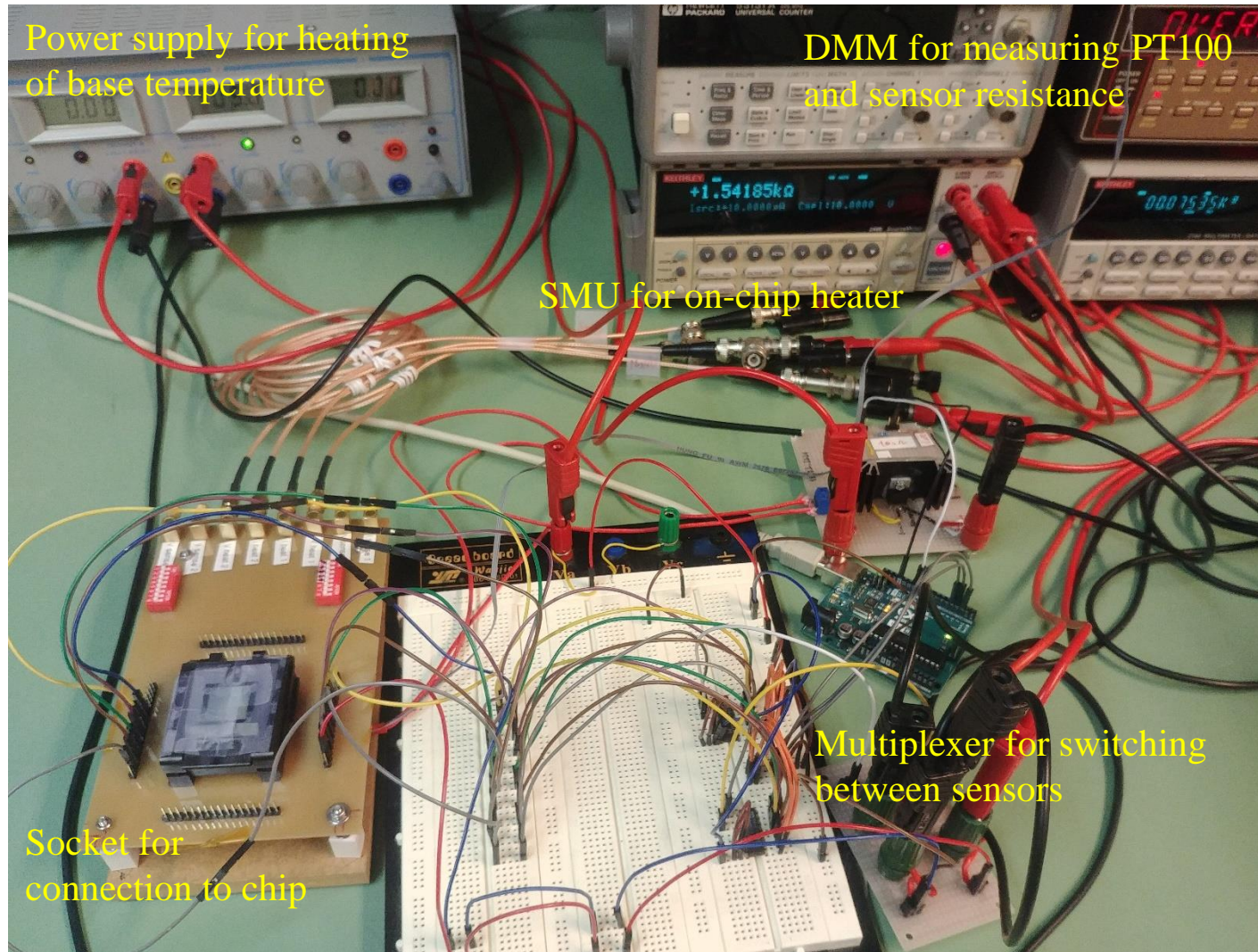


Backside of the wafer after etching of Si through the wafer





# Micro- and Nano temperature sensors



DMMs, SMU, Arduino connected to and controlled by PC via GPIB & USB



# Micro- and Nano temperature sensors

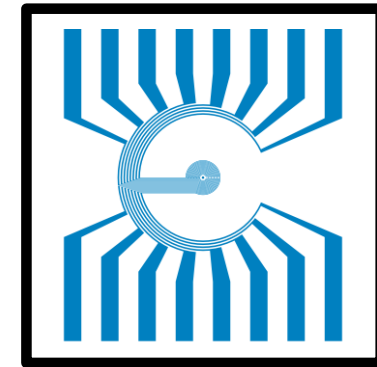
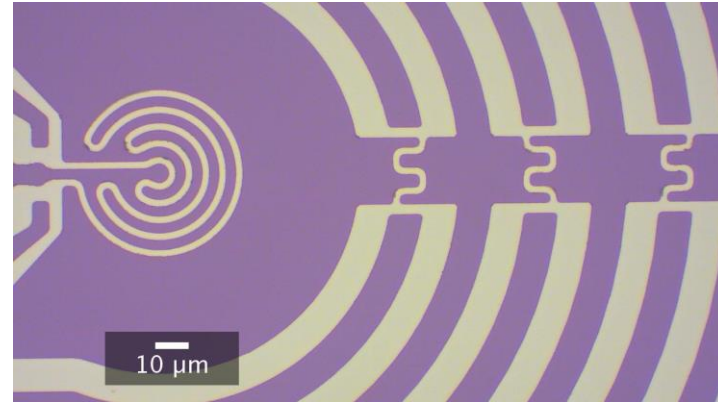
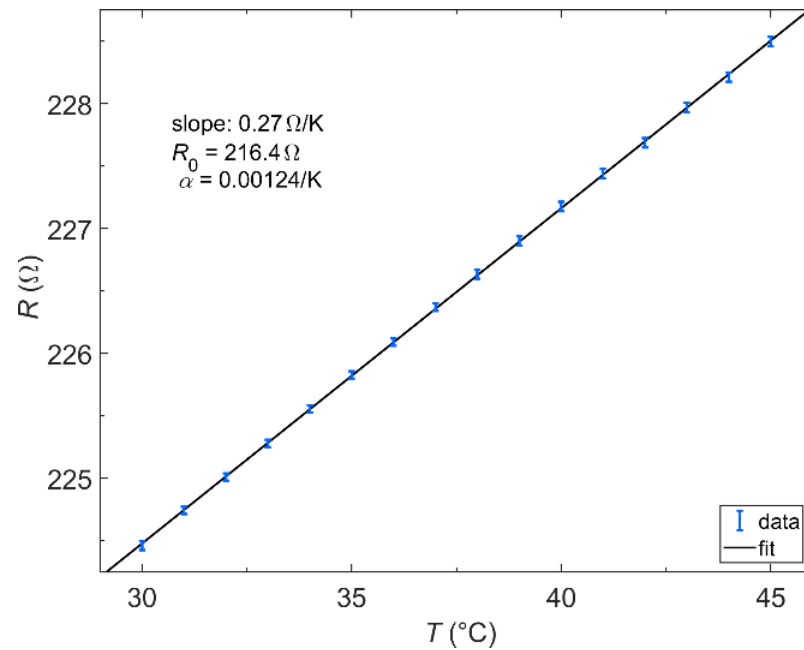
## Chip characterization

Material: 50 nm sputtered Pt

$$R_{\text{heater}} \approx 2.5 \text{ k}\Omega$$

$$R_{\text{sensor}} \approx 220 \text{ }\Omega$$

$$R_{\text{trace}} \approx 8 \text{ k}\Omega$$



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**Thank you very much for your  
attentions**