07.12.2009

Synthesis and Characterization of Silicon Nanowires: Towards Devices and Applications

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Outline

- Si Nanowires: Fabrication and characterization
  - CVD growth / doping
  - wet chemical etching
- Applications:
  - Matrix-free Desorption / Ionization Mass Spectrometry
  - Surface Enhanced Raman Scattering (SERS)
  - Solar cells
  - Chemical and biological sensors

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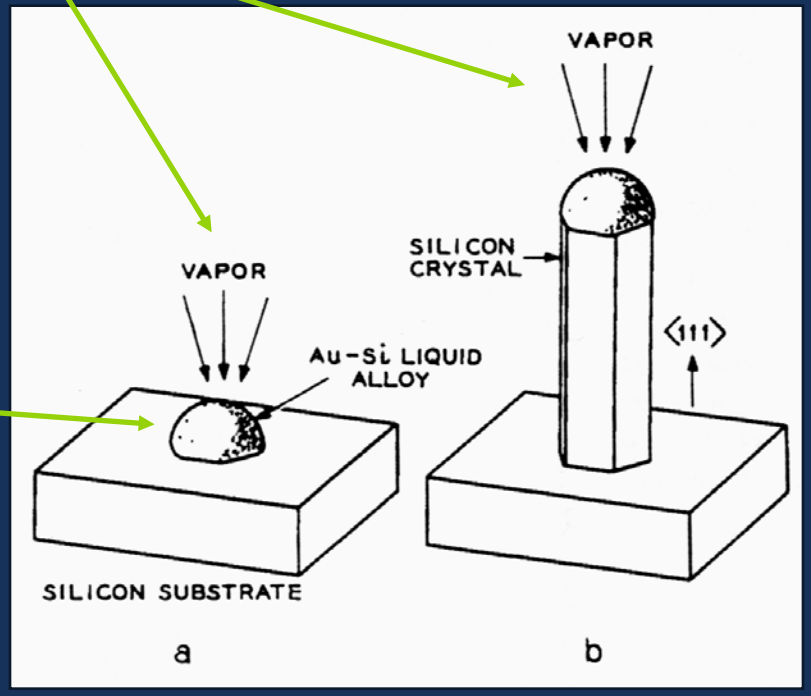
Vapour-liquid-solid (VLS) growth process

Si containing species
(e.g. SiH_4)

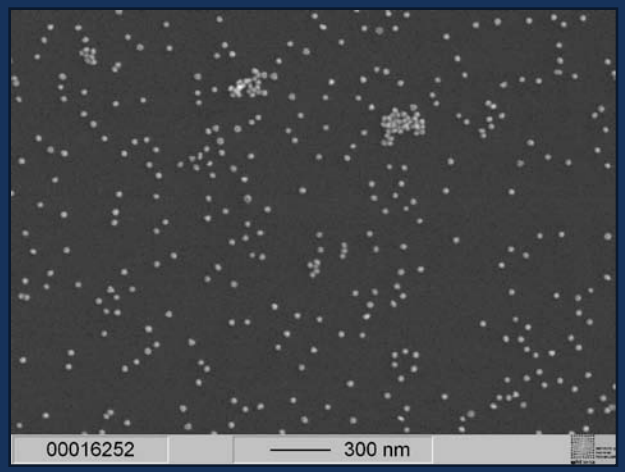
metal particle
as catalyst (e.g. Au)

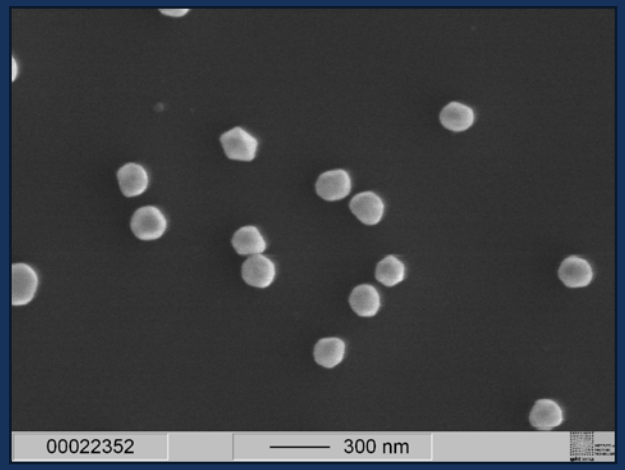


R.S. Wagner and W.C. Ellis, Appl. Phys. Lett. 4 (1964) 89

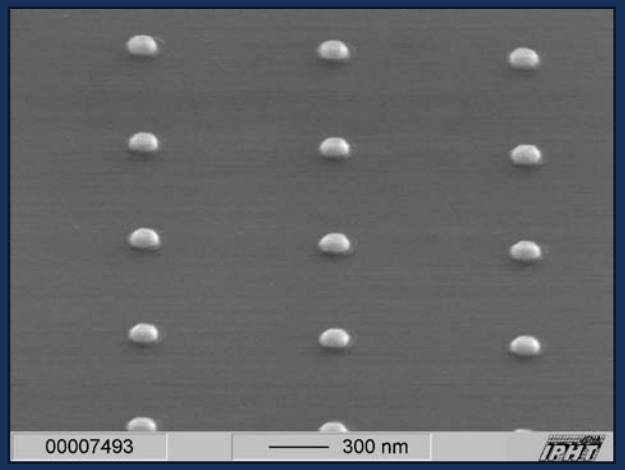
Metal templates

Immobilized Au nanoparticles

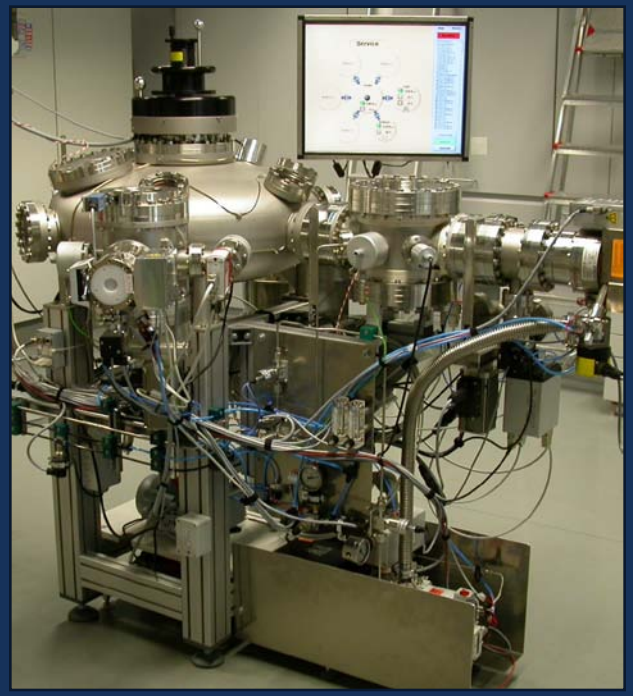




Au dots by EBL



Chemical vapour deposition (CVD)

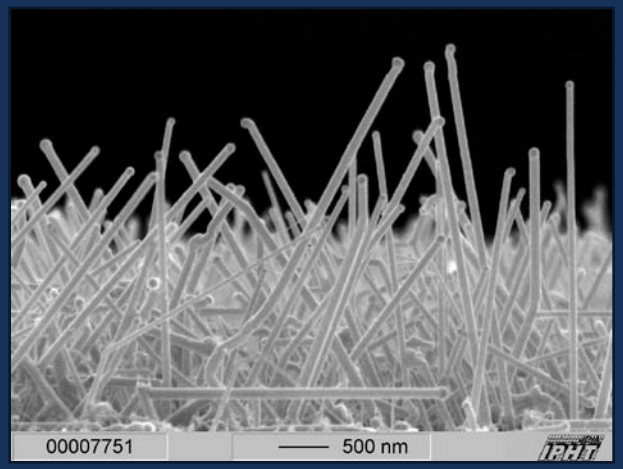


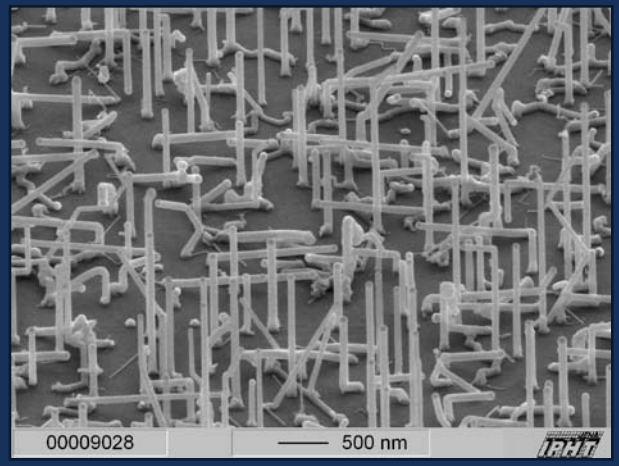
Gases: Ar, He, H_2, SiH_4, B_2H_6, PH_3

Temperature: ≤ 600° C

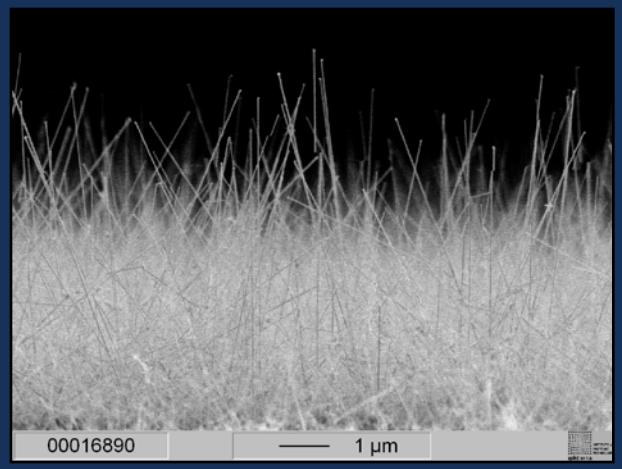
CVD VLS growth

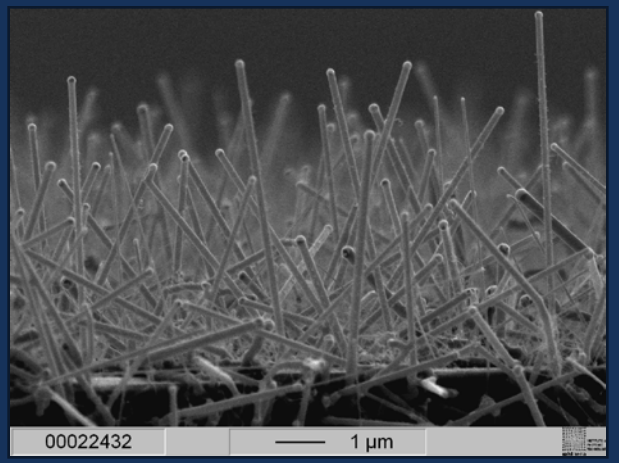
random or epitaxial growth





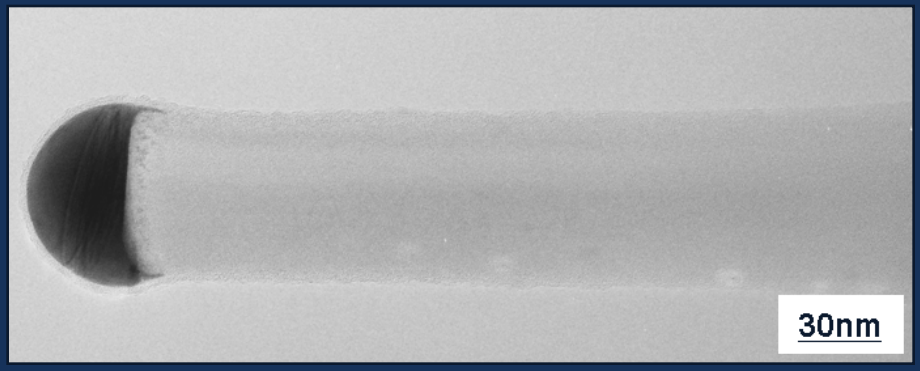
diameter controlled growth

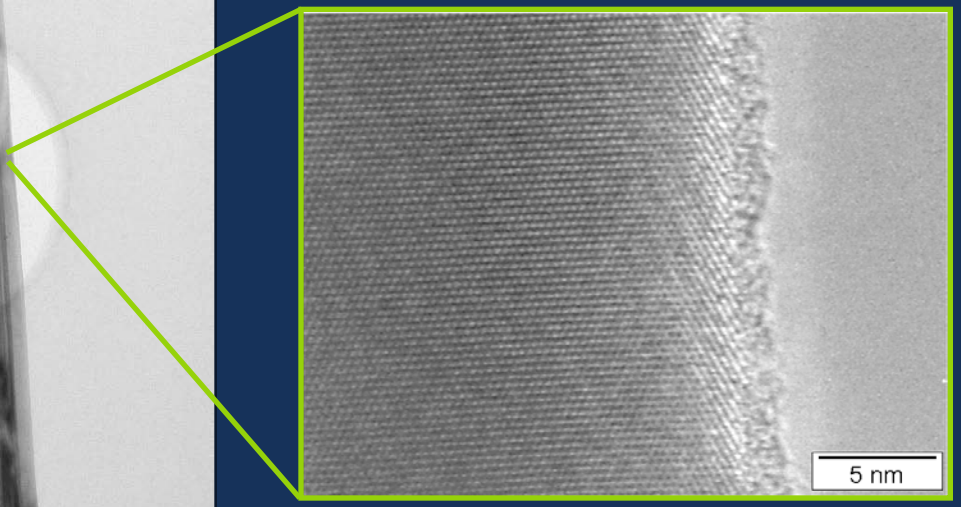




Structural quality

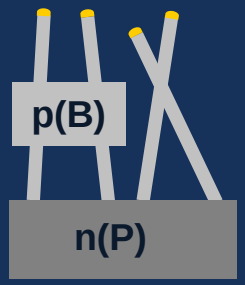
TEM





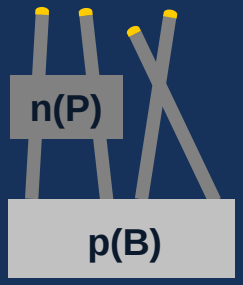
Electrical properties / doping

Electron beam induced current (EBIC) imaging



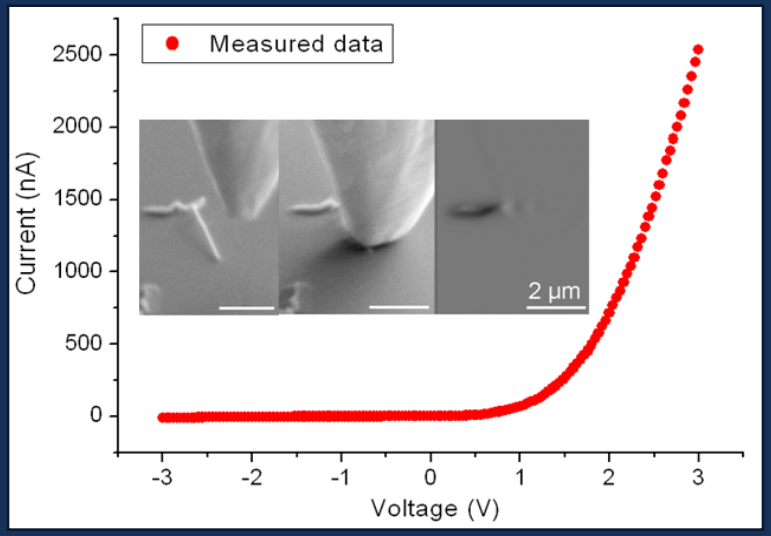
20 sccm Ar / 4 sccm SiH_4
0.1 sccm B_2H_6 (100 ppm in He)

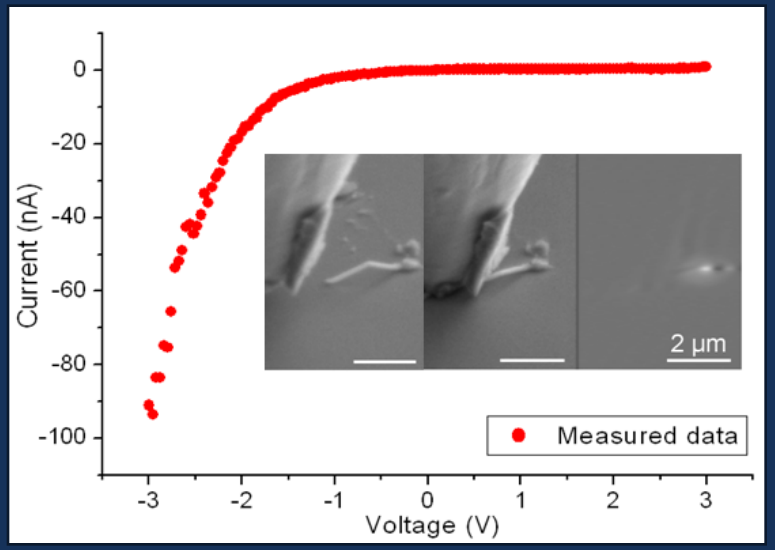
0.1-0.6 Ωcm / 1-8 x 10^{16}cm^{-3}



20 sccm Ar / 4 sccm SiH_4
0.1 sccm PH_3 (100 ppm in He)

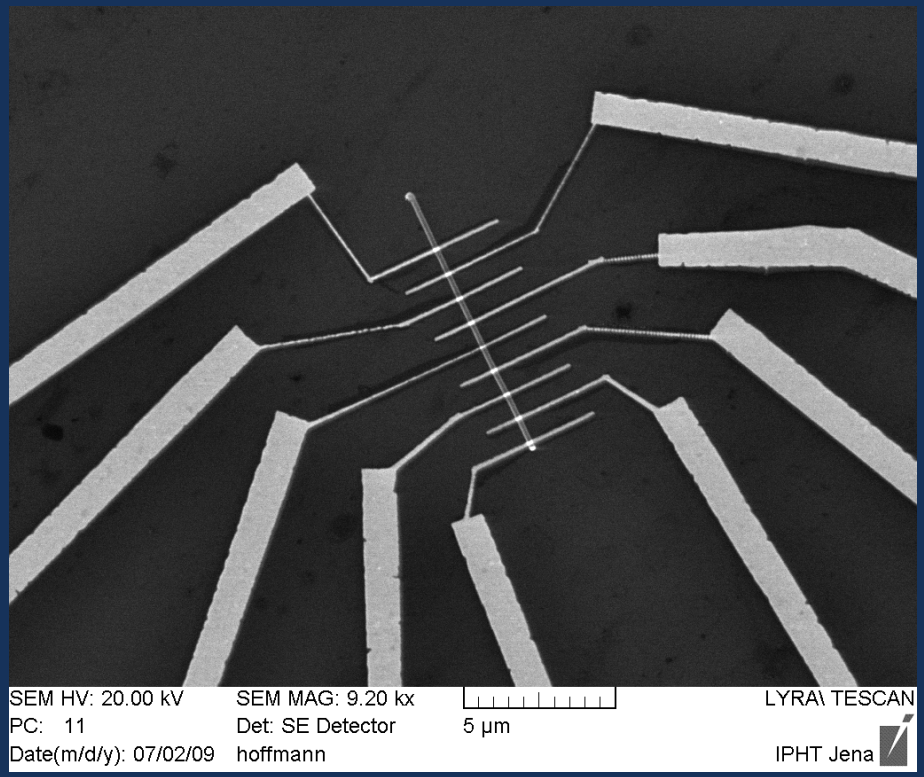
0.1-0.2 Ωcm / 8x10^{16}-2x10^{17} cm^{-3}





Resistivity of individually contacted Si-NRs

Si-NRs contacted by metal electrodes in a multi-terminal layout using e-beam lithography



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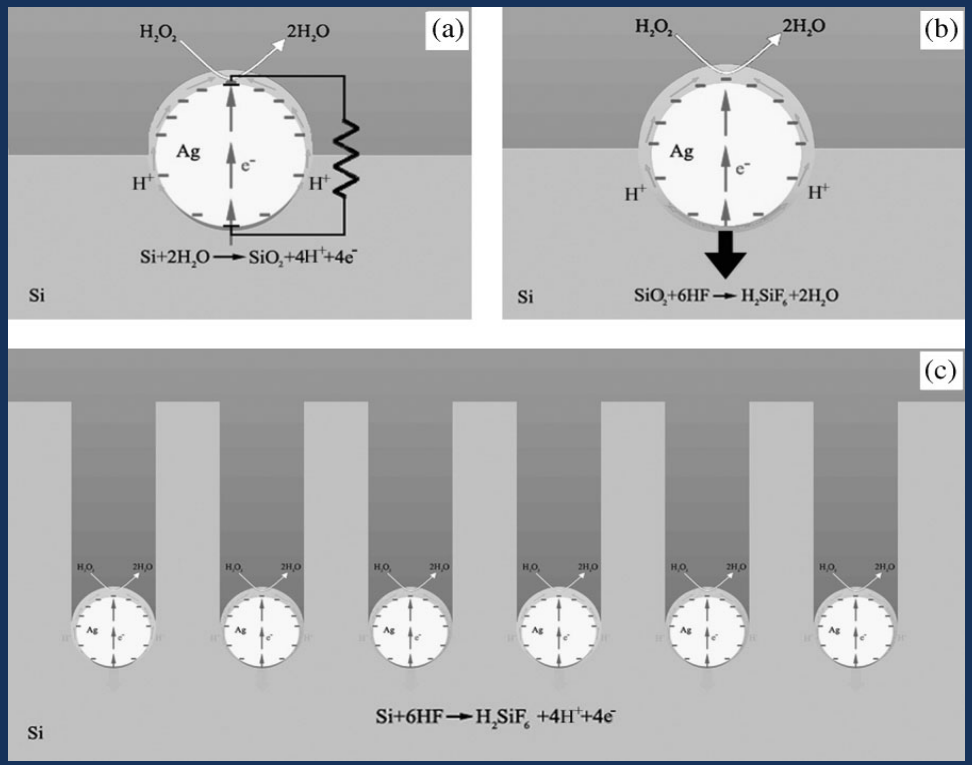
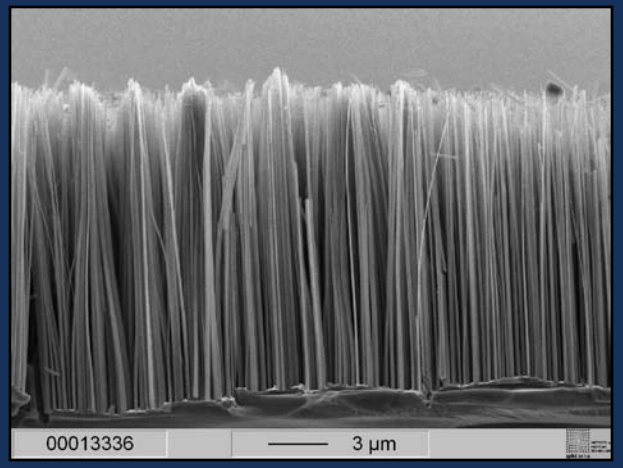
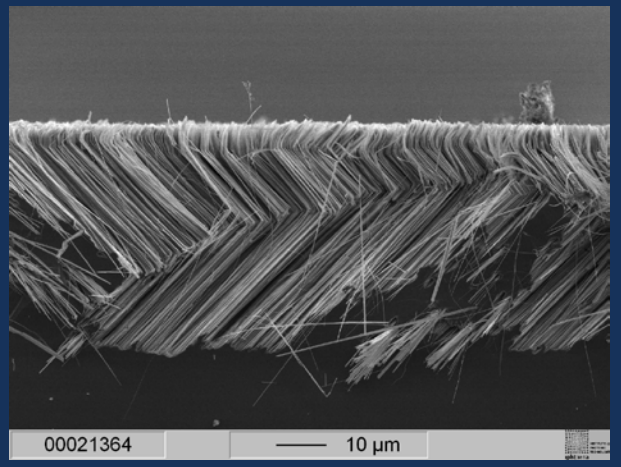
Wet chemical etching of Si

first step: $AgNO_3$ / HF

followed by: H_2O_2 / HF



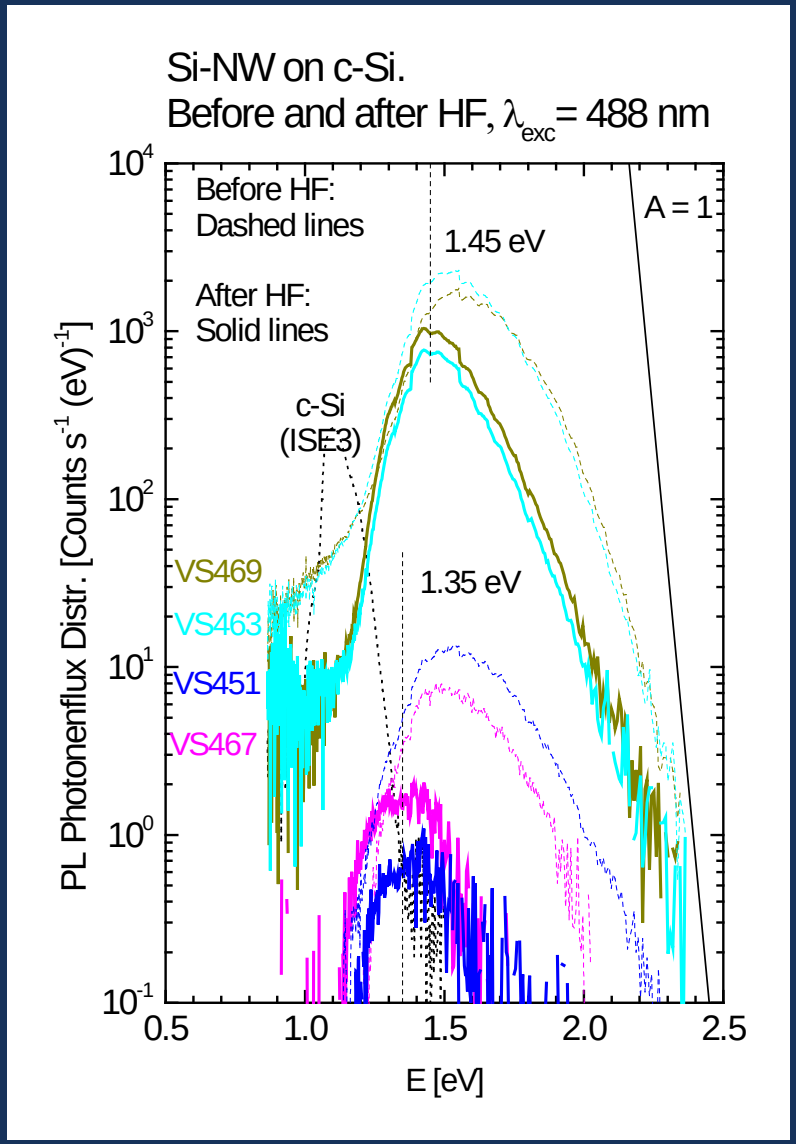




K. Peng, A. Lu, R. Zhang, S.-T. Lee, Adv. Funct. Mater. 18 (2008) 3026

Structural quality / Photoluminescence

TEM



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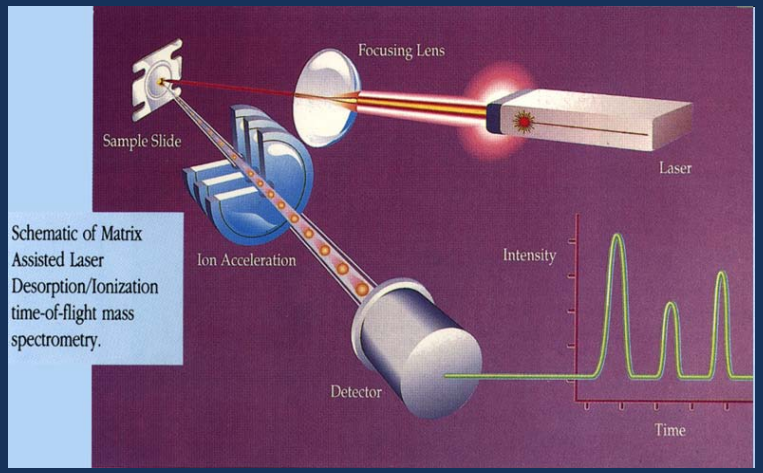
Matrix-free Laser Desorption / Ionization Mass Spectrometry

A. Muck, A. Svatoš (MPI for Chemical Ecology Jena)



matrix-assisted laser desorption/ ionization (MALDI):

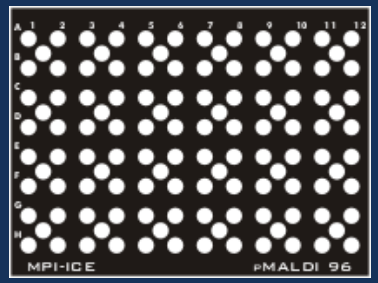
+ soft ionization, high sensitivity
- matrix background signals

laser desorption / ionization from SiNWs:

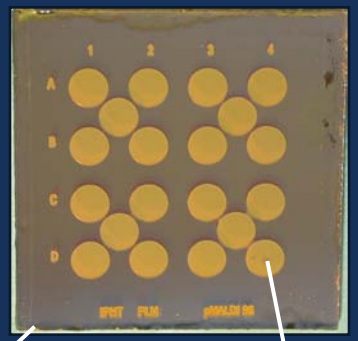
+ much lower laser energy to desorb molecules,
  absorption maximum of SiNWs near the wavelength of the laser (337 nm),
  heating of the silicon core within the insulating oxide sheath
+ high surface area, wick fluids

Preparation of MALDI chips

standard MALDI chip
(5,5 x 4,1 cm)



chip IPHT Jena
(2,54 x 2,54 cm)



substrate
(glass, Si)

1. lithographically patterned pits with Au for NW growth
2. tailored SiNW surface chemistry

A. Muck, T. Stelzner, U. Hübner, S. Christiansen, A. Svatoš,
Lithographically Patterned Silicon Nanowire Arrays for matrix free LDI-TOF/MS Analysis of Lipids,
Lab on a chip (2009) accepted

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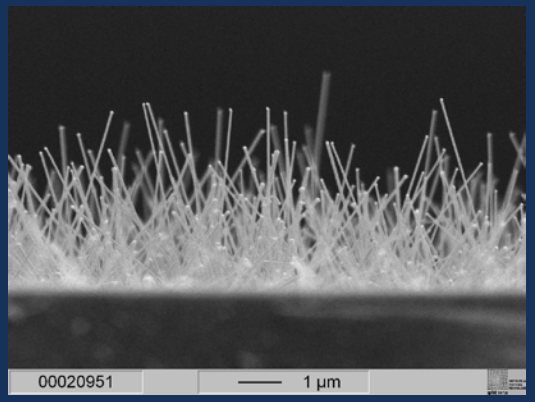
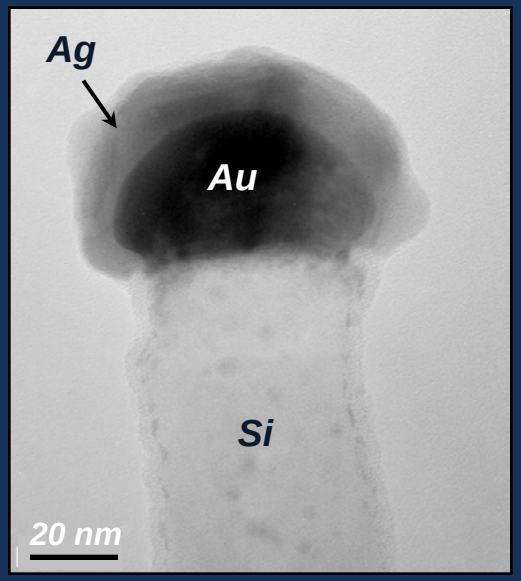
SiNW based SERS substrates

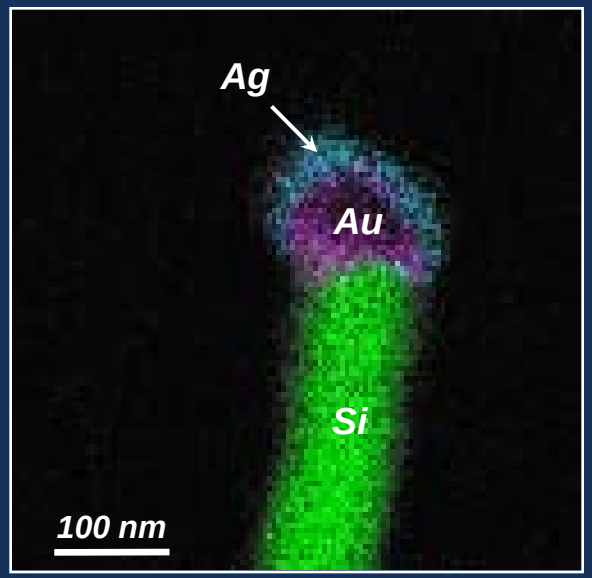
Autometallography:

- catalytic reduction of silver ions to metallic silver on the surfaces of gold particles in the presence of reducing molecules

Gold caps atop SiNWs

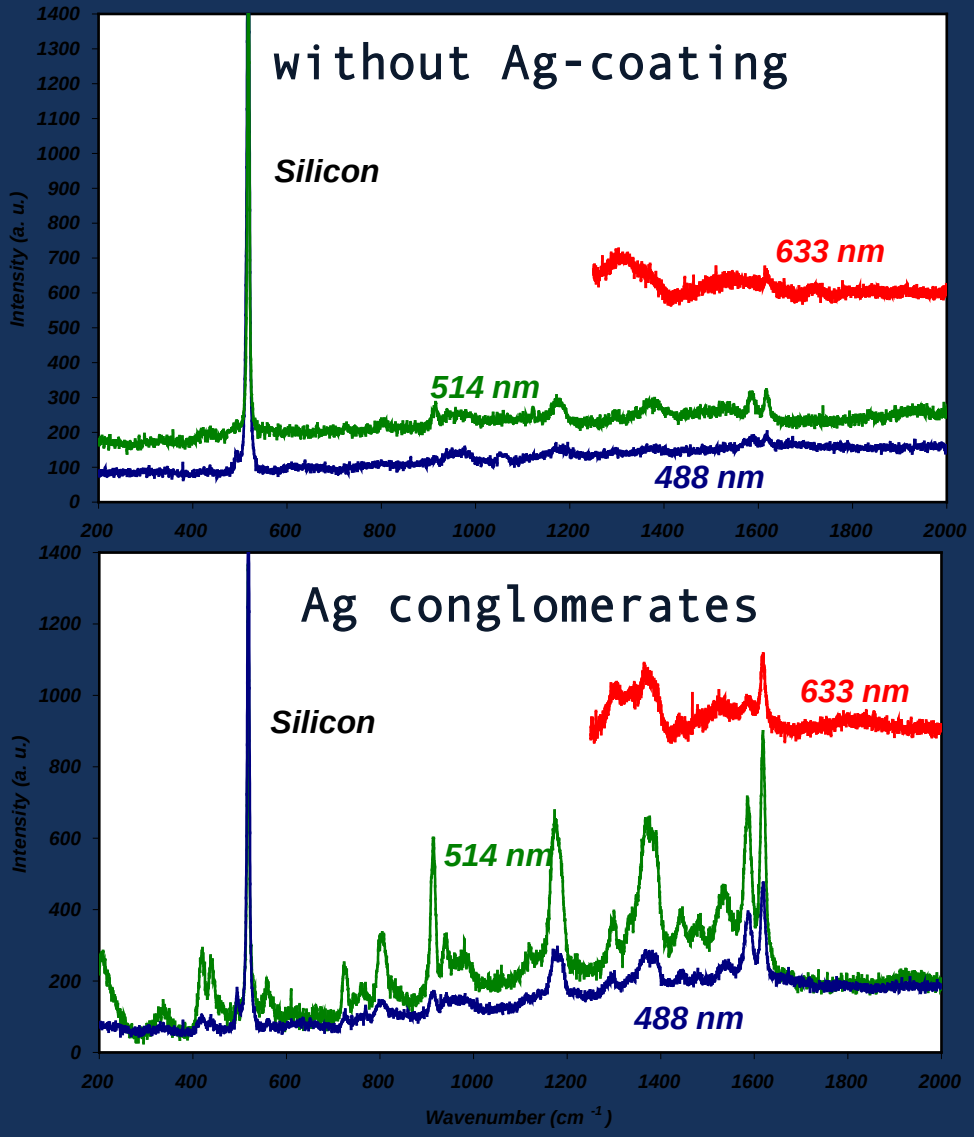




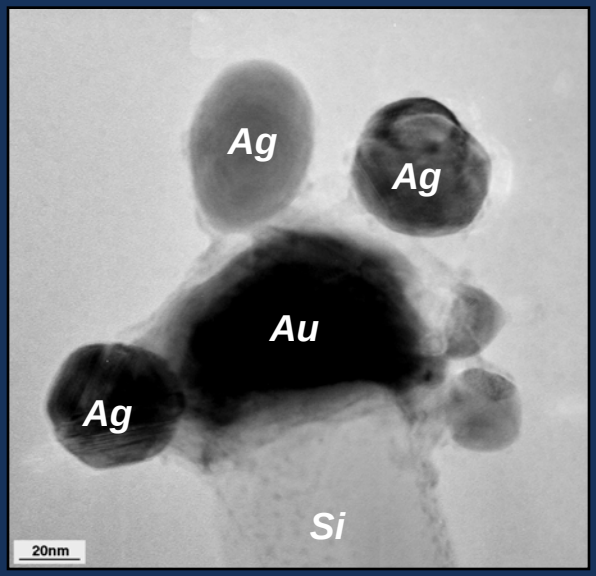


TEM

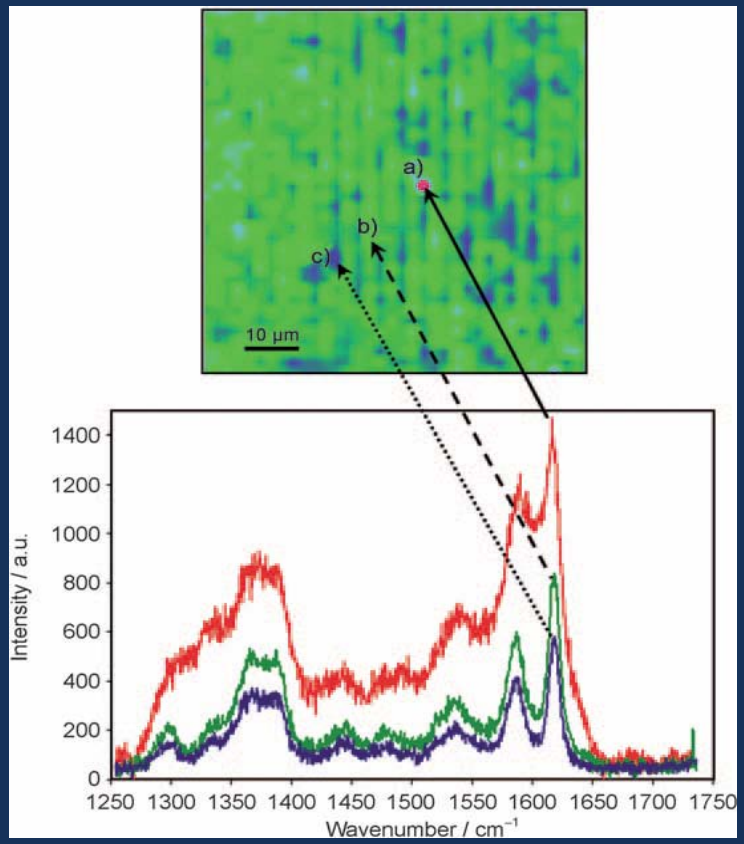
SERS spectra



crystal violet, ~1.7 x 10^3 W/cm^2



Mapping of SERS intensity



crystal violet,

HeNe laser (633 nm), ~160 µW,

3.5 µm spot size

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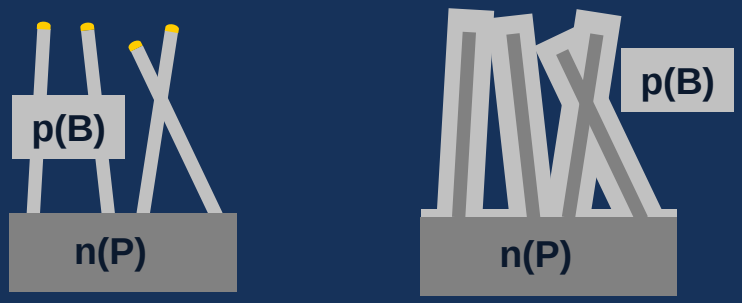
Solar cells - concepts

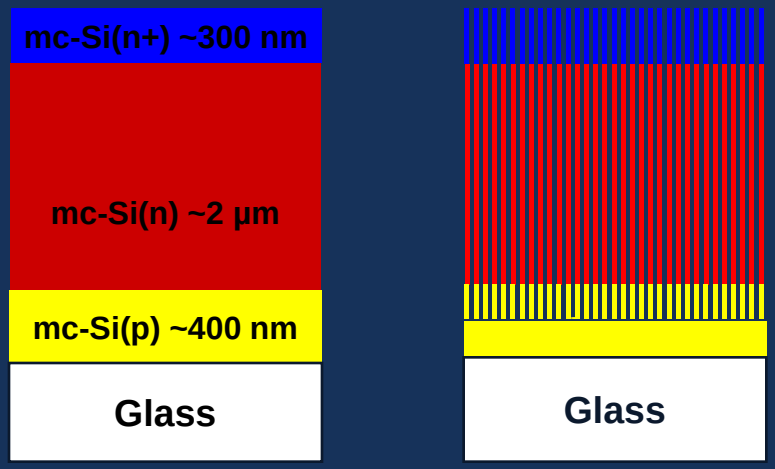
Thin film solar cells

- cheap substrates (glass, metal foils)
- Si nanorods with core-shell structure,
  decouple absorption from charge transport by lateral diffusion of minority carriers

Axial and radial p-n junction



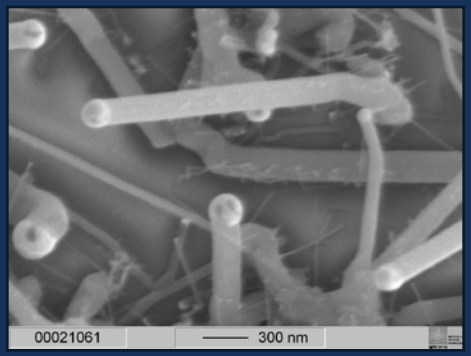
Wet chemical etching

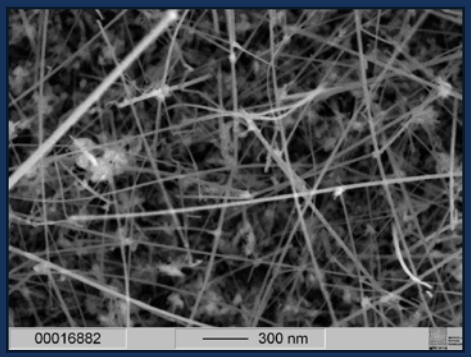


max. efficiency: 4.4%

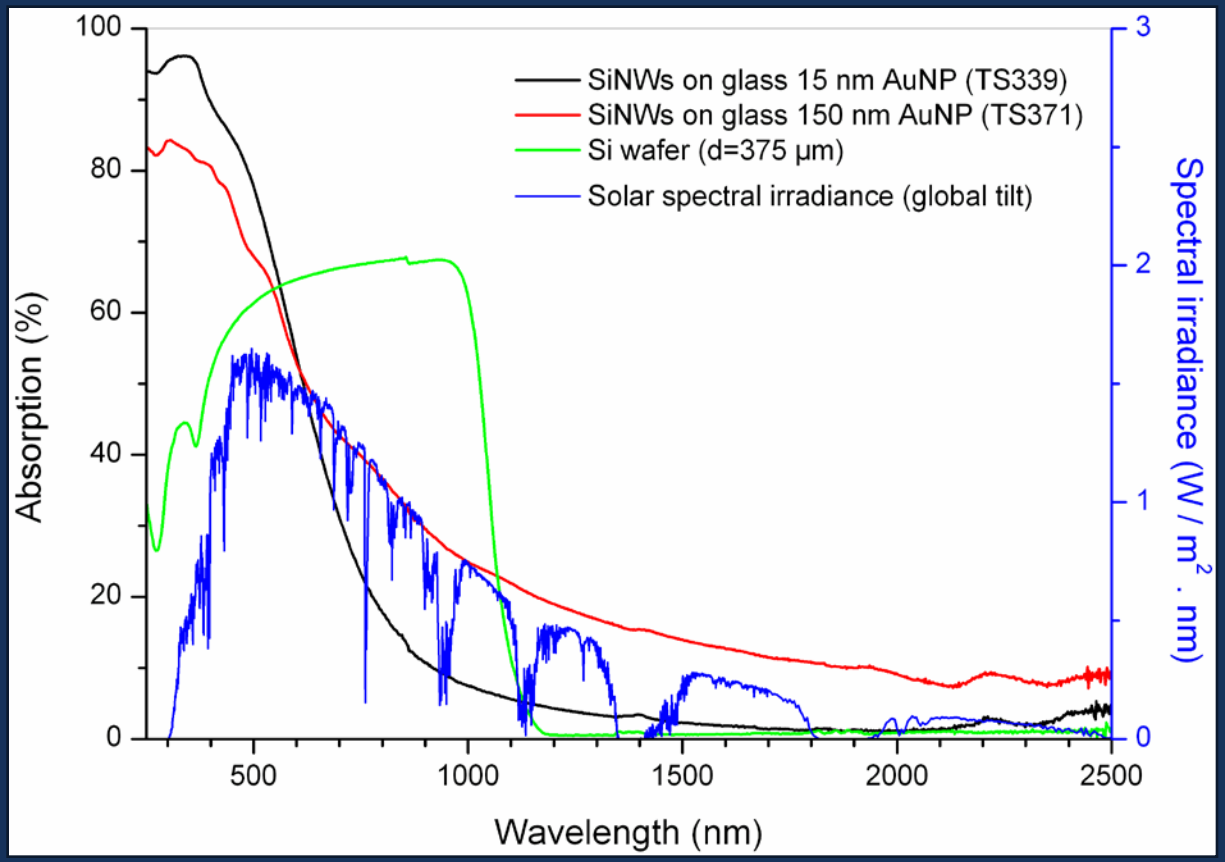
Optical properties

Reflection and transmission measured with an integrating sphere (A=1-R-T)





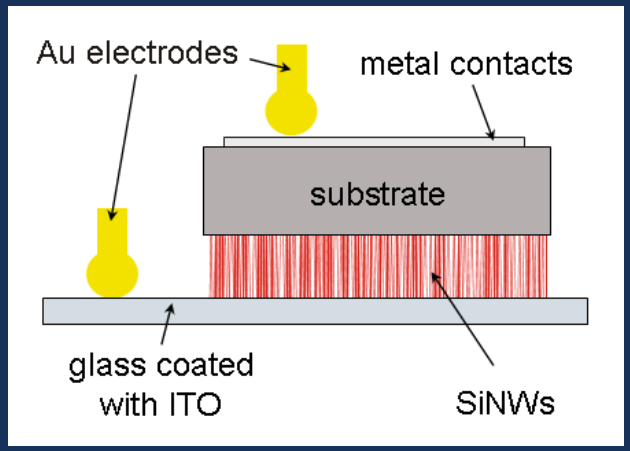
diameter, (length, pitch)

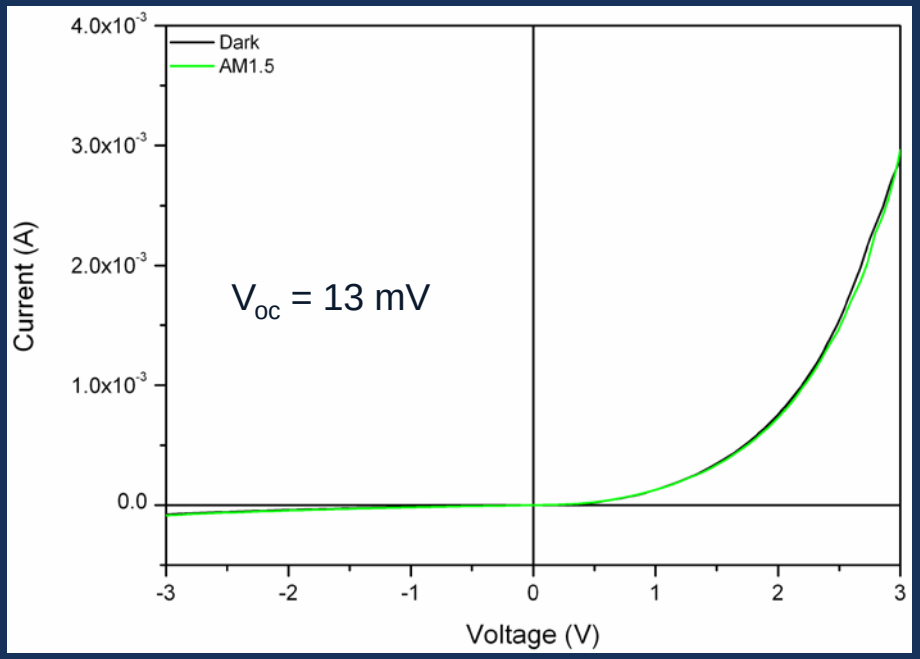


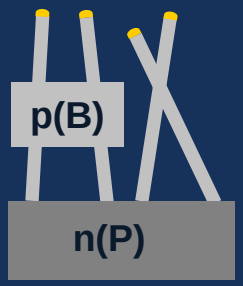
I-V characteristics

axial p-n junction

measurement setup







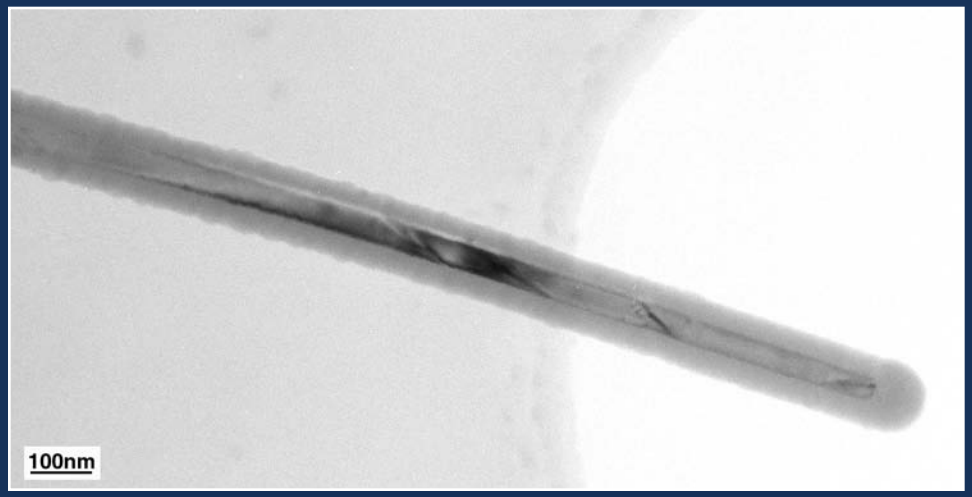
20 sccm Ar / 4 sccm SiH_4

0.05 sccm **B_2H_6** (2 % in He)

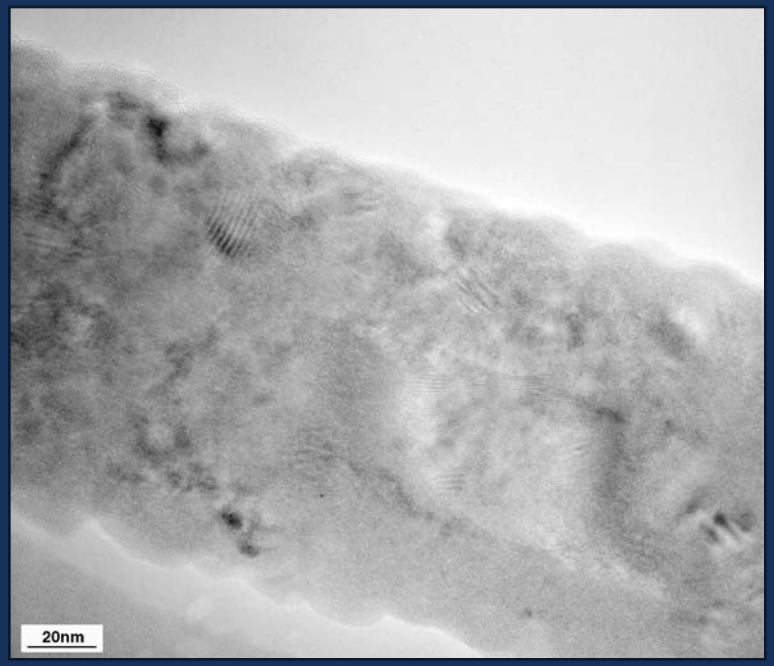
0.1-0.6 Ωcm / 1-8 x 10^{16} cm^{-3}

Core-shell p-n junction structures

a-Si with PECVD



600° C, 6 h



Current work

EU project ROD_SOL

- elaborate cell concepts based on simulations

- avoid the use of Au as a catalyst

- single-crystalline core-shell p-n junction structures

- passivation and contacting of SiNWs

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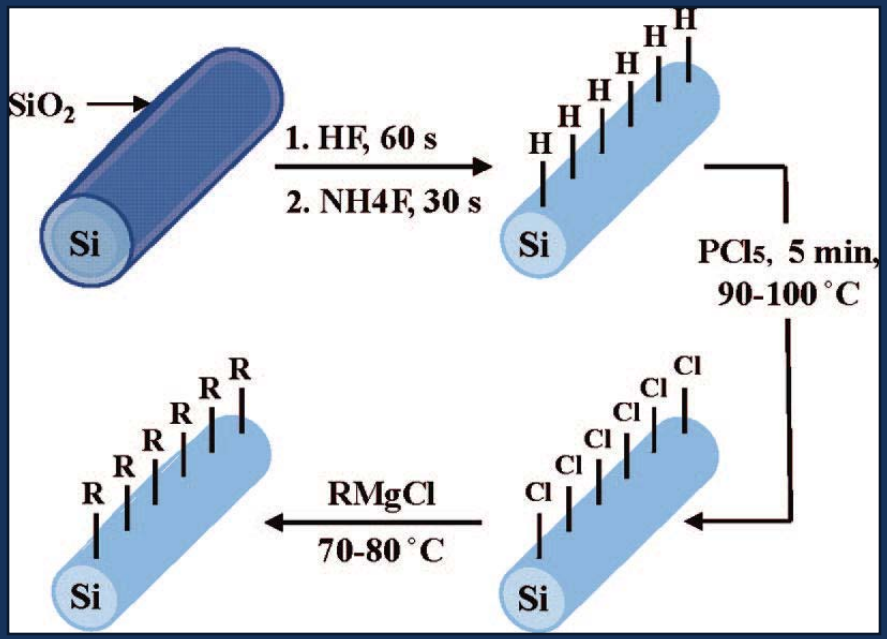
SiNW field-effect transistors as sensors

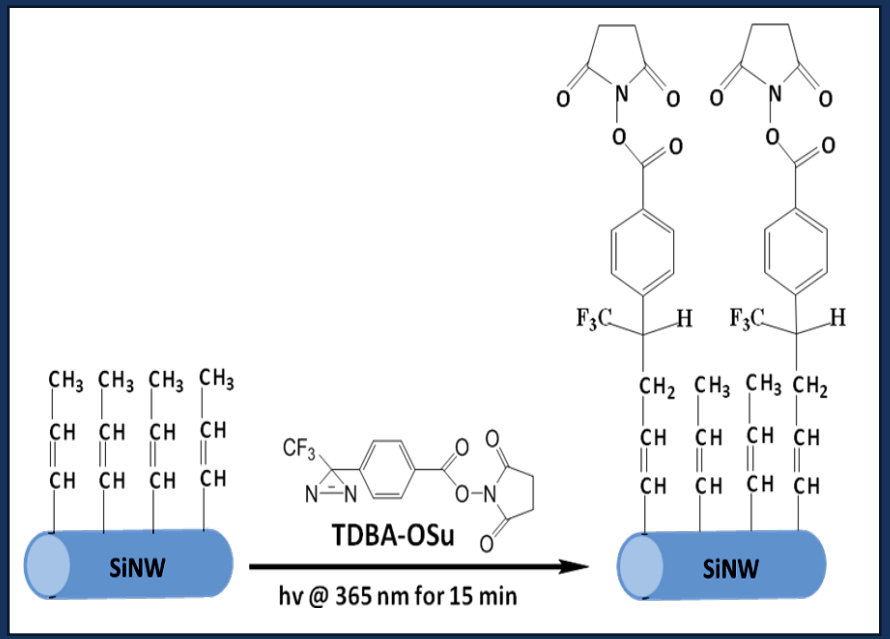
- SiNWs: high surface to volume ratio, high carrier mobility, controlled functionalization
- sensors: ‚lock-and-key' design
  cross-reactive sensors in conjunction with pattern recognition

Chemical modification of SiNW surfaces

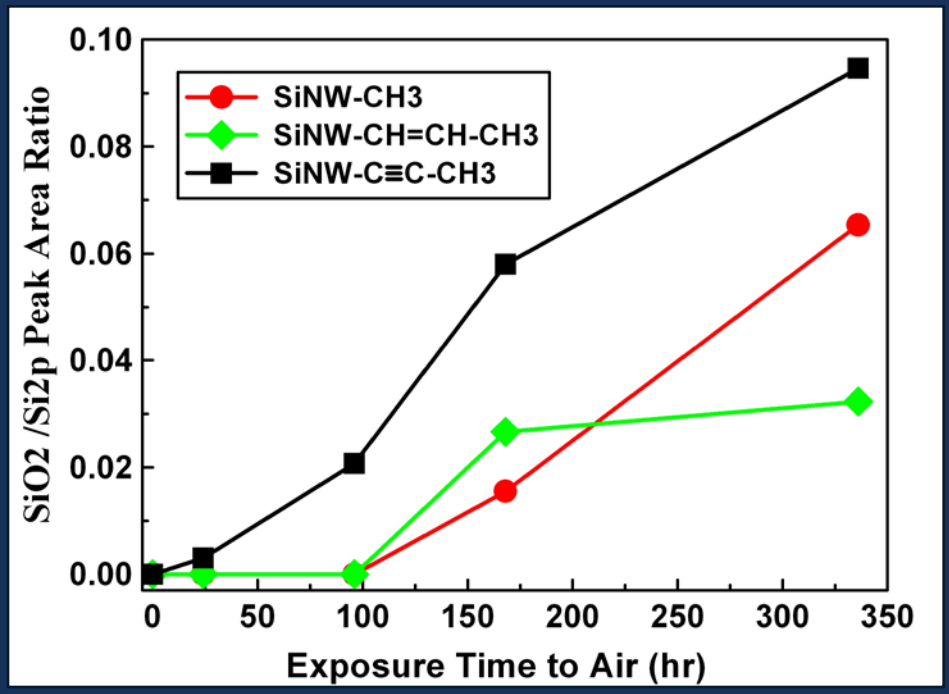
M.Y. Bashouti, O. Assad, S.R. Puniredd, H. Haick (Technion-Israel Institute of Technology)

Functionalization





Stability against oxidation



- all groups give nearly full coverage
- propenyl functionality:
  - combination of stability and subsequent covalent functionalization,

Current work

- understanding of the signal transduction mechanism for various volatile organic compounds

- improved sensitivity in the presence of e.g. humidity

- develop sensor arrays to detect lung cancer

Acknowledgments

IPHT Jena:

S. Christiansen, A. Berger, M. Becker, V. Sivakov, F. Voigt, D. Lerose,

B. Hoffmann, U. Hübner, A. Dellith, H. Köbe, A. Steinbrück

Thanks to:

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European Commission (ROD_SOL, FP7-NMP-227497)

Thank you for your attention!