

# Three dimensional nanowire networks fabricated by ion track nanotechnology and their applications

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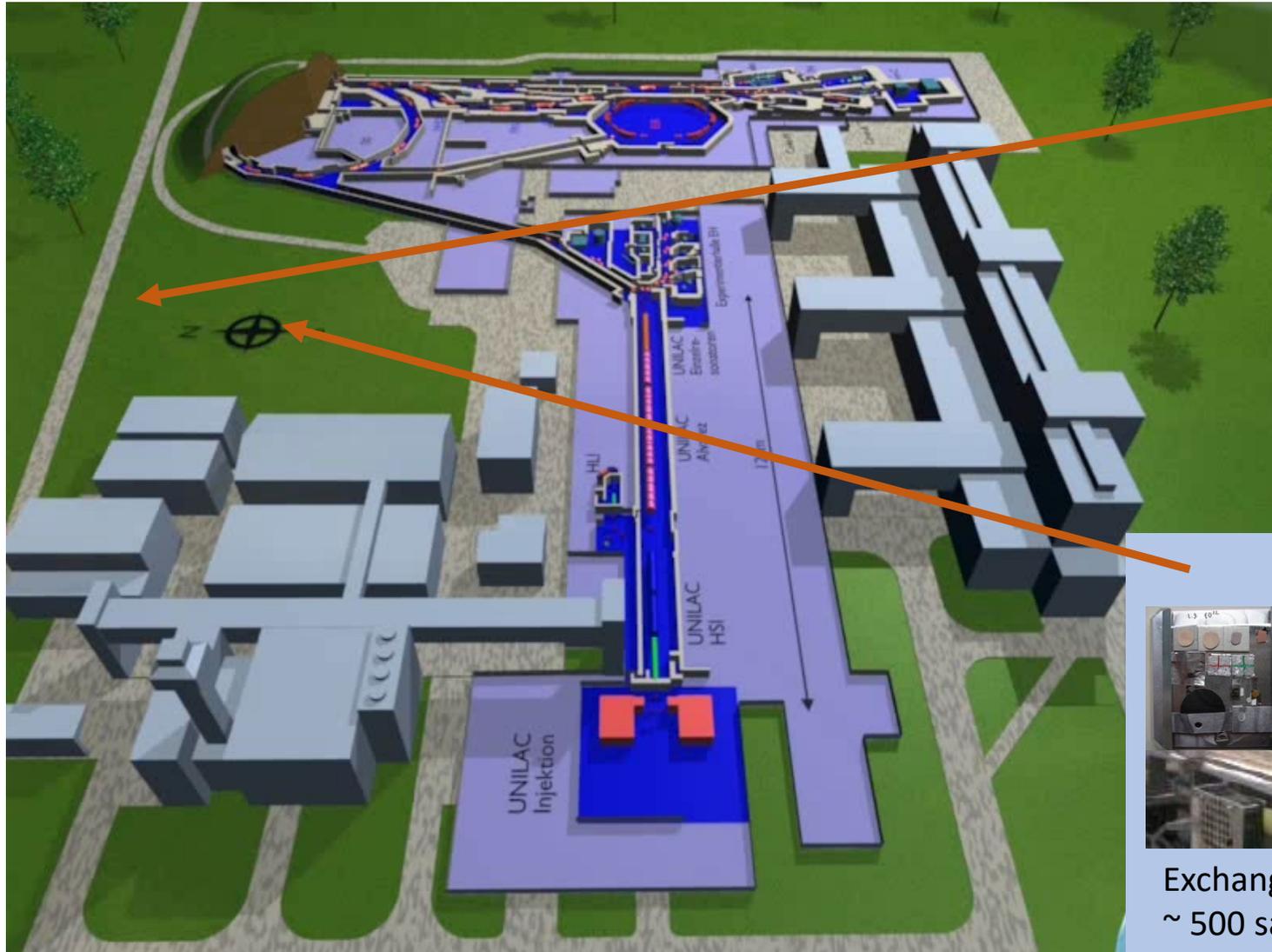
INTERNATIONAL CONFERENCE ON  
**ACCELERATORS FOR RESEARCH  
AND SUSTAINABLE DEVELOPMENT**

From good practices towards socioeconomic impact

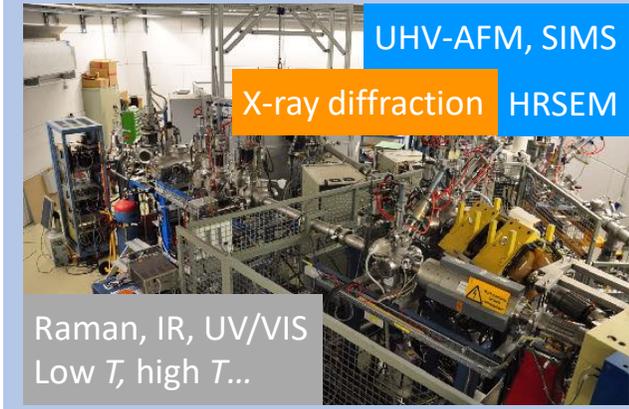


**23–27 May 2022**

IAEA Headquarters, Vienna, Austria



## M1 – M3



UHV-AFM, SIMS

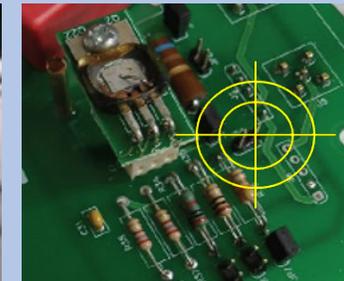
X-ray diffraction HRSEM

Raman, IR, UV/VIS  
Low T, high T...

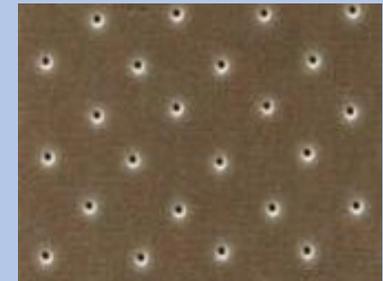
## X0 and heavy ion microprobe



Exchange system  
~ 500 samples/h



Radiation hardness  
of space electronics



Regular patterns



## Radiation effects

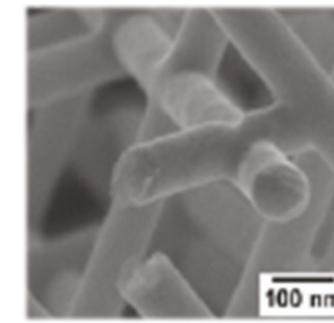
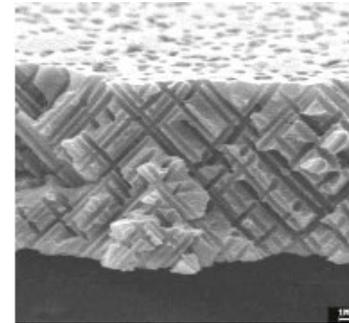
- in-situ analysis of radiation effects in bulk and nanomaterials
- FAIR relevant materials
- beam-induced desorption
- radiation hardness test
- high pressure irradiations



Philipp Bolz et al. Shock and Vibration 2021 (2021)  
V. Velthaus et al. Vacuum 194 (2021)  
M. Lang et al., Comprehensive Nuclear Mat. 2<sup>nd</sup> edition V.1 (2020)

## Ion-track nanotechnology

- membranes
- nanostructures



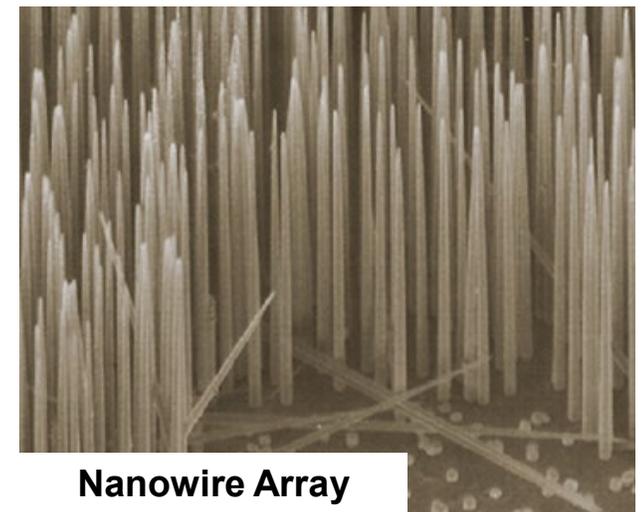
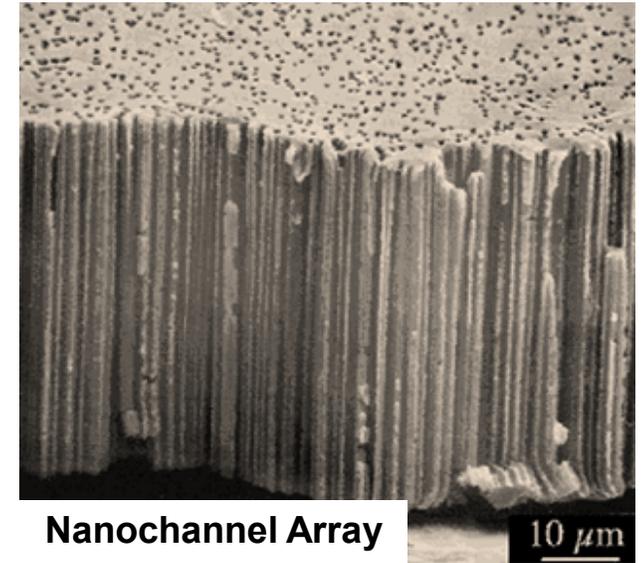
M.E. Toimil-Molaes, Beilstein J. Nanotechnol. 3 (2012)



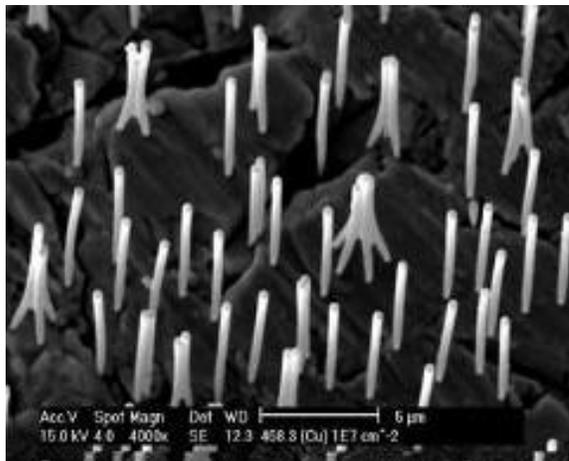
## User facility + irradiation service

- support for external users
- user samples ( $1 - 10^{14}$  ions/cm<sup>2</sup>)
- testing electronic devices

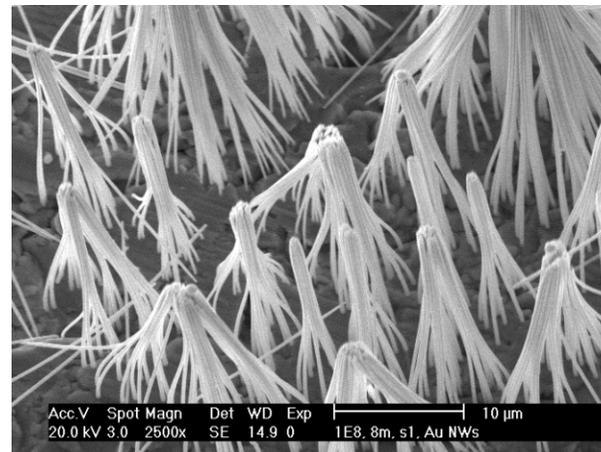
- **Combination of ion track technology and electroplating is powerful nanostructuring tool**
- **Low dimensional materials exhibit unique properties:**
  - size effects influence transport
  - high surface to volume ratio



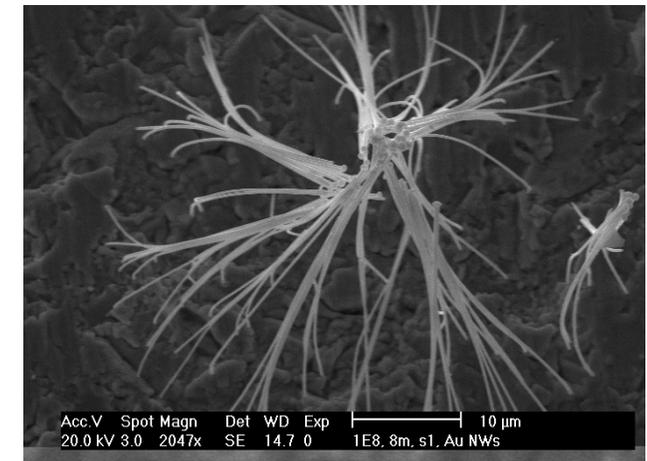
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increasing  
➔  
aspect ratio

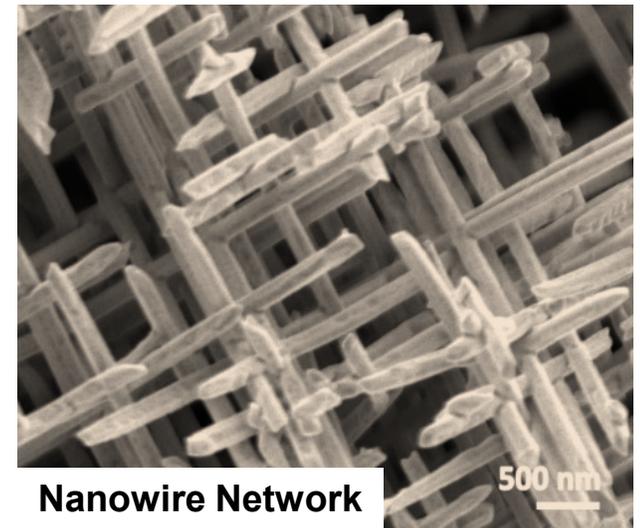
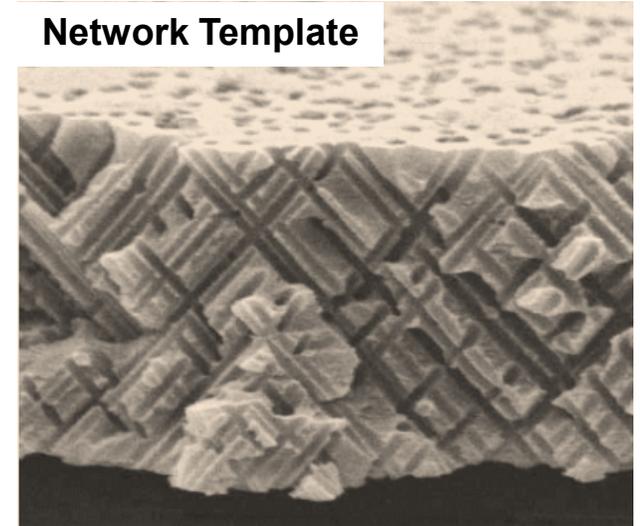


increasing  
➔  
aspect ratio



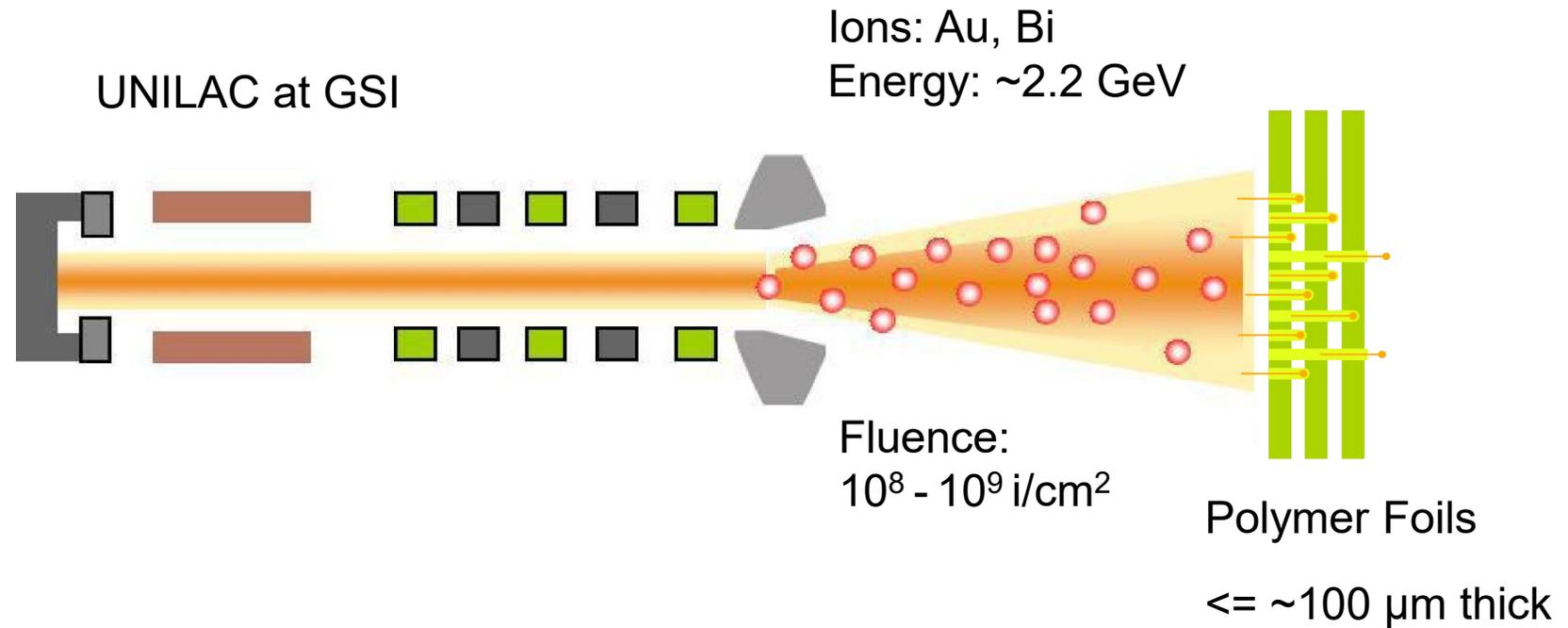
- **Combination of iontrack technology and electroplating is powerful nanostructuring tool**
- **Low dimensional materials exhibit unique properties:**
  - size effects influence transport
  - high surface to volume ratio
- **Nanowire networks ideal structure for applications:**
  - mechanically self supporting
  - reliable electrical transport vs. damage
  - „nano“ properties in macroscopic objects
  - low material usage

Network Template

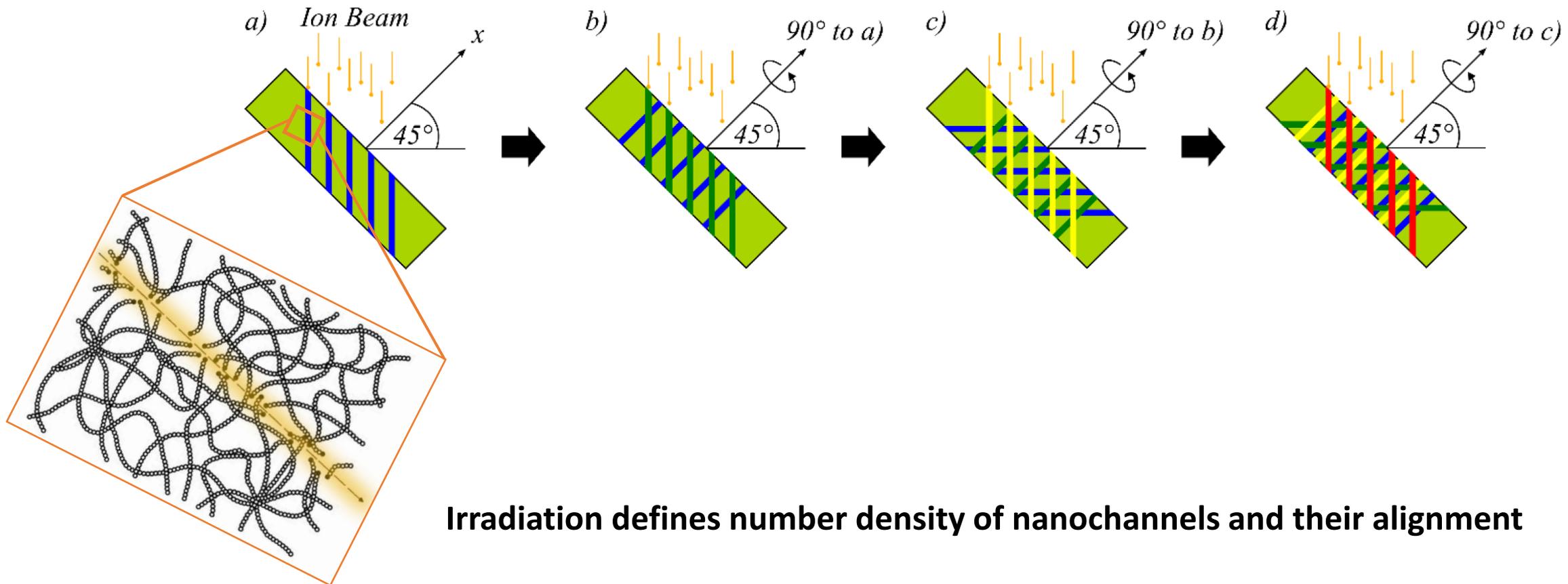


Nanowire Network

## UNILAC linear accelerator at GSI

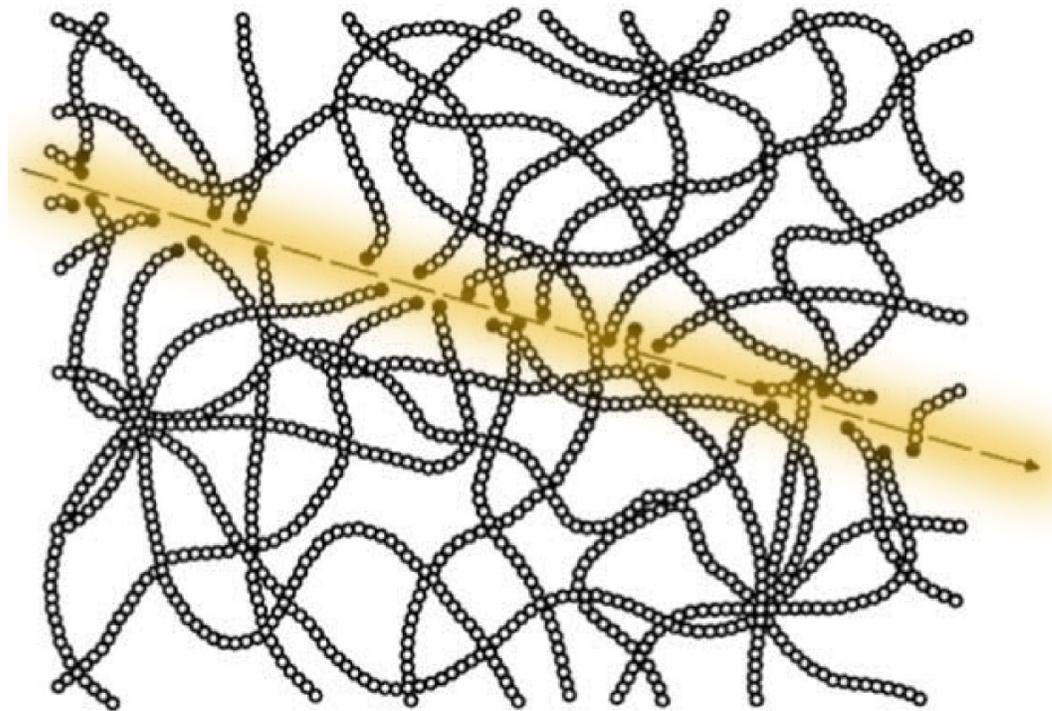


M.E. Toimil-Molares, Beilstein J. Nanotechnol. 3 (2012)



Fleischer, Nuclear Tracks in Solids, University of California Press (1975)

M.E. Toimil-Molares, Beilstein J. Nanotechnol. 3 (2012)



**Each swift heavy ions generate damage tracks in polymers**

Irradiation effects:

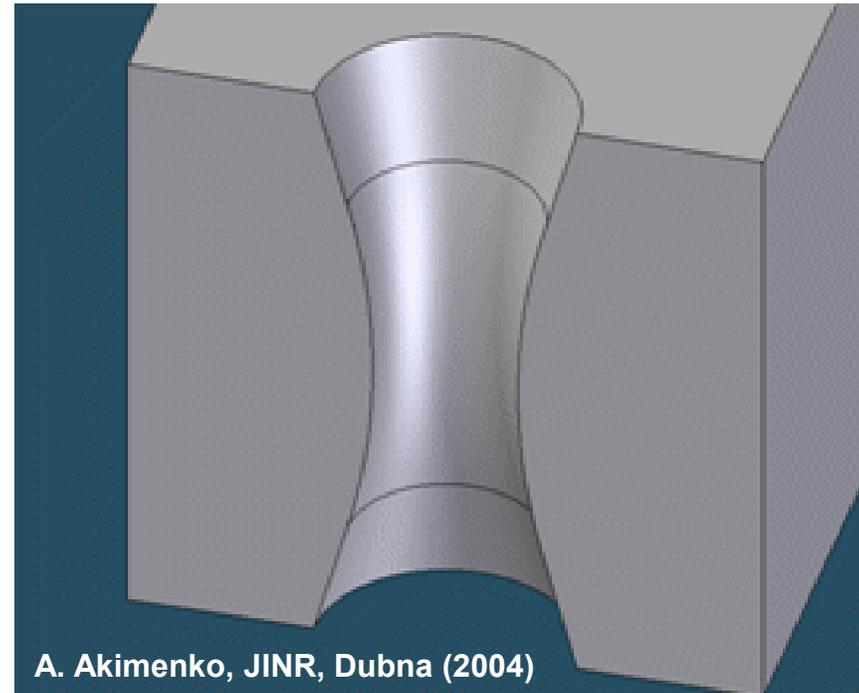
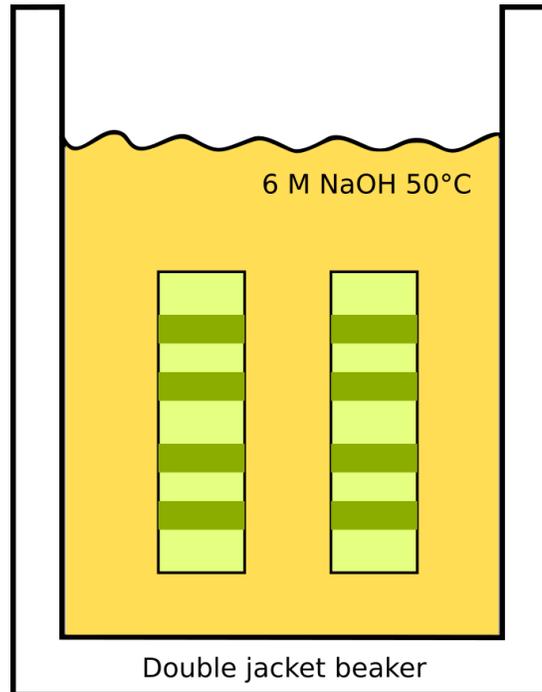
Chain scission

creation of unsaturated bonds

Formation of radicals

Outgassing of small molecules ( $\text{CO}_n$ ,  $\text{C}_n\text{H}_m$ ,...)

Etc...

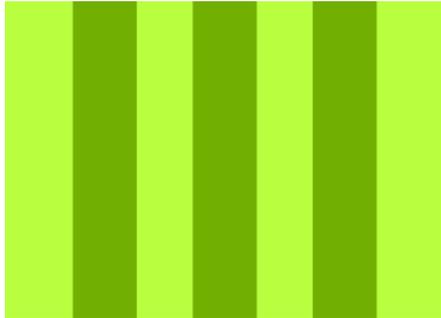


**Etching conditions control size and shape of pores**

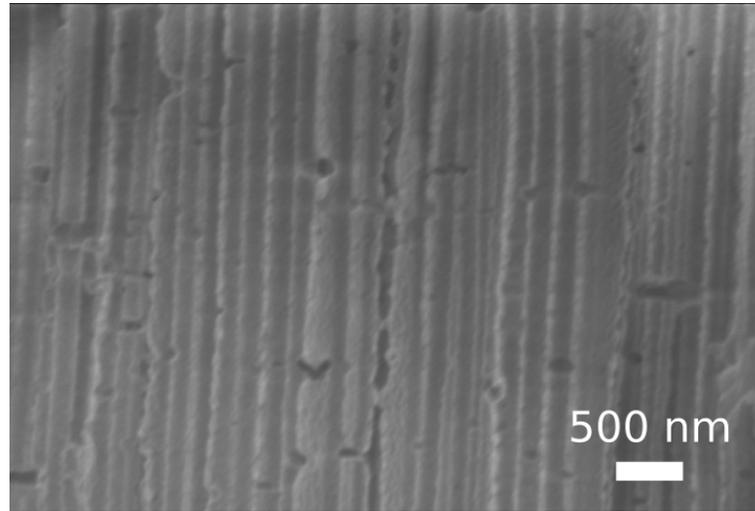
M.E. Toimil-Molares, Beilstein J. Nanotechnol. 3 (2012)

# Pore Geometry: Control

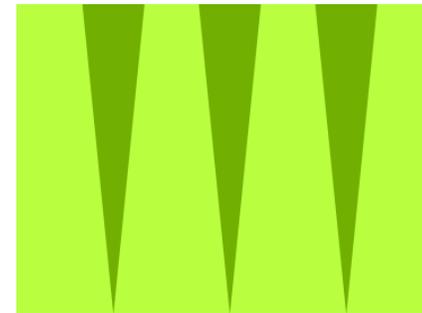
Array / Cylinder



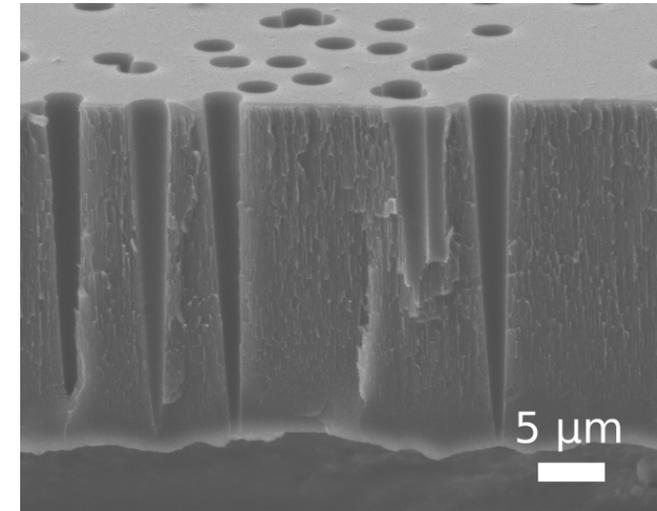
P.L.J. Lee et al.,  
*Nanotechnology* 32 (2021)



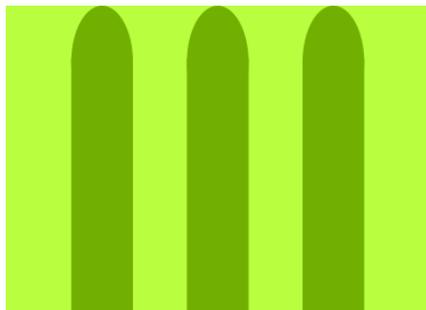
Array / Conical



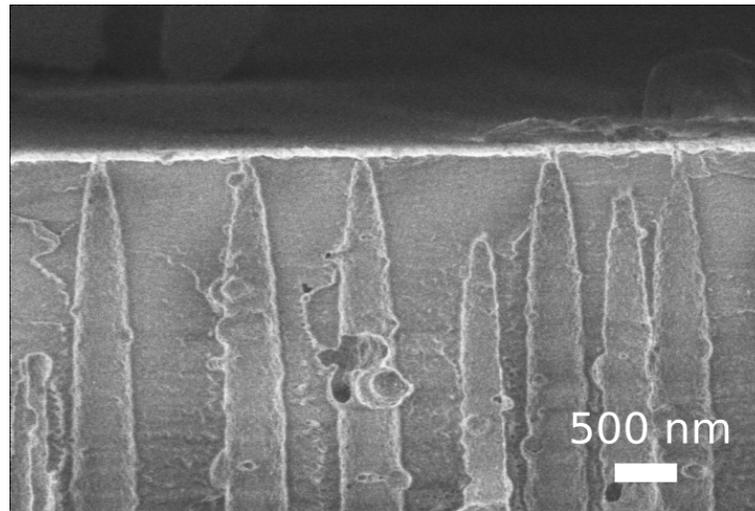
N. Ulrich et al.,  
*Nanomaterials* 11 (2021)



Array / Bullet



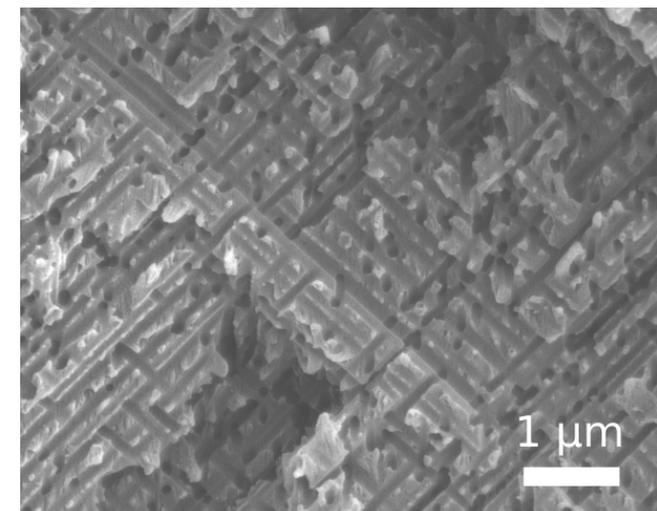
G. Laucirica et al.,  
*Nano Energy* 71 (2020)



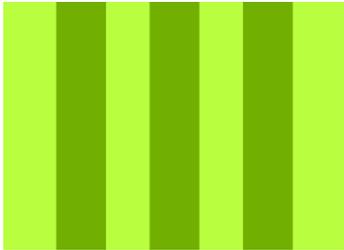
Network / Cylindrical



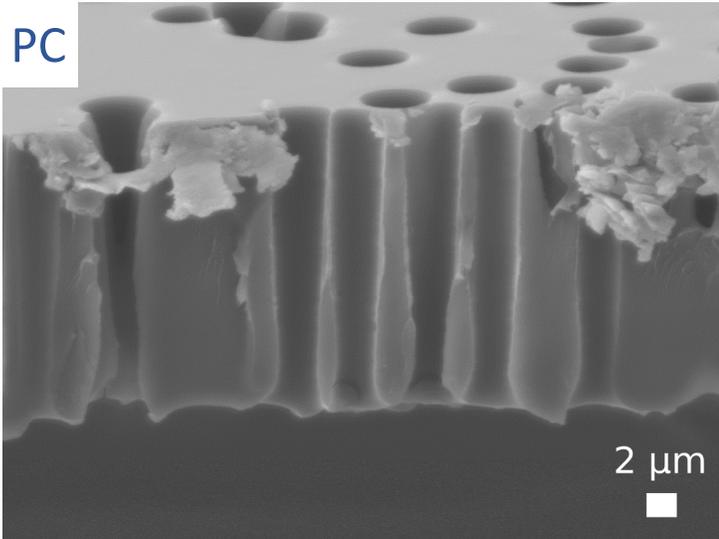
L. Movsesyan et al.,  
*Nanomaterials* 8 (2018)



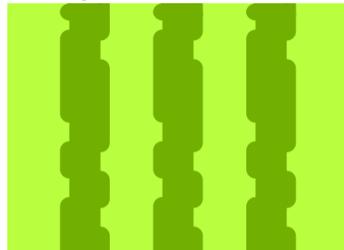
smooth  
pore walls



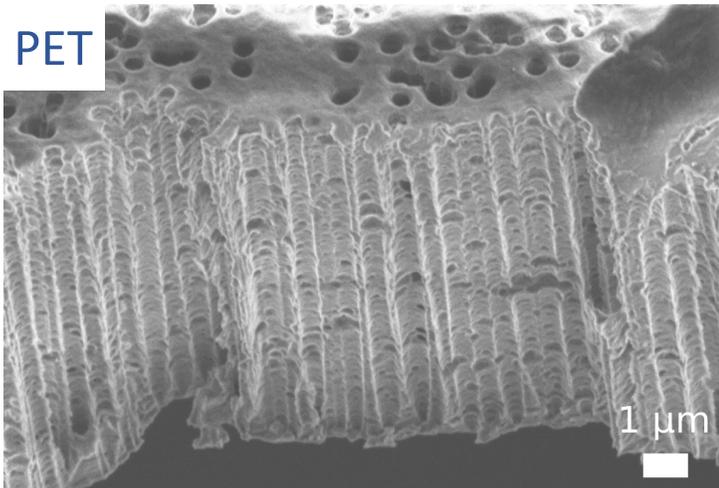
S. Dutt et al., J. of Mem-  
brane Science 638 (2021)



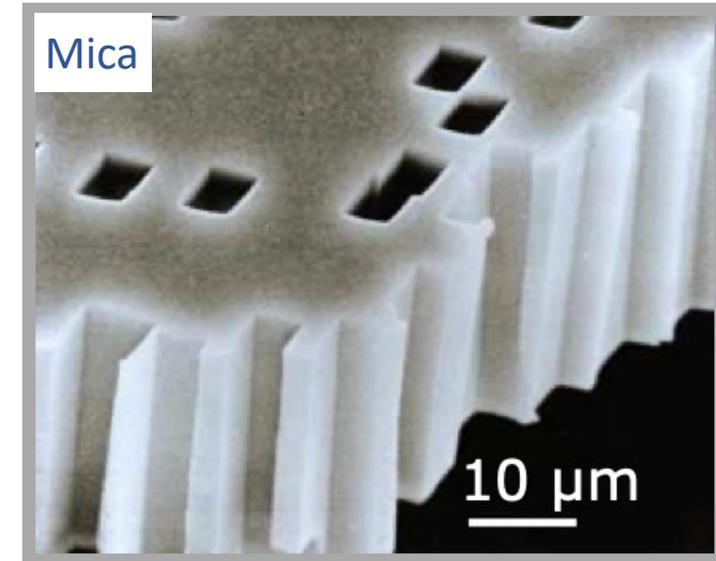
rough  
pore walls



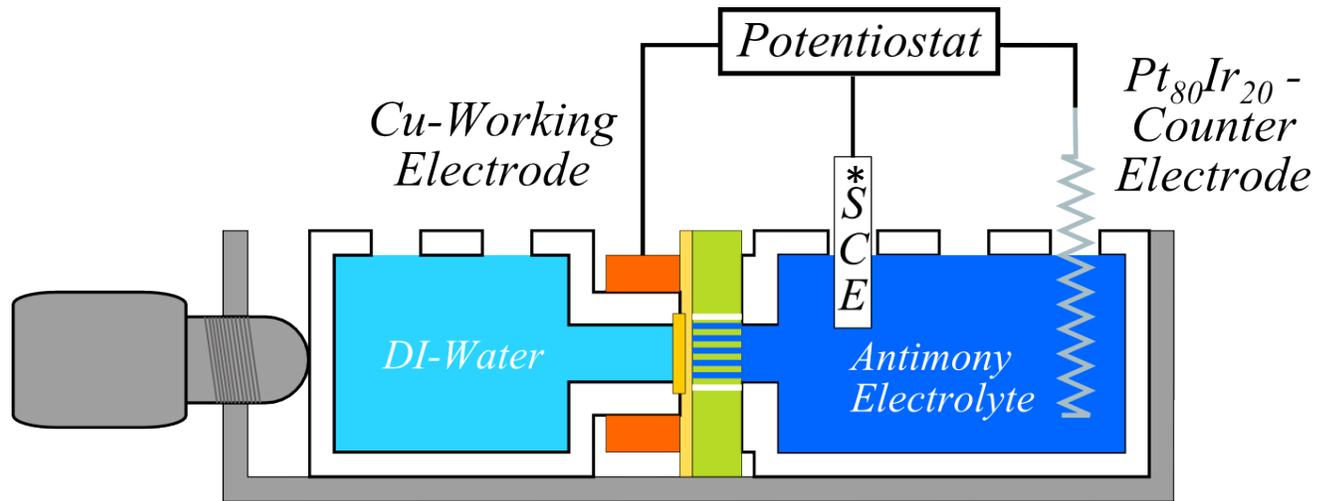
G. Laucirica et al.,  
Chem. Sci. 12 (2021)



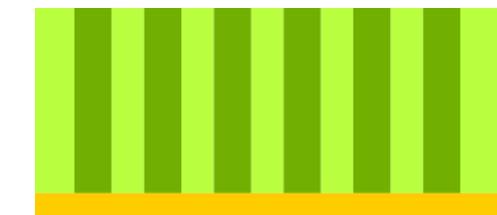
Square pores



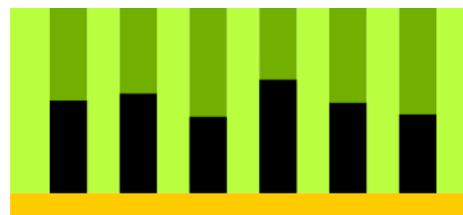
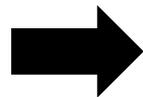
Fischer et al. Naturwissenschaften 75 (1988) 57



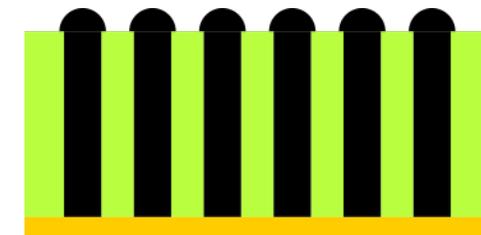
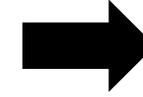
\*SCE: Standard calomel electrode



Template with metal layer



Electroplating

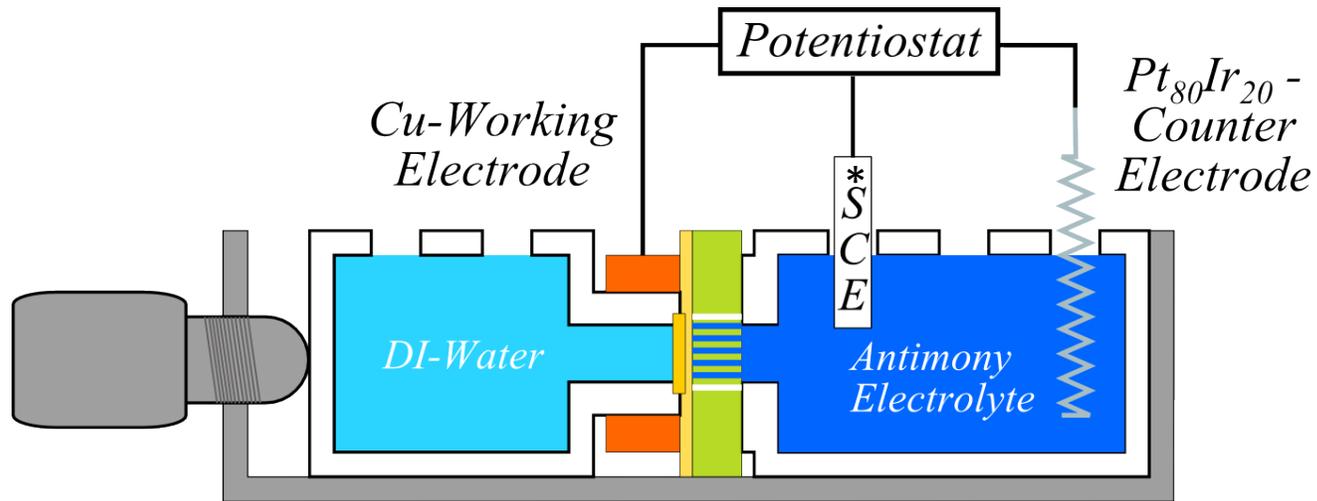


Finished Sample

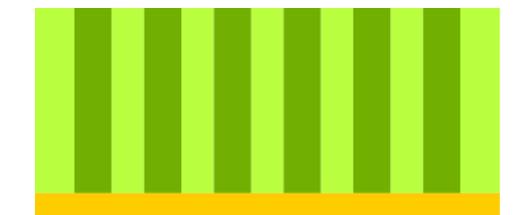
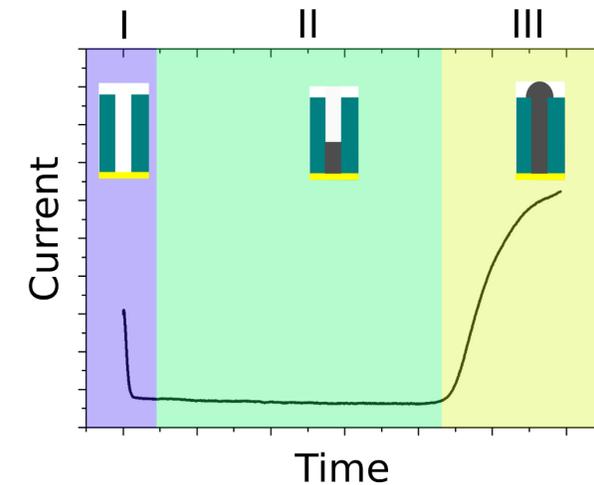
**Parameters can be optimized for homogeneous growth with preferred crystallinity**

M.E. Toimil-Molares, Beilstein J. Nanotechnol. 3 (2012)

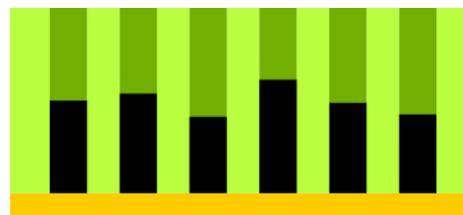
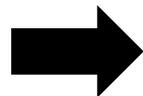
# Electrodeposition in Templates



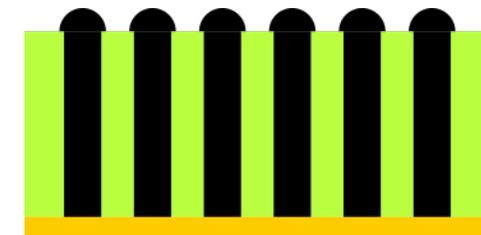
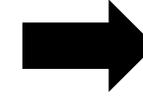
\*SCE: Standard calomel electrode



Template with metal layer



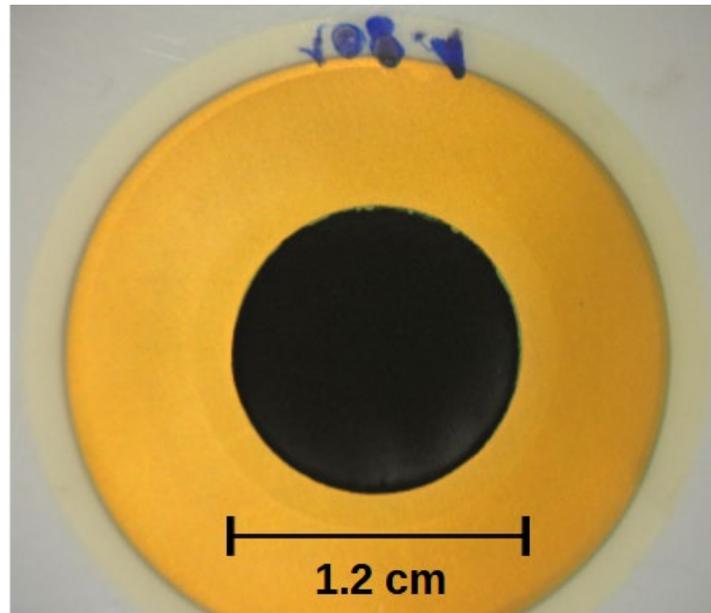
Electroplating



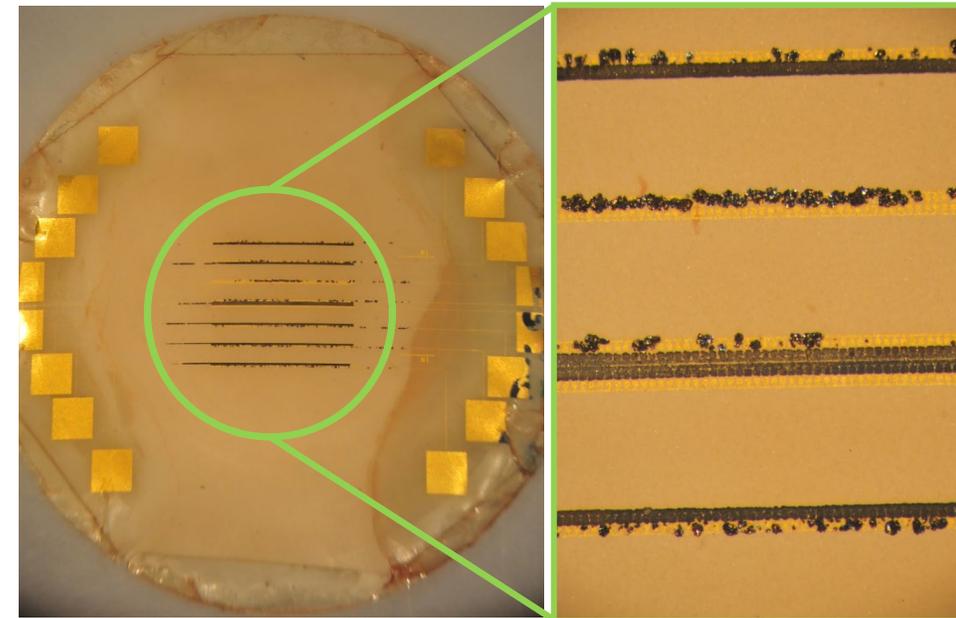
Finished Sample

**Parameters can be optimized for homogeneous growth with preferred crystallinity**

M.E. Toimil-Molares, Beilstein J. Nanotechnol. 3 (2012)



Whole-area electroplating



Structured localized electroplating

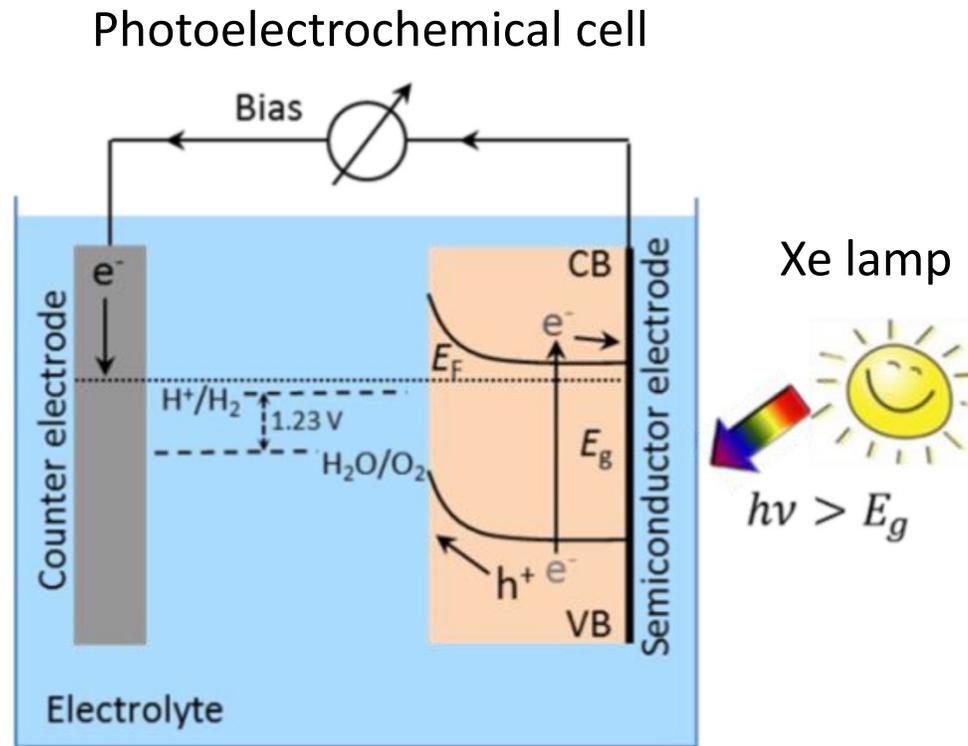
**Use of structured electrodes allow localized electroplating and device fabrication**







Liana Movsesyan



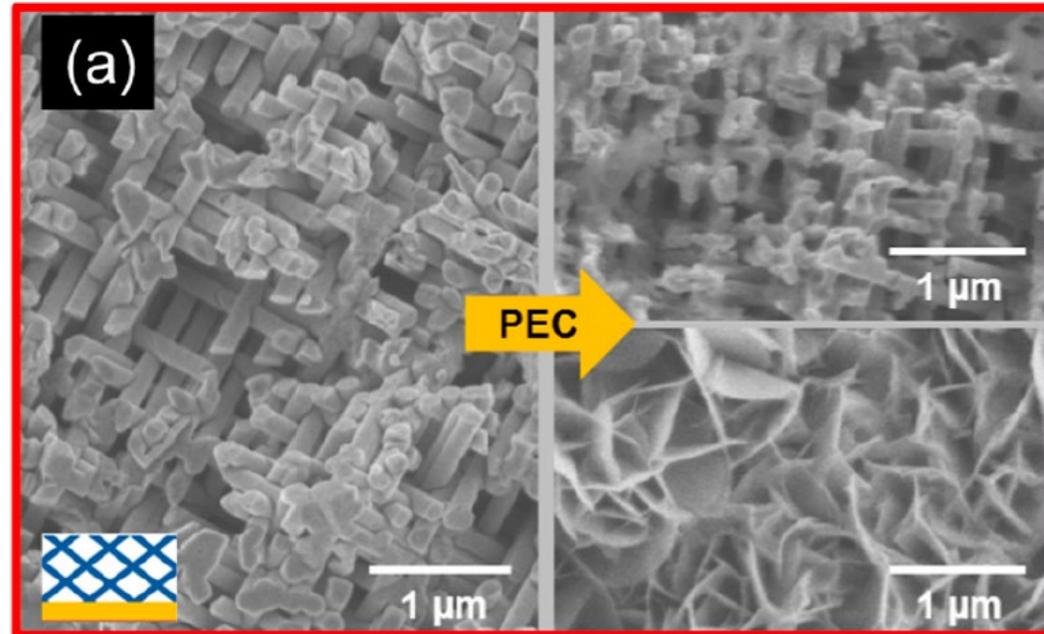
- Light absorption causes charge carrier separation
- Charges diffuse to electrode surface and split water



Network with  $4 \times 2 \cdot 10^9$  i/cm<sup>2</sup>, 150 nm wire diameter

before

after



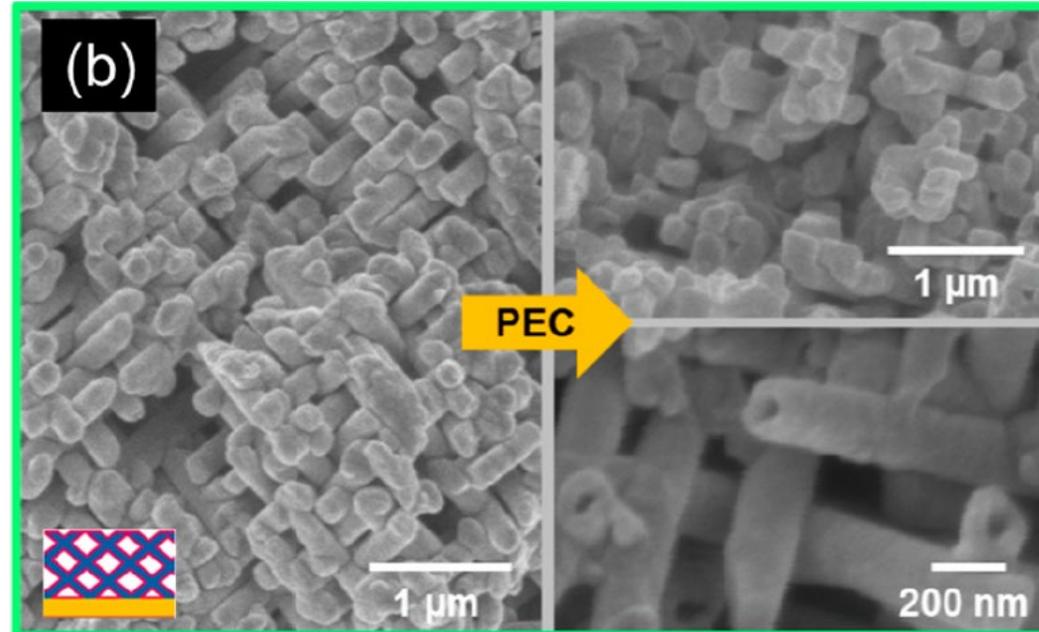
Photocorrosion after 1h of reaction

Nanowires deteriorate, recrystallization occurs

Network with  $4 \times 2 \cdot 10^9$  i/cm<sup>2</sup>, 150 nm wire diameter + 20 nm TiO<sub>2</sub> layer

before

after

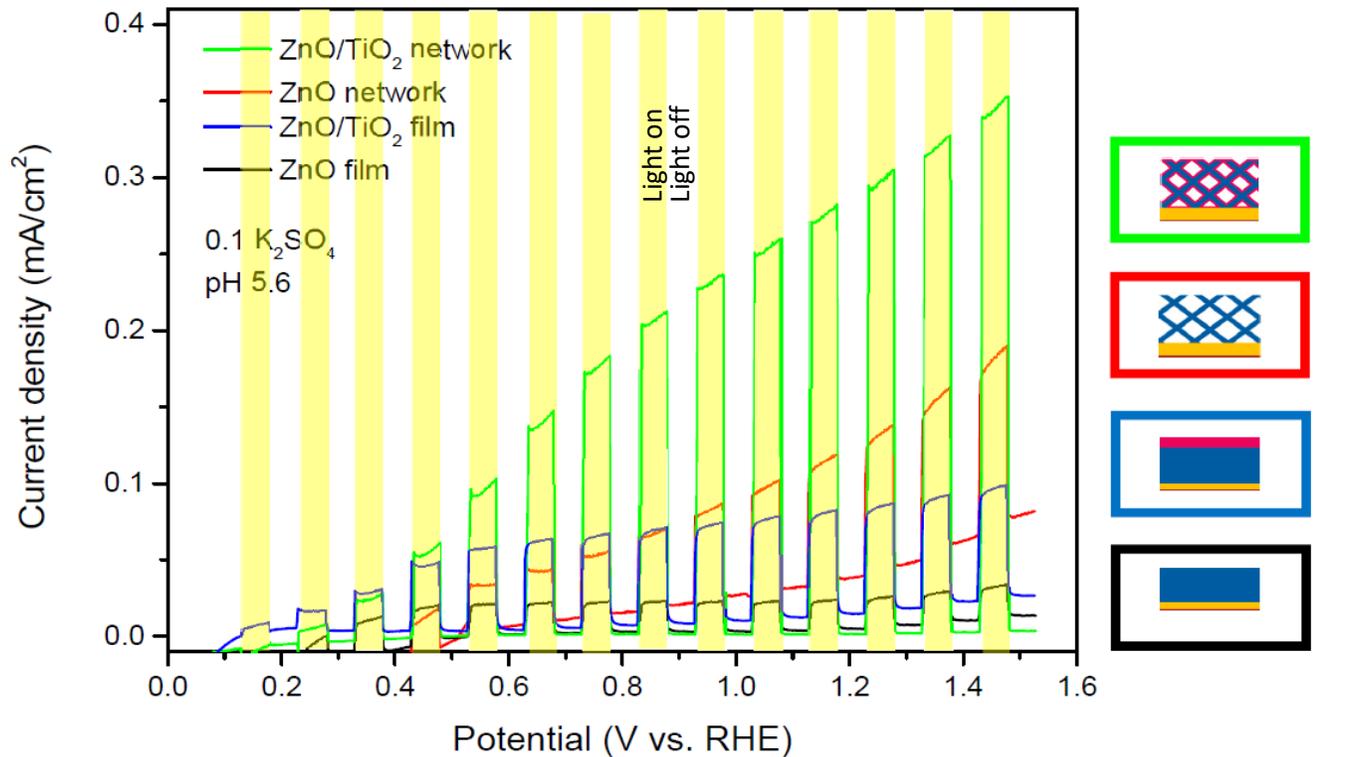


TiO<sub>2</sub> layer prevents photocorrosion

No or minimal corrosion after 3h of reaction

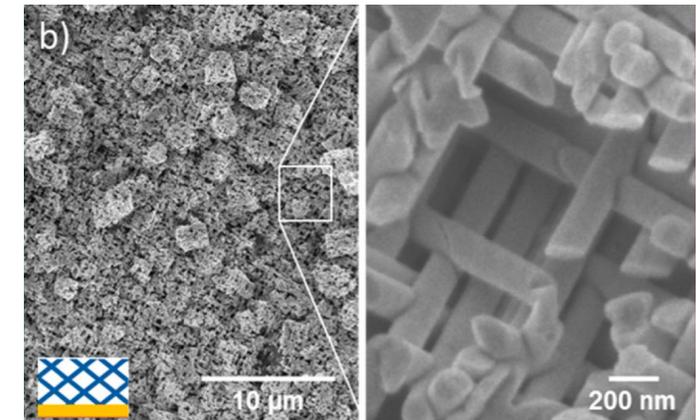
# Nanowire Networks vs. Films

Linear sweep voltammometry under chopped light

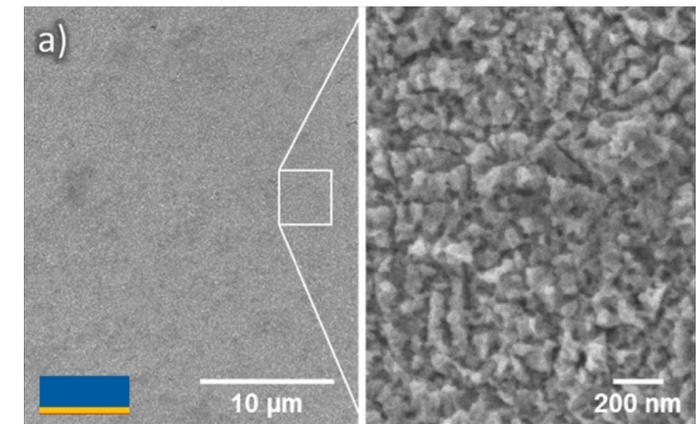


**Networks show higher photocurrents compared to bulk films**

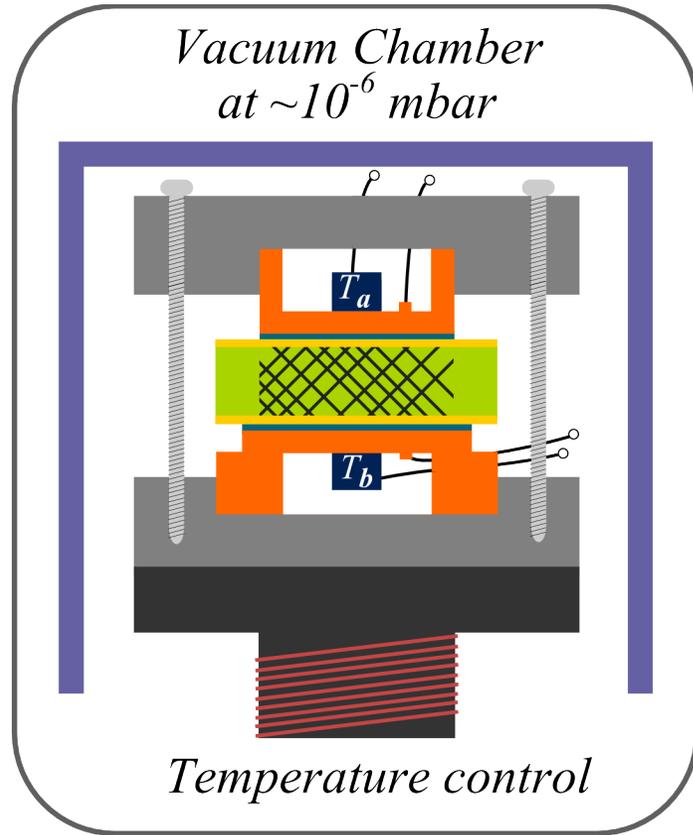
Network  $4 \times 5 \cdot 10^8 \text{ i}/\text{cm}^2$ , 150 nm wire diameter



Film 10 μm thickness

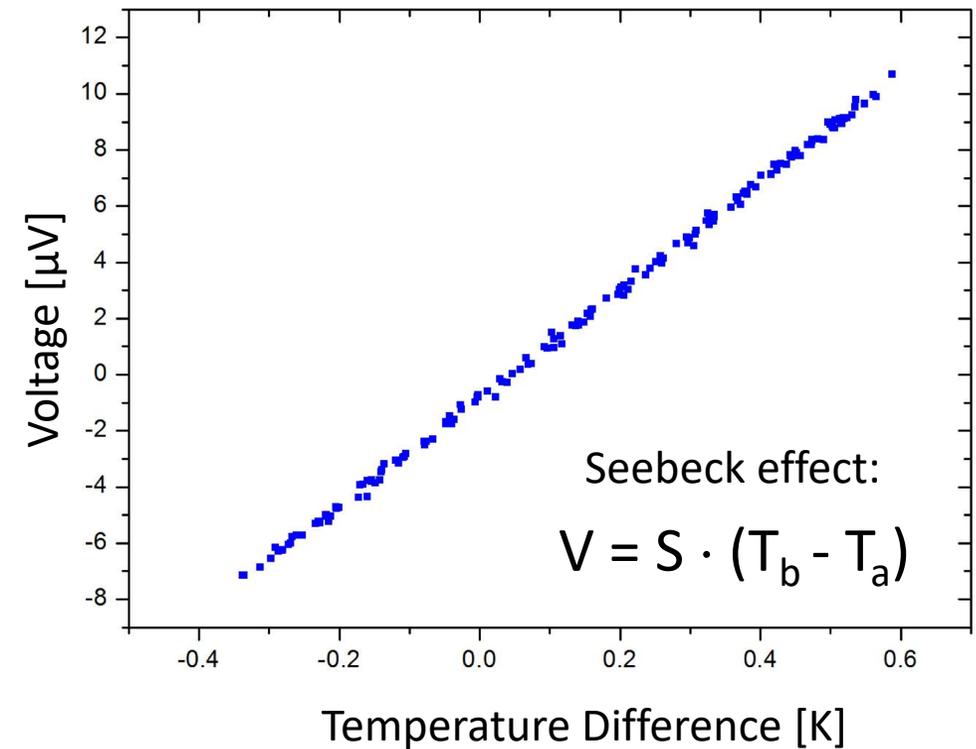


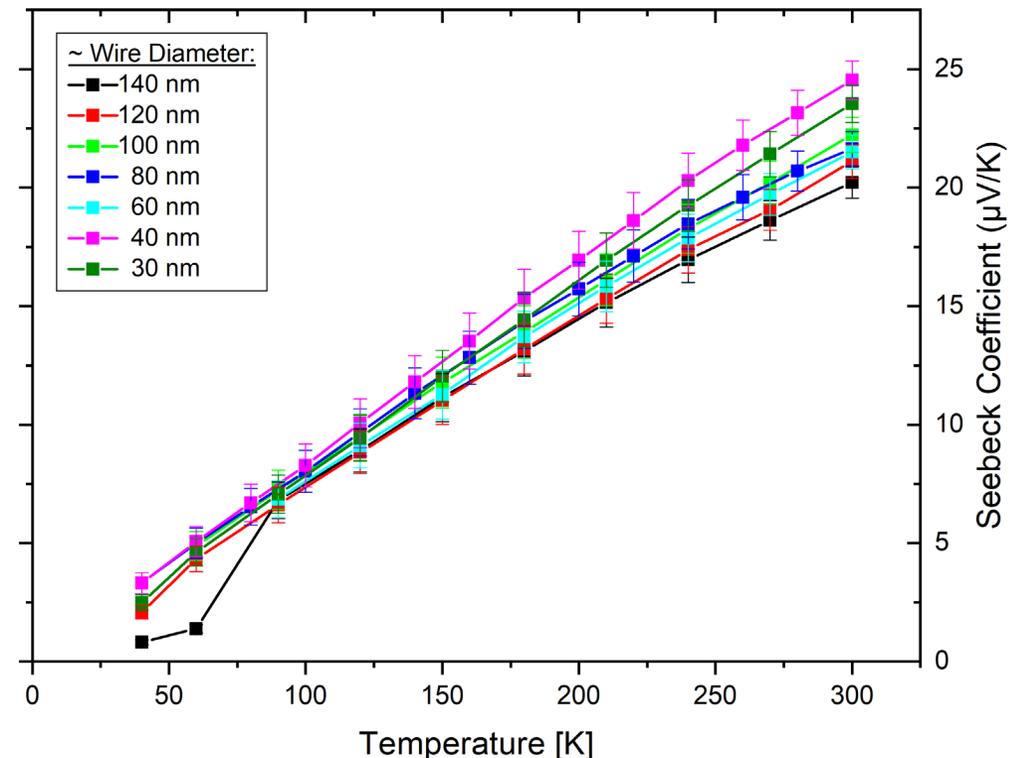
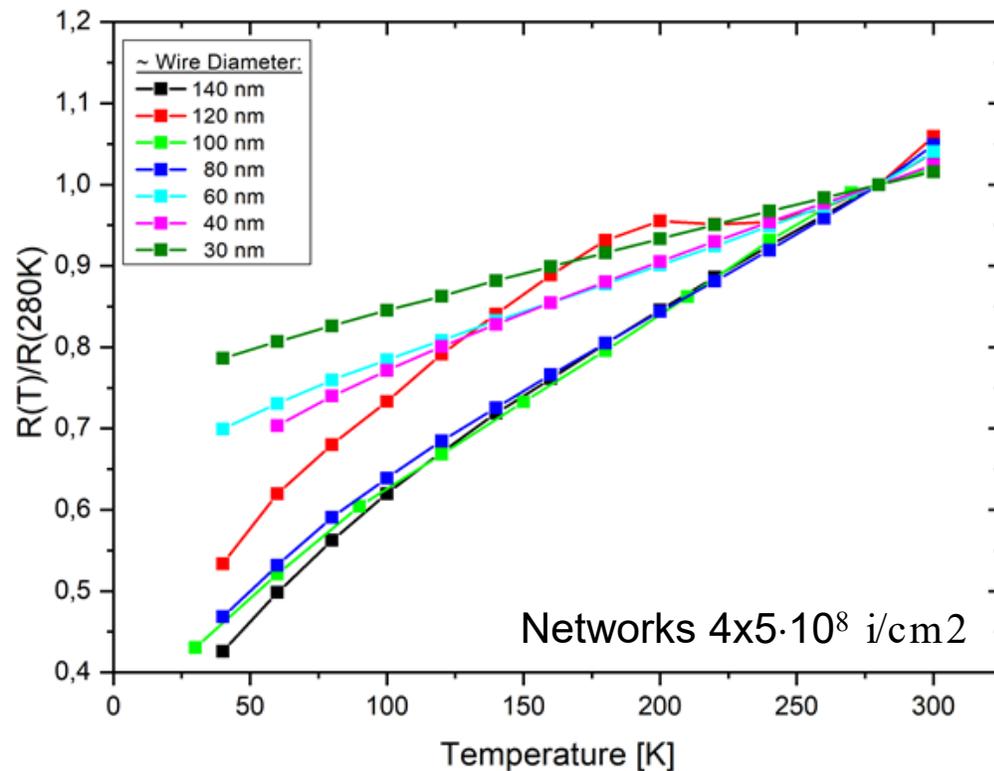
# Setup for Thermoelectric Characterization



- Heating Wire
- Cooling Finger
- Nanowire Network/Array
- Silicon Diodes to measure  $T_a$  and  $T_b$
- Shielding
- Cu Heat Sink / Contacts
- Thermal Paste

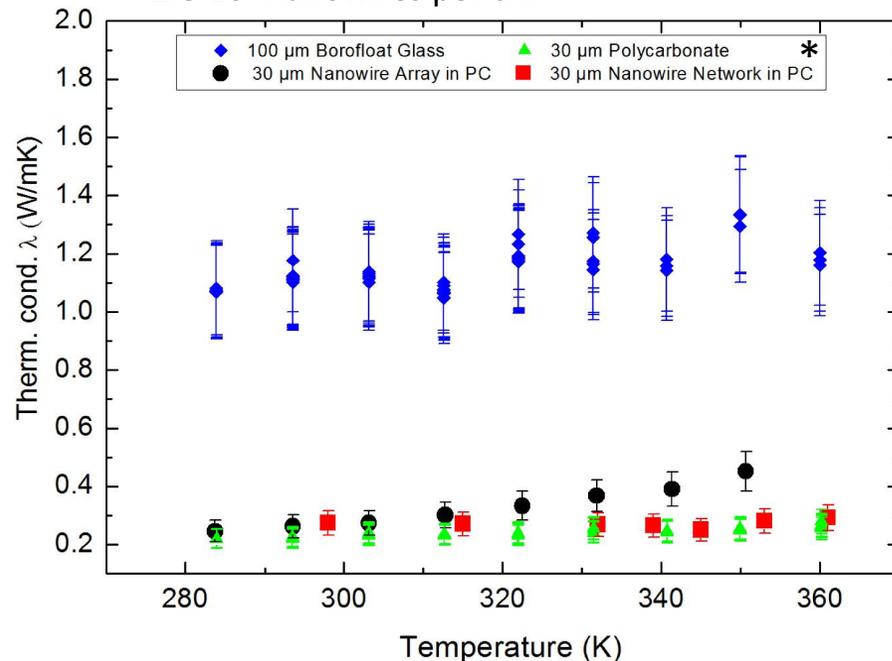
Seebeck coefficient @ 300K





**Size effect on electrical resistance, but no significant size effects on Seebeck coefficient**

\* Nanowire network: 150 nm wire diameter,  
2.8·10<sup>9</sup> nanowires per cm<sup>2</sup>



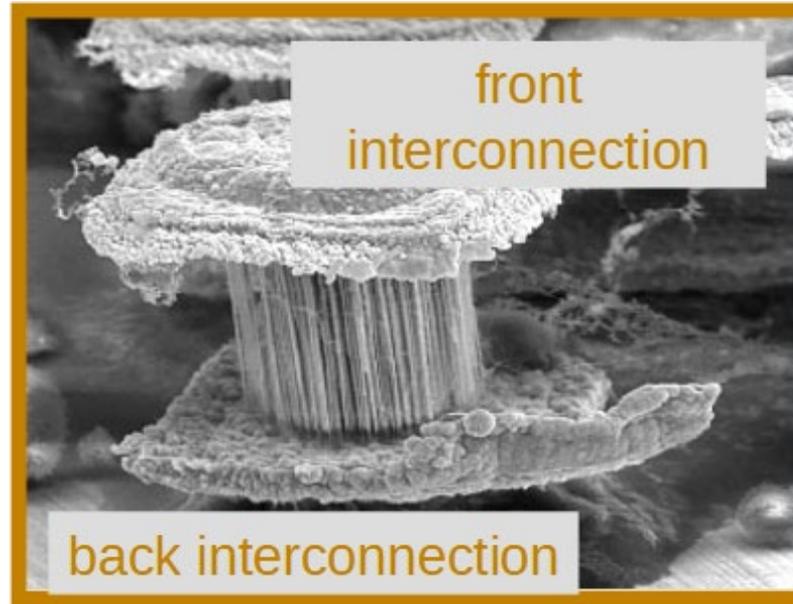
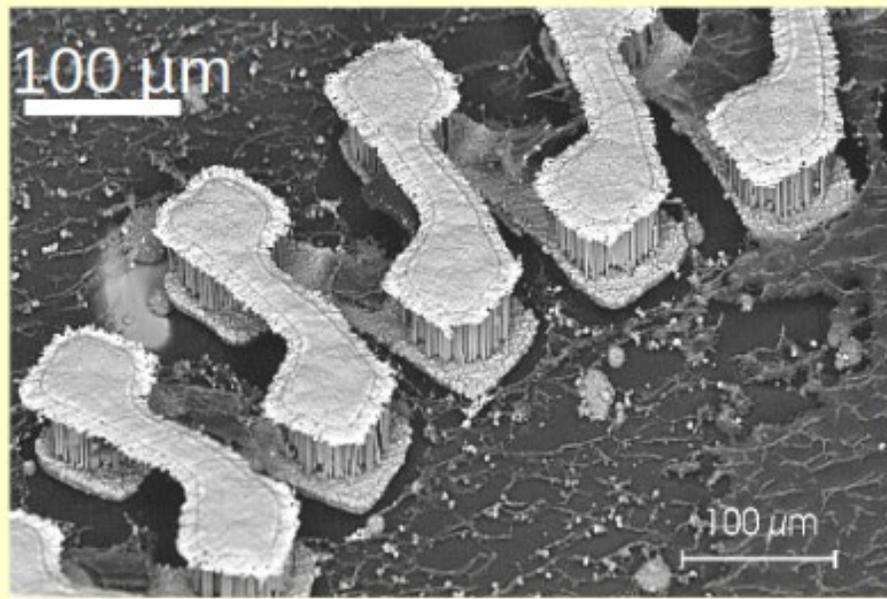
Thermoelectric figure of merit:

$$zT = \frac{S^2 \cdot \sigma}{\lambda_{el} + \lambda_{ph}}$$

- S: Seebeck coefficient
- σ: Electrical conductivity
- λ<sub>el</sub>: Thermal conductivity of charge carriers
- λ<sub>ph</sub>: Thermal conductivity of phonons
- T: Absolute temperature

**Networks have significantly reduced thermal conductivity which leads to increased thermoelectric efficiency**





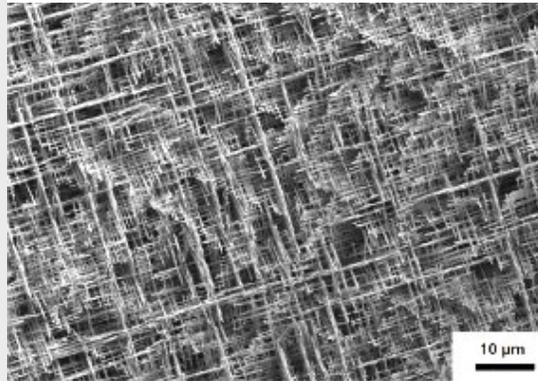
**Fabrication of nanowire structures and nanowire-based IR-Sensors based on ion-track nanotechnology on a larger scale is feasible**

Lindeberg et al., Sens. Actuat. A 105 (2003)



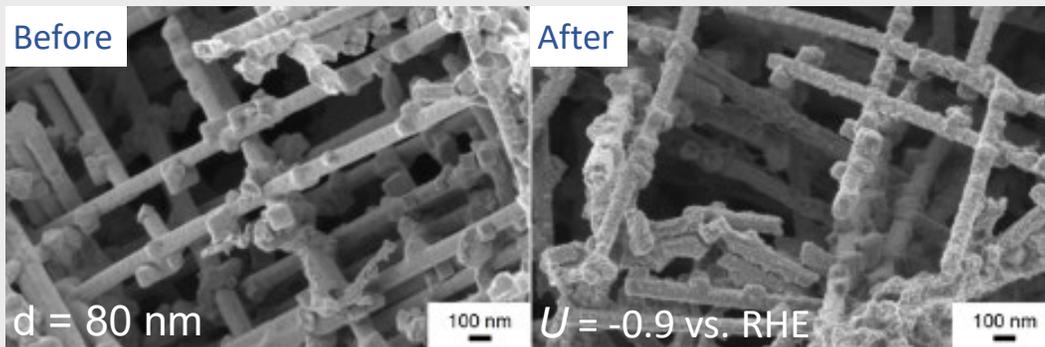
Nils Ulrich

## Cu nanowire networks

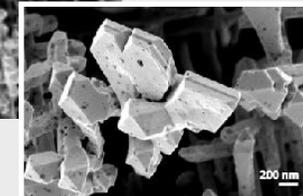
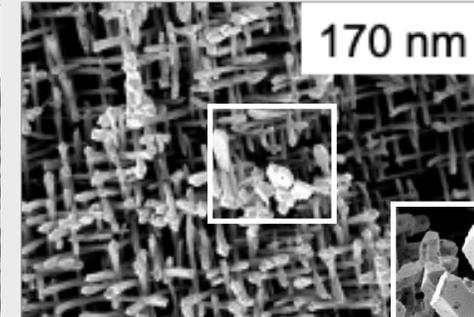
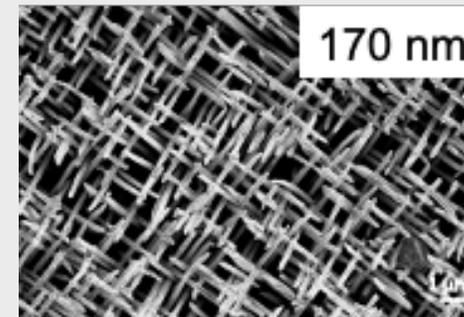


$d_{\text{wire}} \sim 140 \text{ nm}$   
 $8 \cdot 10^8 \text{ wires/cm}^2$

- surface area increase factor  $> 300$  ( $500 \text{ cm}^2$ )
- $\text{CO}_2$  reduction in collaboration with AG Etzold (TU Darmstadt)
- structural analysis by SEM and TEM
- performance and stability

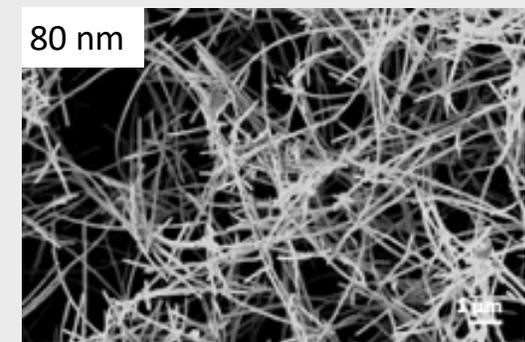
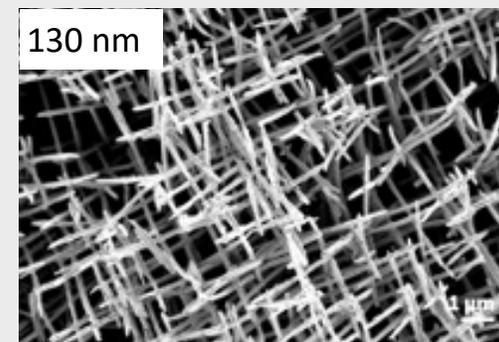


## Au nanowire networks

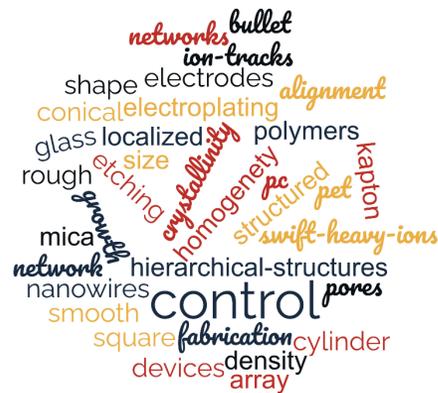
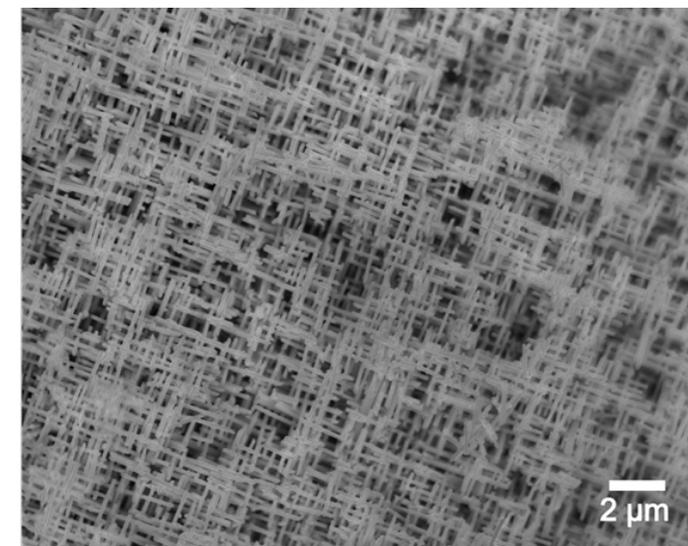
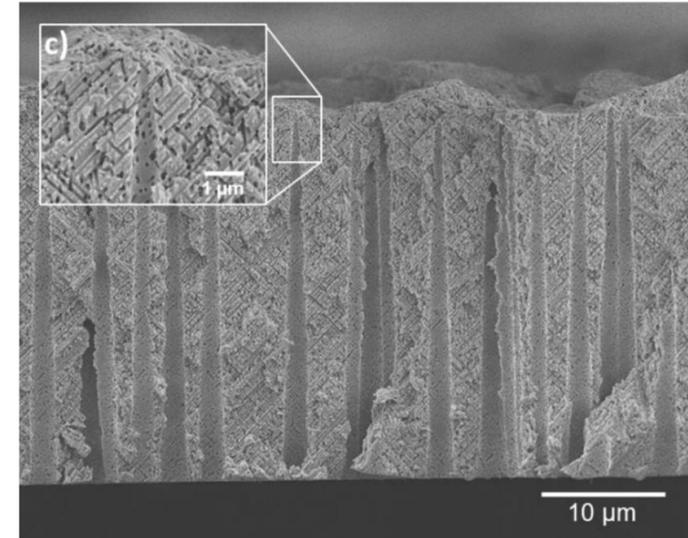


Mohan Li

- optimization electrodeposition conditions
- analysis before/after methanol oxidation reaction
- geometry-dependent wettability



- Nanowire networks are promising structures for applications in various fields
- Combination of iontrack technology and electroplating is a powerful tool to fabricate tailored low dimensional materials





Thank you

Activities on Bi and Sb nanowires are part of Innovation Pool Project **MadQuant**

We gratefully acknowledge support by:



INTERNATIONAL CONFERENCE ON  
**ACCELERATORS FOR RESEARCH  
AND SUSTAINABLE DEVELOPMENT**  
From good practices towards socioeconomic impact



**23–27 May 2022**

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