ipht jena

Программа Фонда Дмитрия Зимина «Династия» „Краткосрочные визиты иностранных ученых в Россию“

Novel Discovery of Silicon

Династия

Vladimir Sivakov

Leibniz Institute of Photonic Technology,
Jena/Germany

Mitglied der
Leibniz-Gemeinschaft

“Semiconductor Nanostructures” Group at Leibniz IPHT e. V. Jena

Vladimir Sivakov

vladimir.sivakov@ipht-jena.de

Mitglied der

Leibniz-Gemeinschaft

Department Facilities

Chemical Vapor Deposition: 2D a-Si:H; 2D mc-Si; 1D Si; 1D Ge; 1D SnO_2; 1D VO_x; 1D $Fe_3O_{4;}$ Au, Ag

Atomic Layer Deposition: ZnO, Al_2O_3; Al:ZnO; TiO_2; $SiO_{2;}$ HfO2; ZrO2

Physical Vapor Deposition: a-Si, mc-Si, Ti, Al, Au, Ag, Pd, Cr

Wet @Dry Etching and Surface Modification@Functionalization: RIE

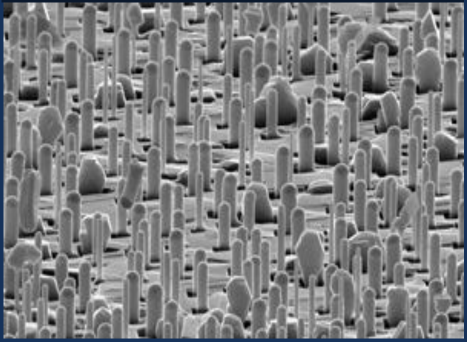
Focused Electron Beam Technology: FEI Helios; Tescan Lyra

Surface Structuring: Photolithography, EB Lithography, PS

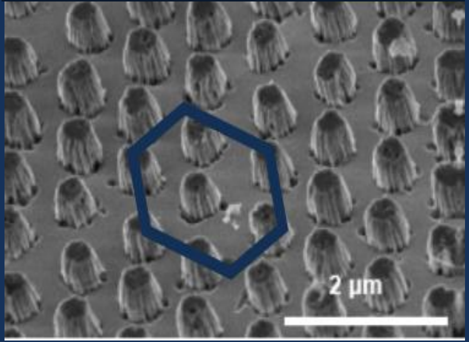
Characterization: SEM, AFM, PL, CL, µ-PL, XRD, Ellipsometry, EBSD, EBIC, I-V, C-V, Raman, CARS SER(S)S, µ-Raman

Material Facilities

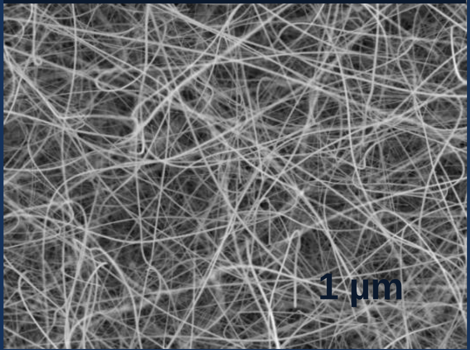
Bottom-up SiNWs



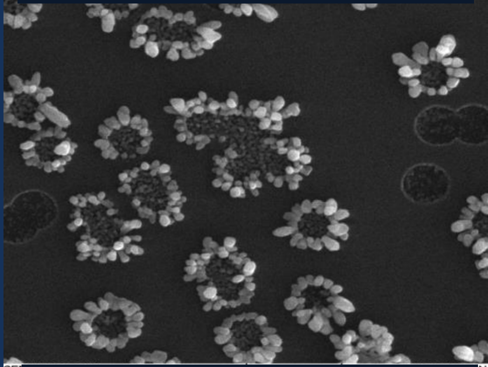
Top-down SiNWs Array



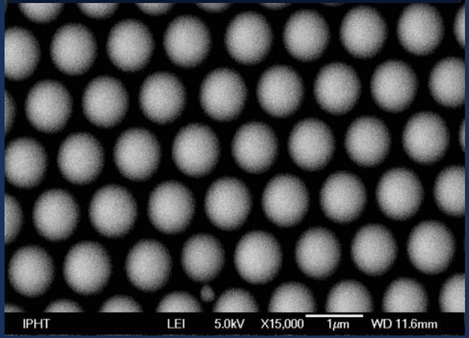
SnO_2 Nanowires Carpet



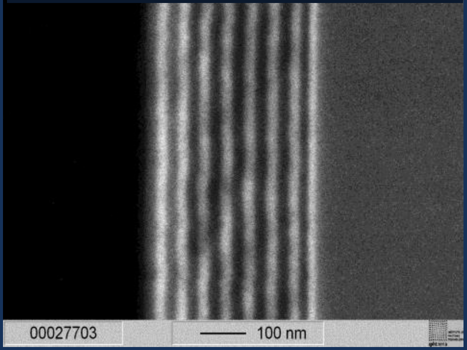
Silver „Sun-Flowers“



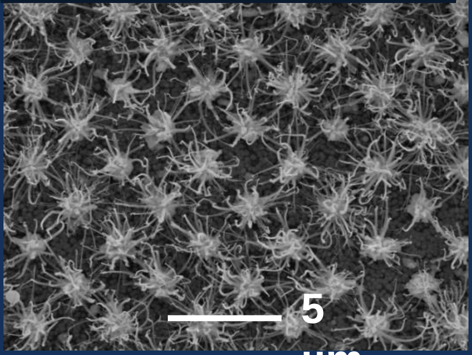
Au Array



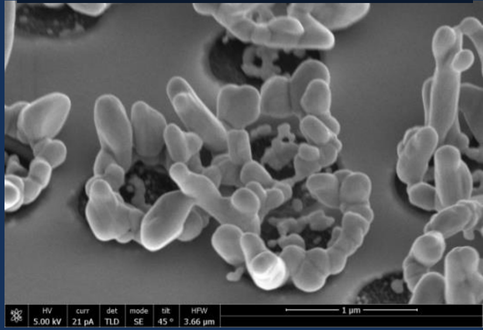
Al_2O_3-ZnO ALD heterostructure



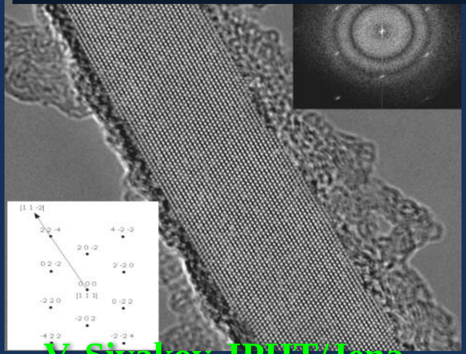
Bottom-up GeNWs



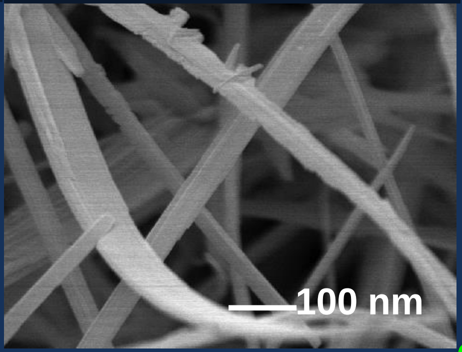
Silver for SERS



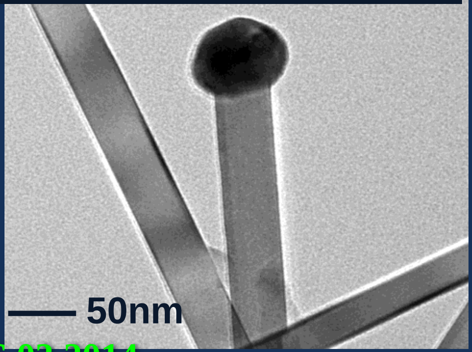
Single Ge Nanowire



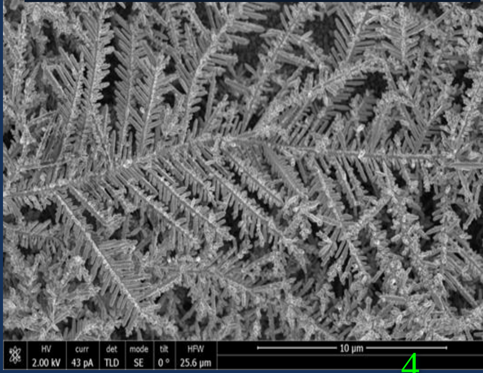
VO_x Nanobelts



SnO_2 Nanowire



Silver Dendrites



Application

Energy

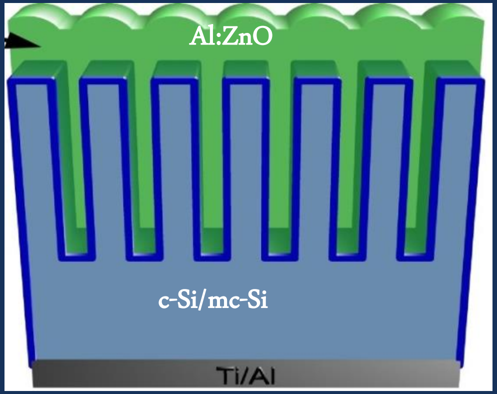
Third generation photovoltaic and fuel cell

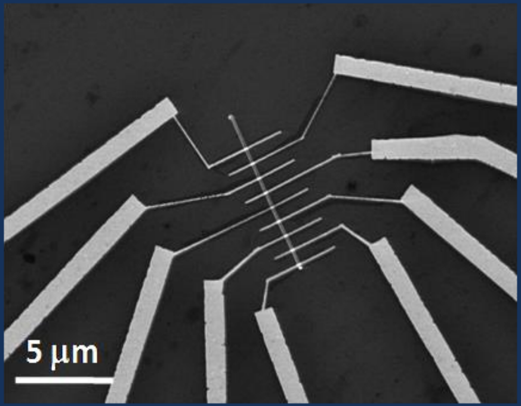
Sensoric

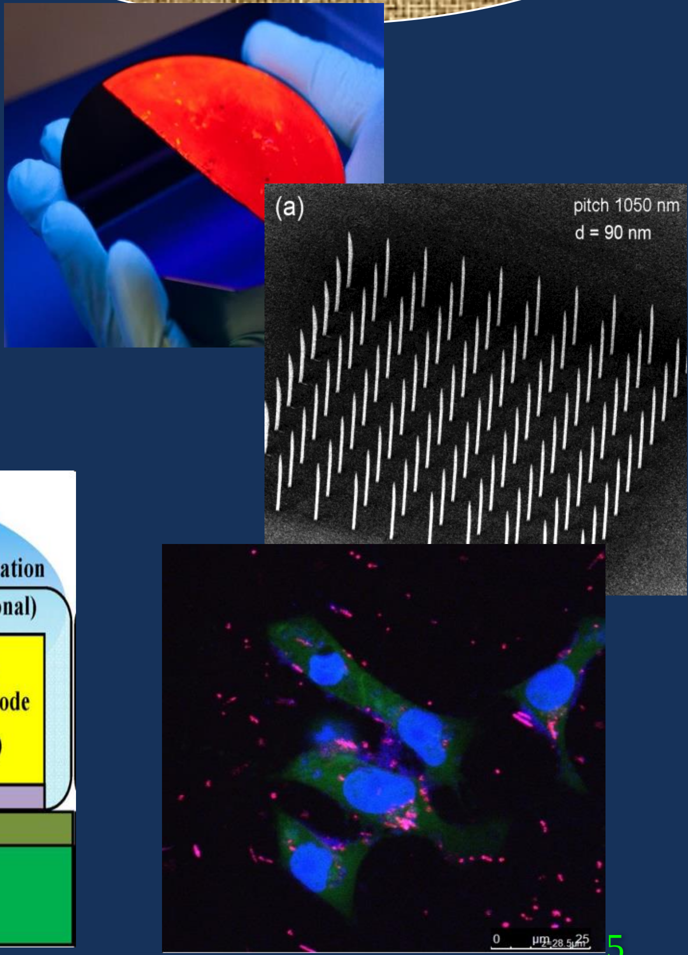
Life Science, Gas, Civil Security

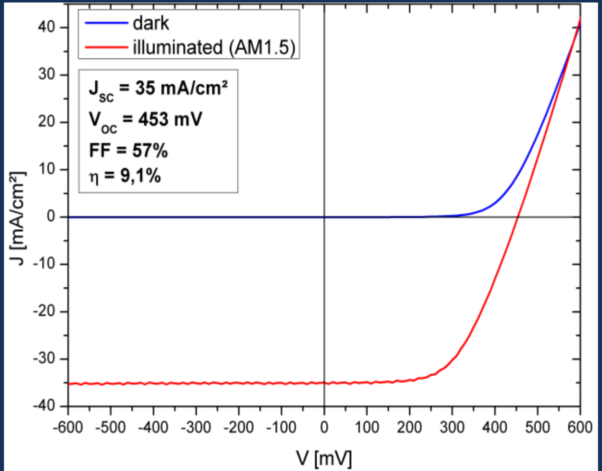
(Bio)-Plasmonic, (Bio)-Photonic

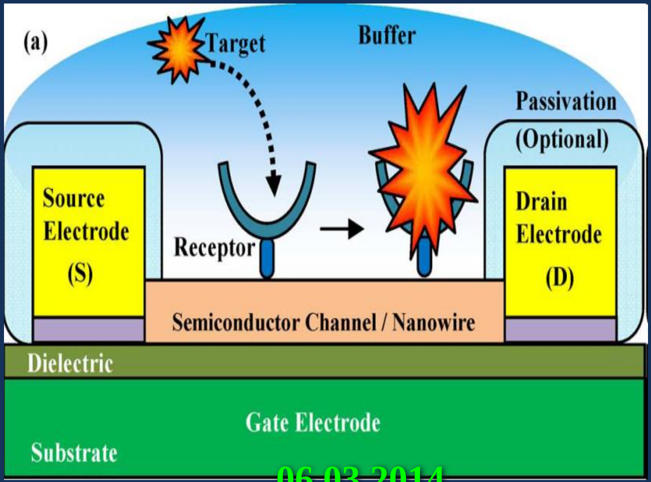
SERS/TERS, Theranostics









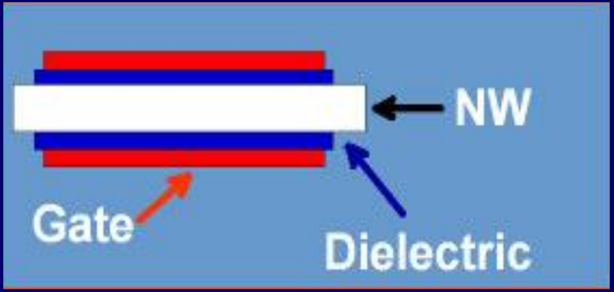


Outline

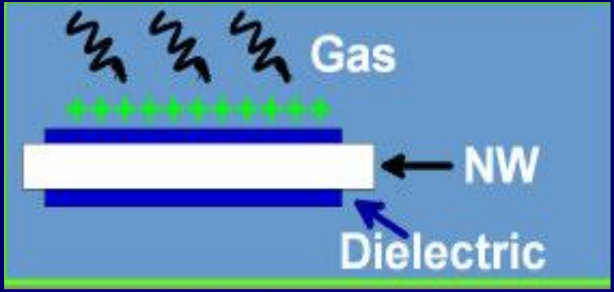
1. Top-down Technology
2. Bottom-up Technology
3. Top-down vs Bottom-up
4. NWs a Key for Novel Devices

Why Semiconductor Nanowires?

Applications of Nanowires

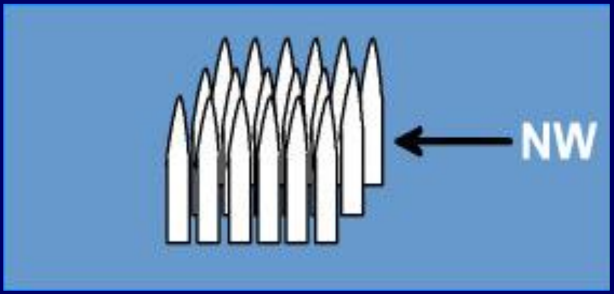


Micro-/Nanoelectronics (‚Next-generation‘ CMOS)

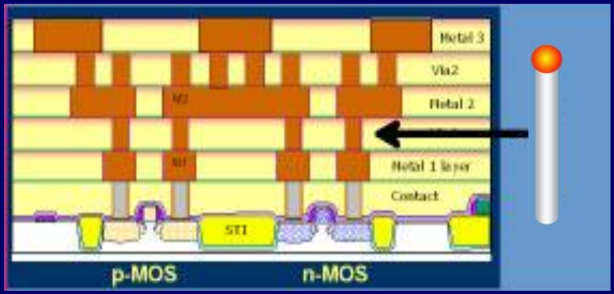


Sensors (Life sciences, Gas, Bio-Med.)

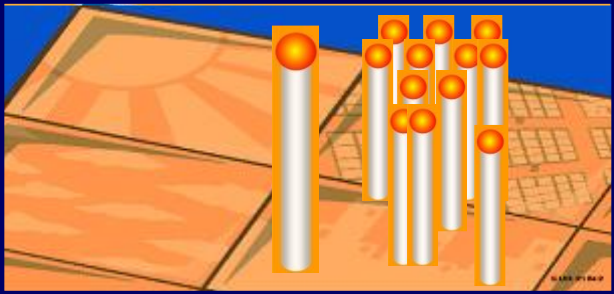
Optoelectronic/Photonic (LED, Laser)



Fieldemitter



Interconnects

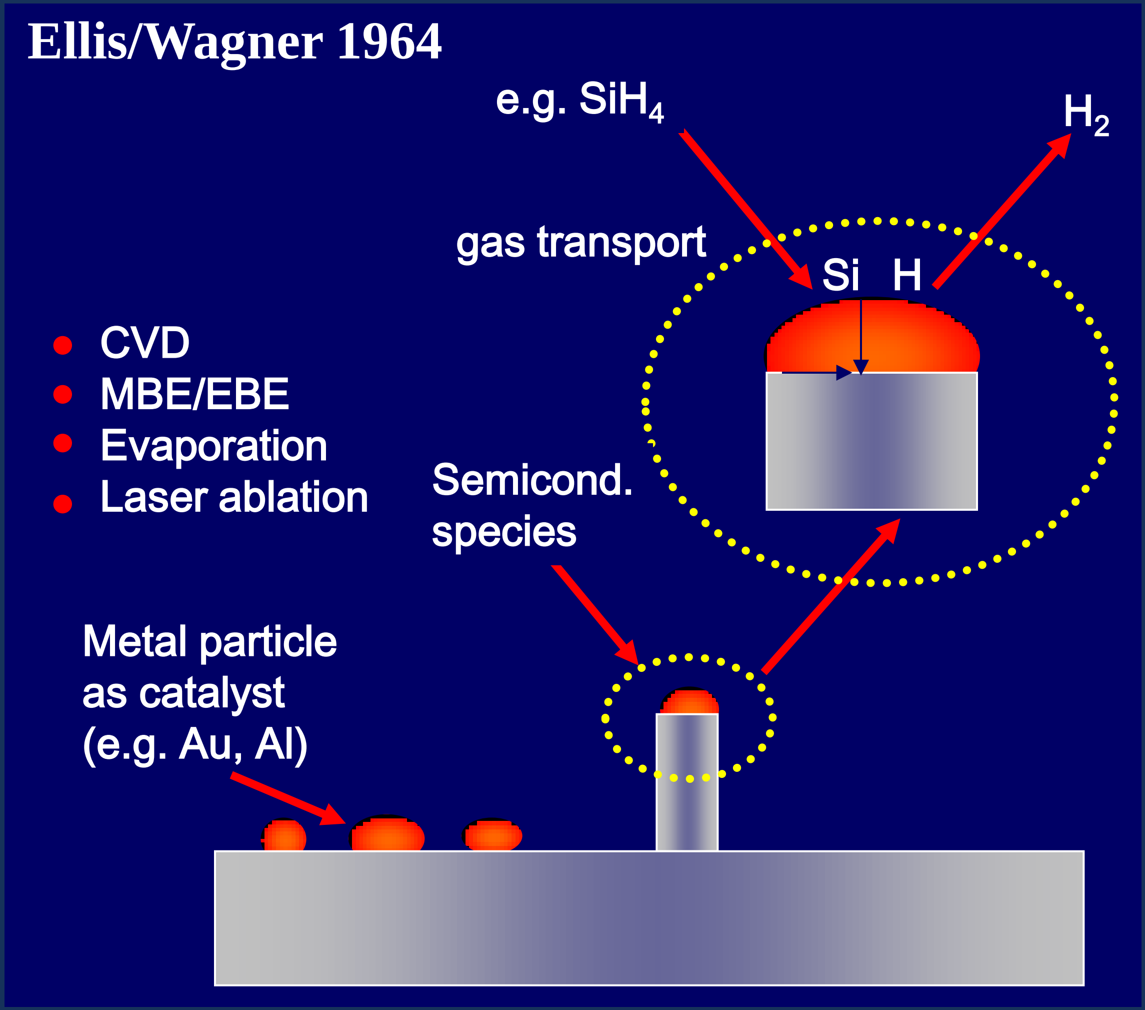


Photovoltaic/Energy

How to grow SiNWs?

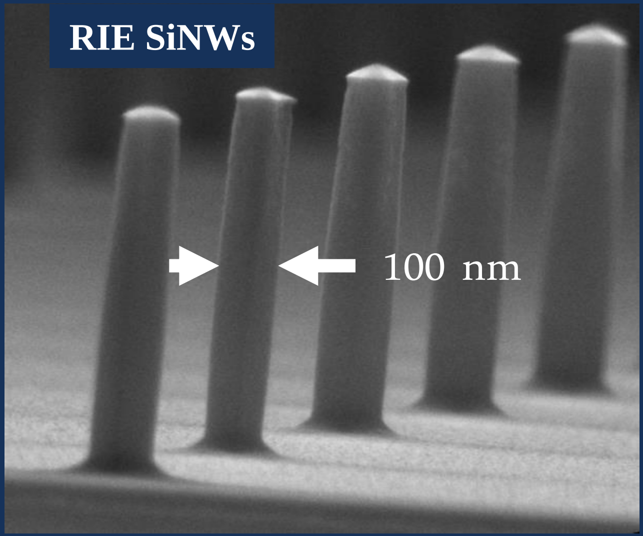
SiNWs Growth

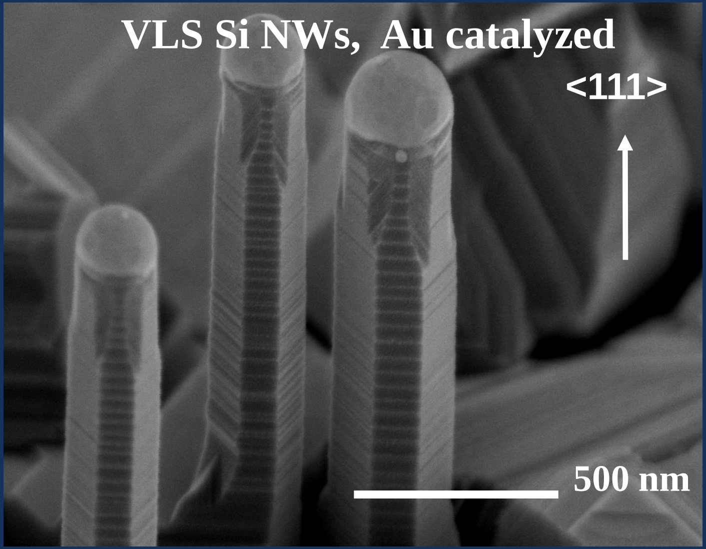
„Bottom-up“@„Top-down“ Technologies



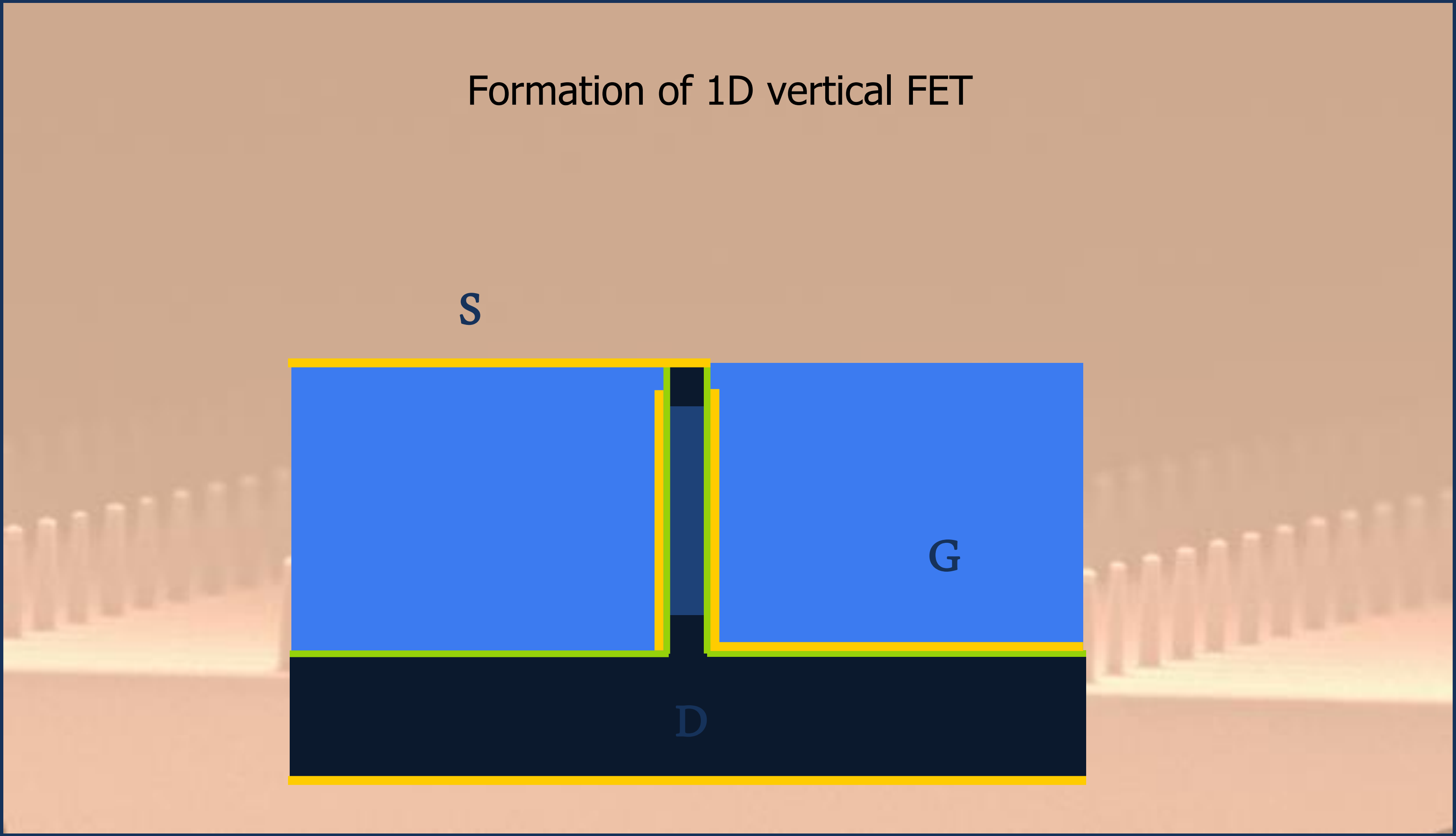
Ellis/Wagner 1964

- CVD
- MBE/EBE
- Evaporation
- Laser ablation





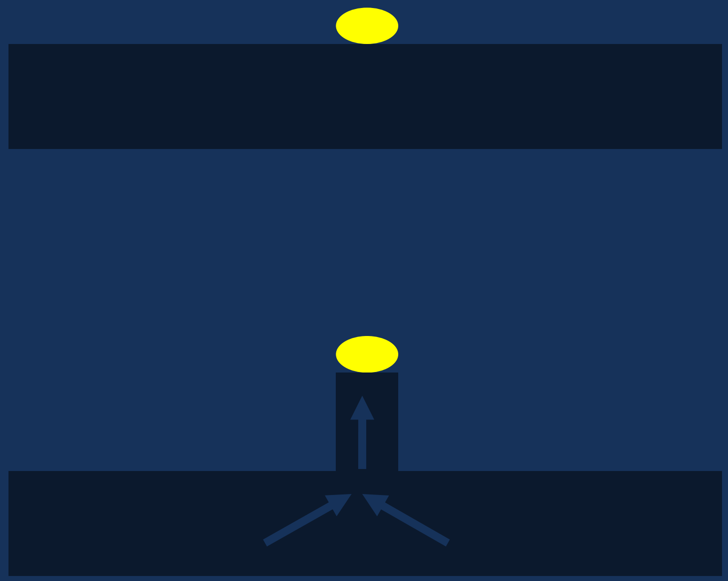
SiNWs Growth


Formation of 1D vertical FET

SiNWs Growth

Bottom-up

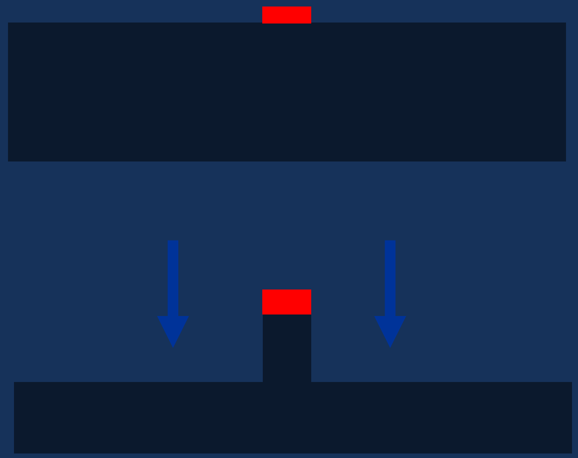
Catalyst



SLS, VLS

Top-down

Photolack



Lithography, Reactive Ion Etching

SiNWs Growth

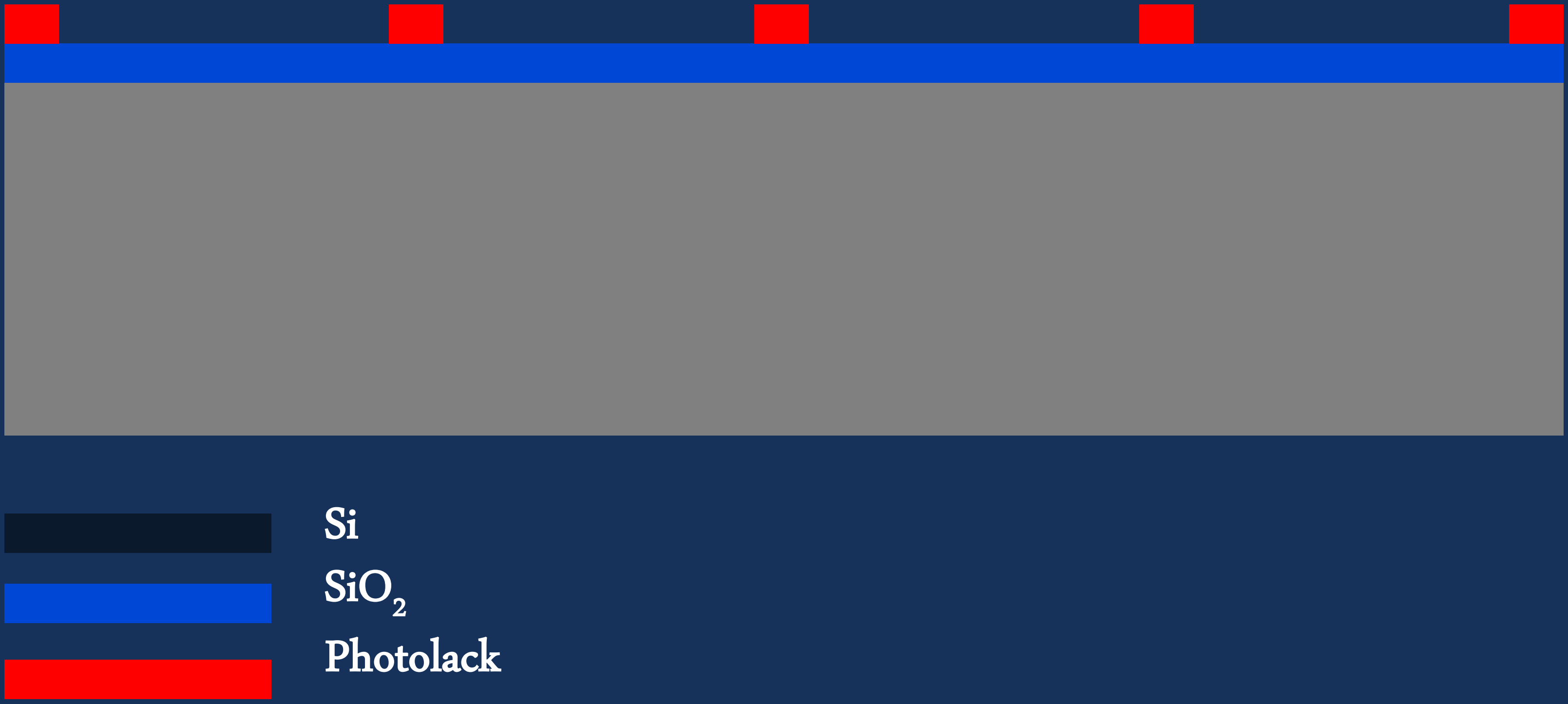
Oxidized Silicon Wafer

■ Si

🟦 SiO_2

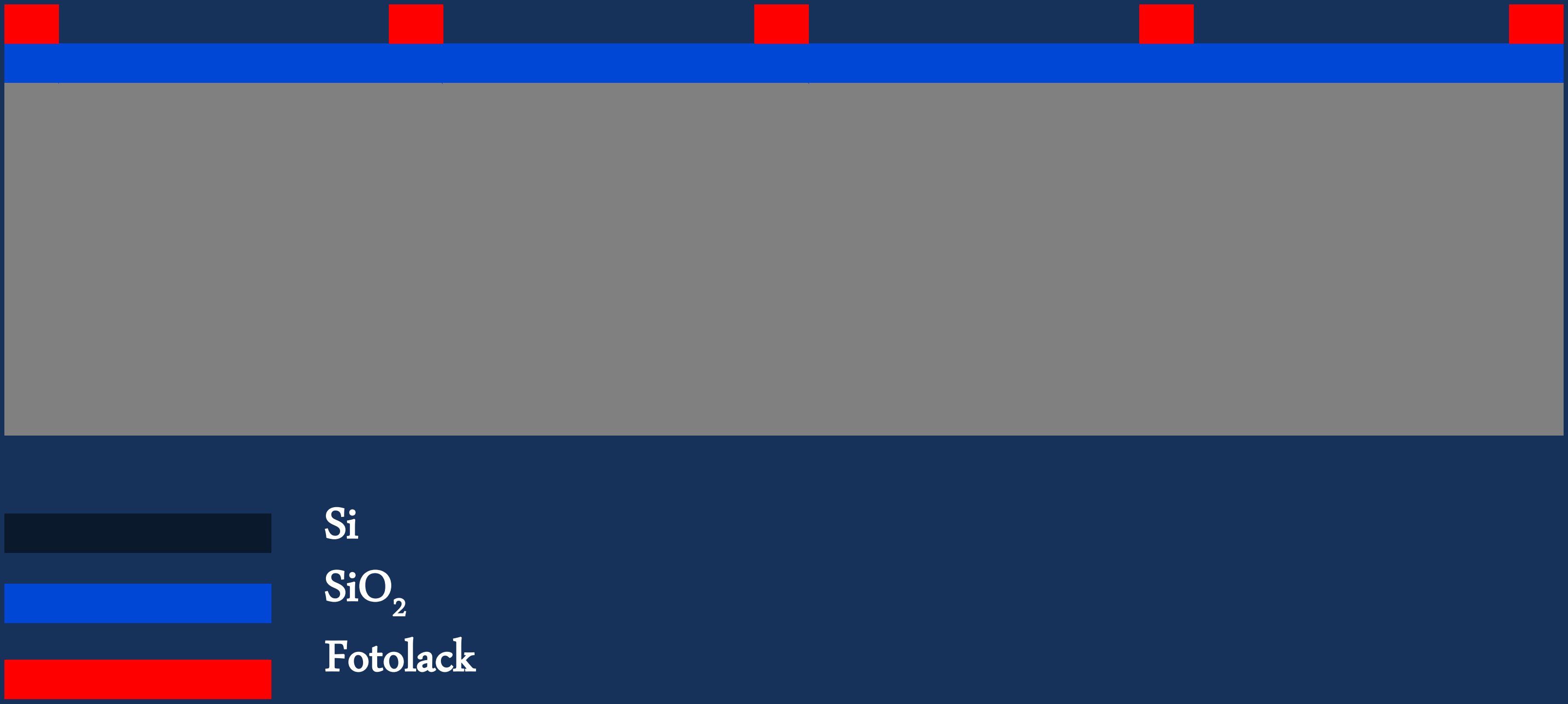
SiNWs Growth

Lithography



SiNWs Growth

Wet Chemical Etching



Si

SiO_2

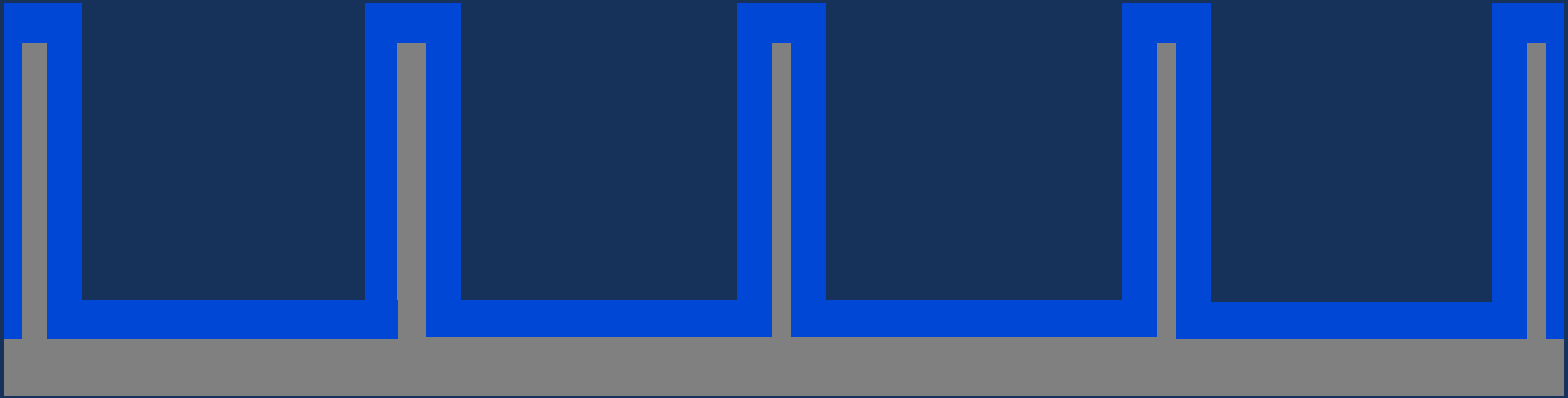
Fotolack

SiNWs Growth

Reactive Ion Etching

SiNWs Growth

Thermal Treatment



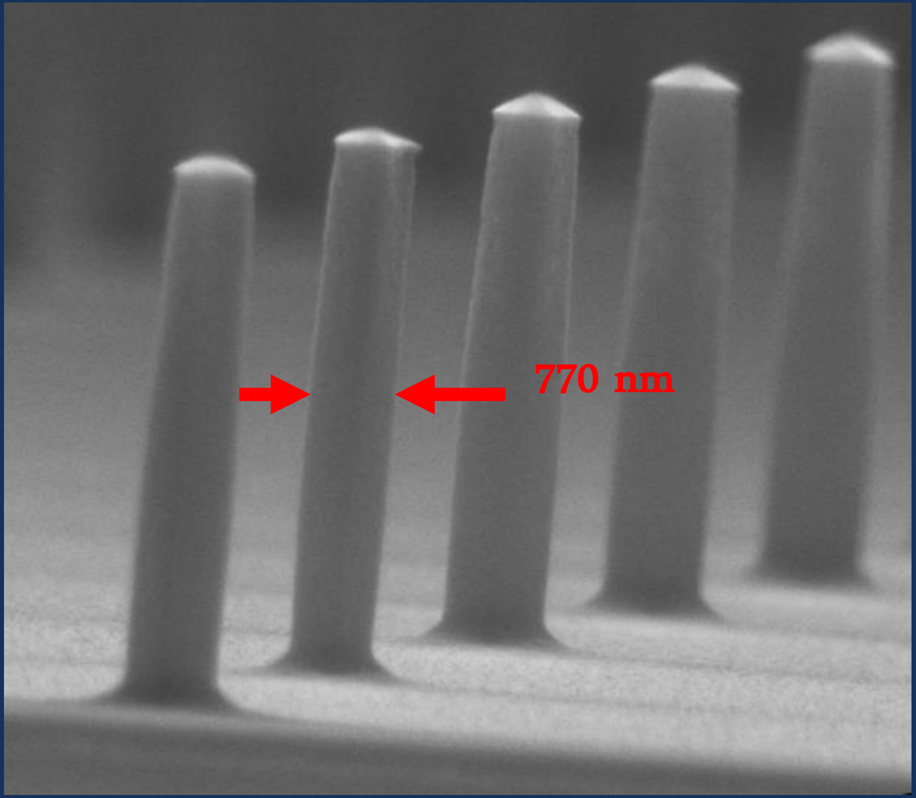
⬛ Si

🟦 SiO_2

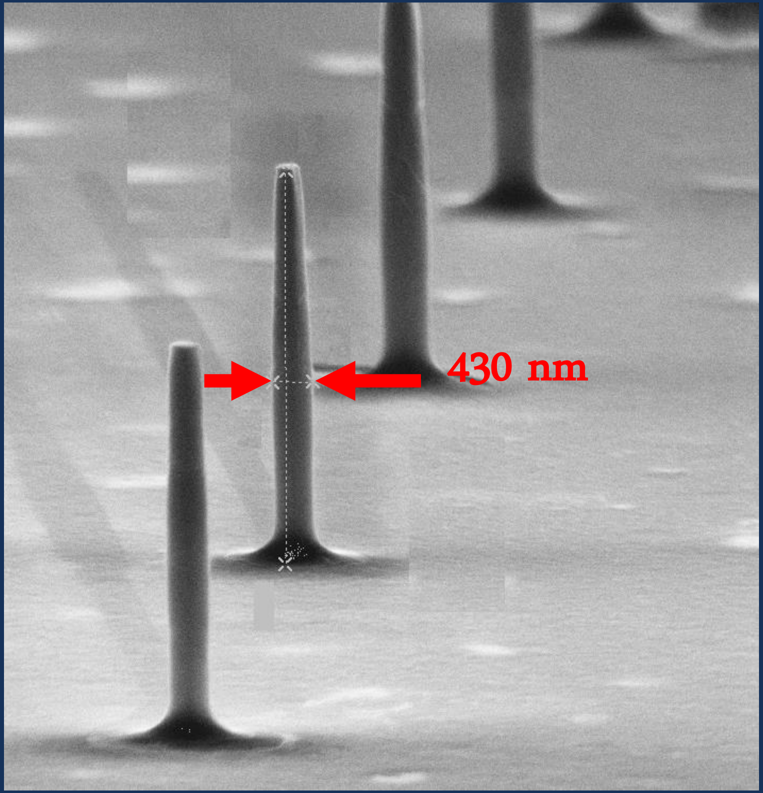
SiNWs Growth

Wet Chemical Etching

SiNWs Growth

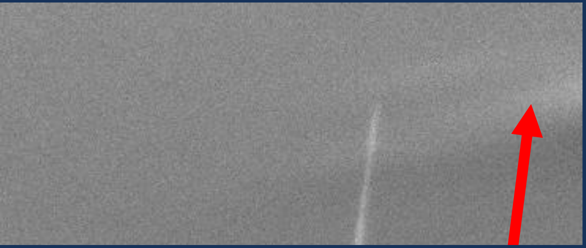


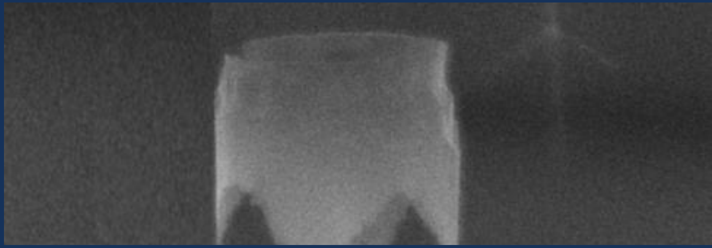
After RIE



1 x Oxidation

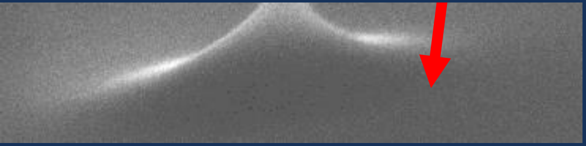
SiNWs Growth





Disadvantages of Top-Down Process:

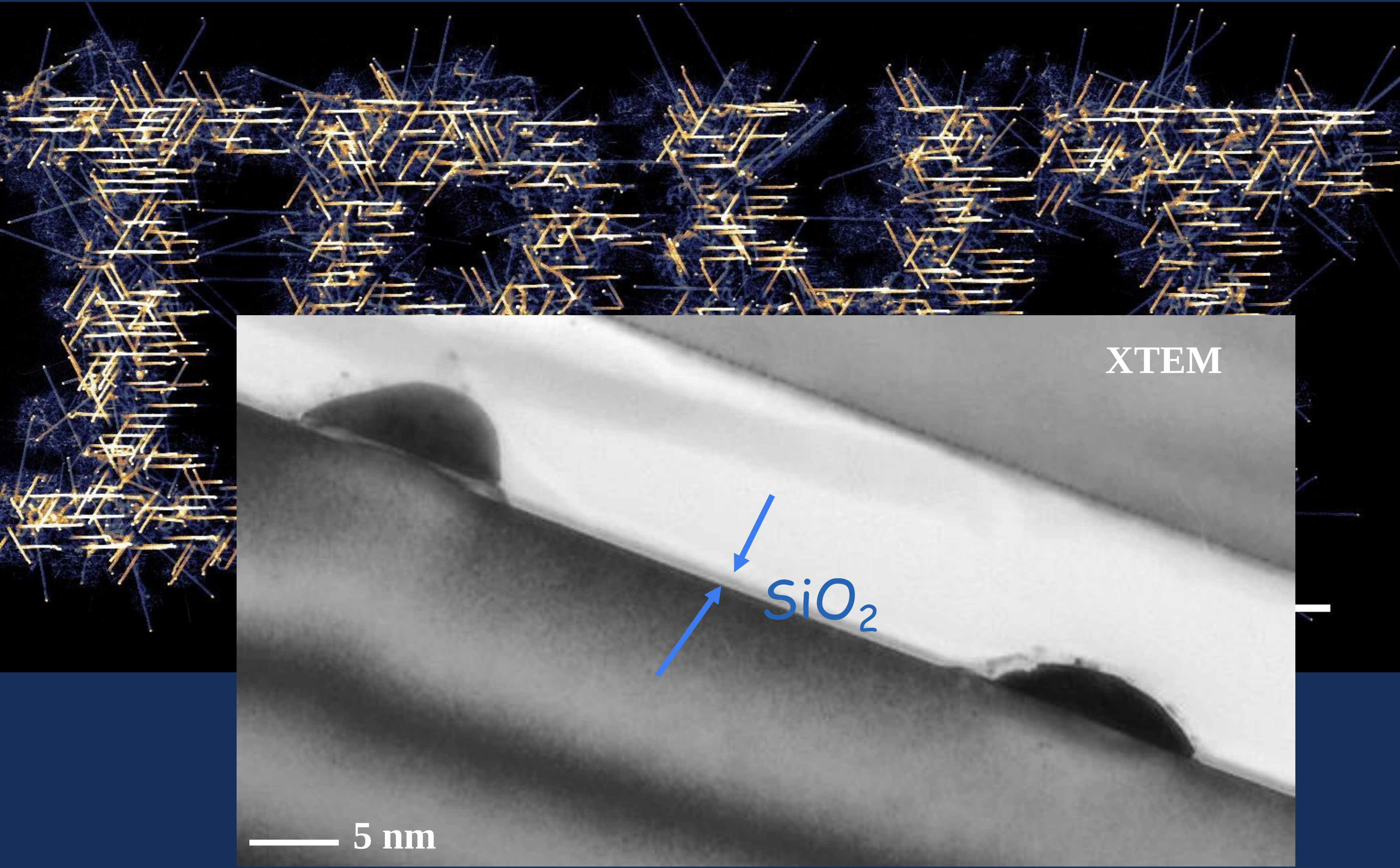
(i) Many steps process
(ii) Expensive
(iii) Min NWs diameter only ca. 70 nm
(iv) Non-ideal geometry and high roughness of NWs sidewalls



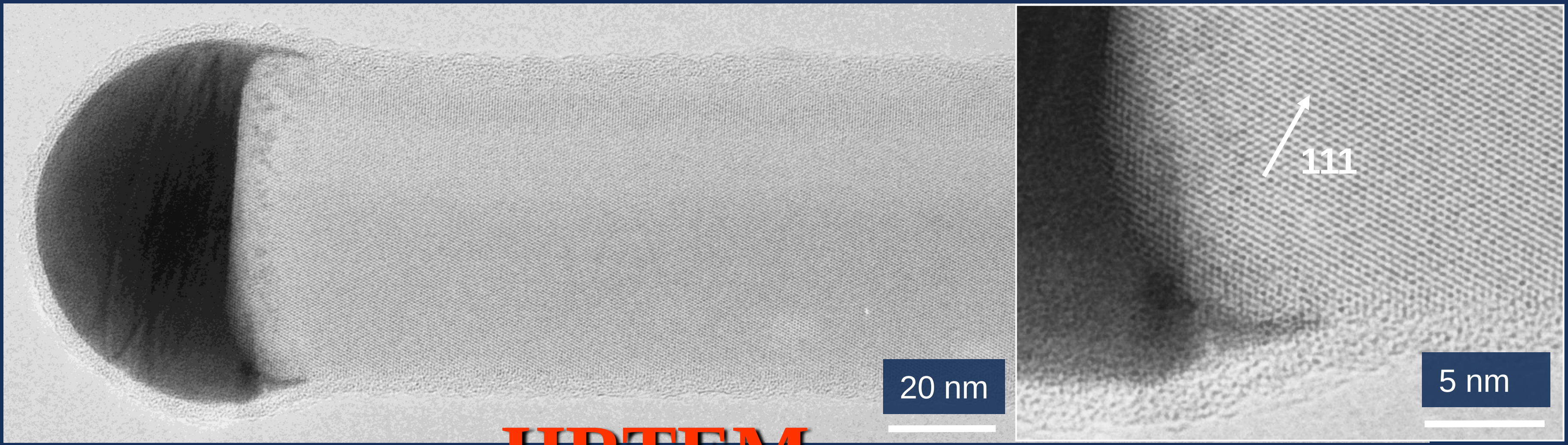
Bottom-up: CVD

Chemical Vapor Deposition

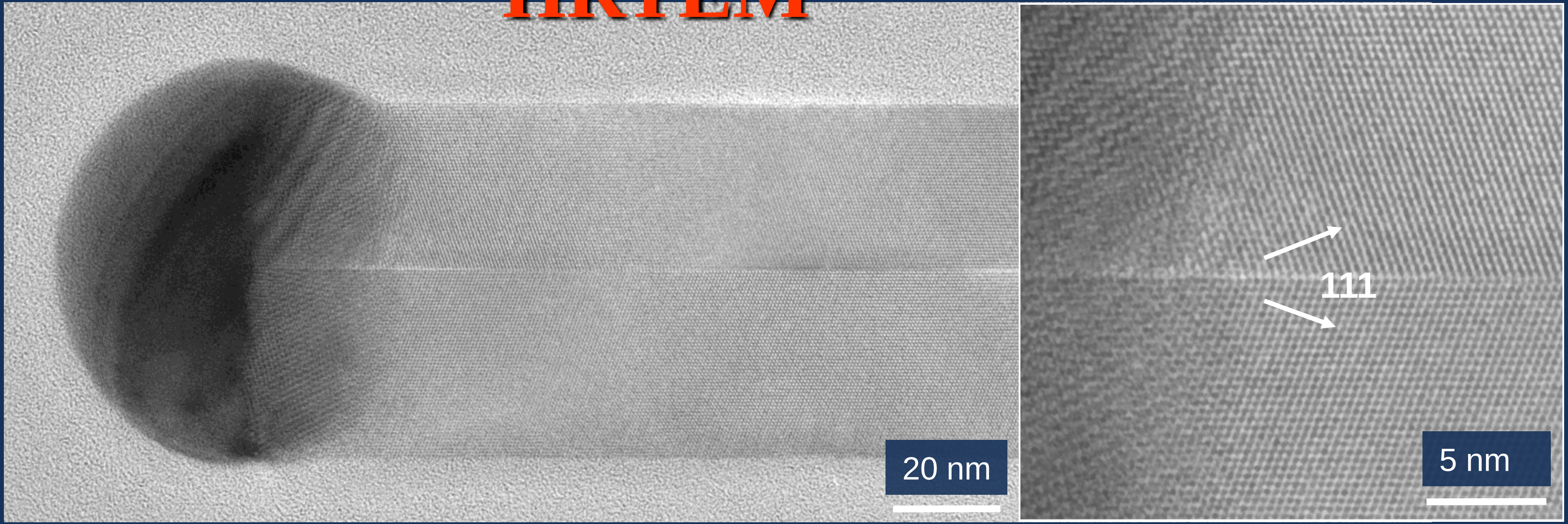
Bottom-up: CVD



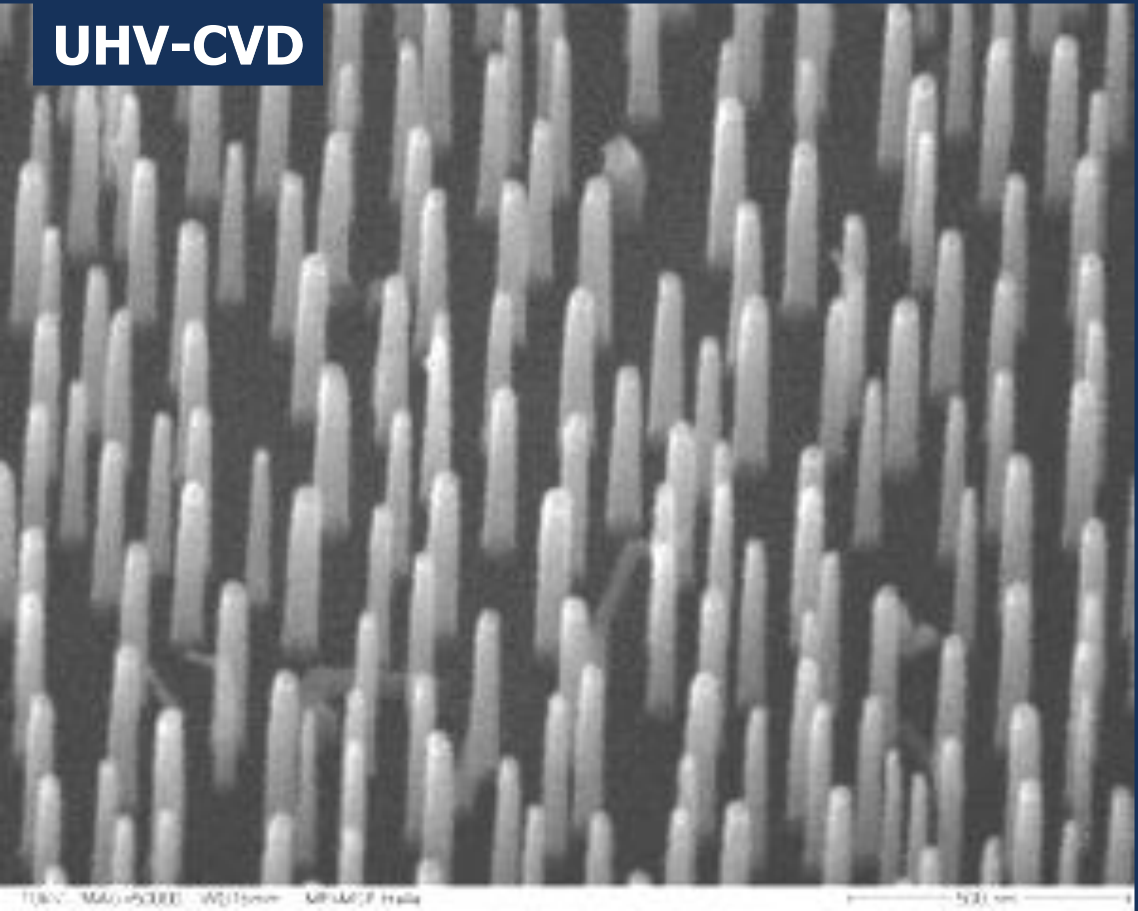
Bottom-up: Gold Catalyst

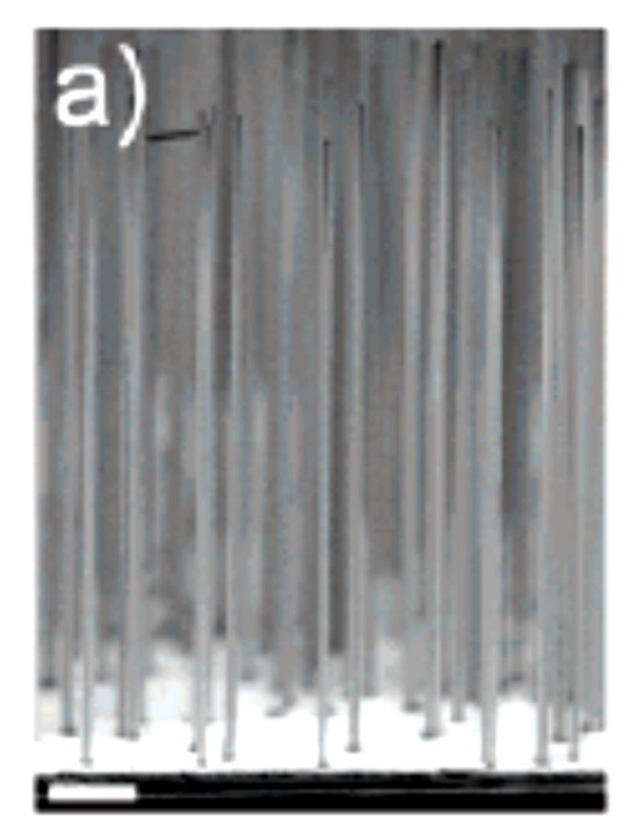


HRTEM



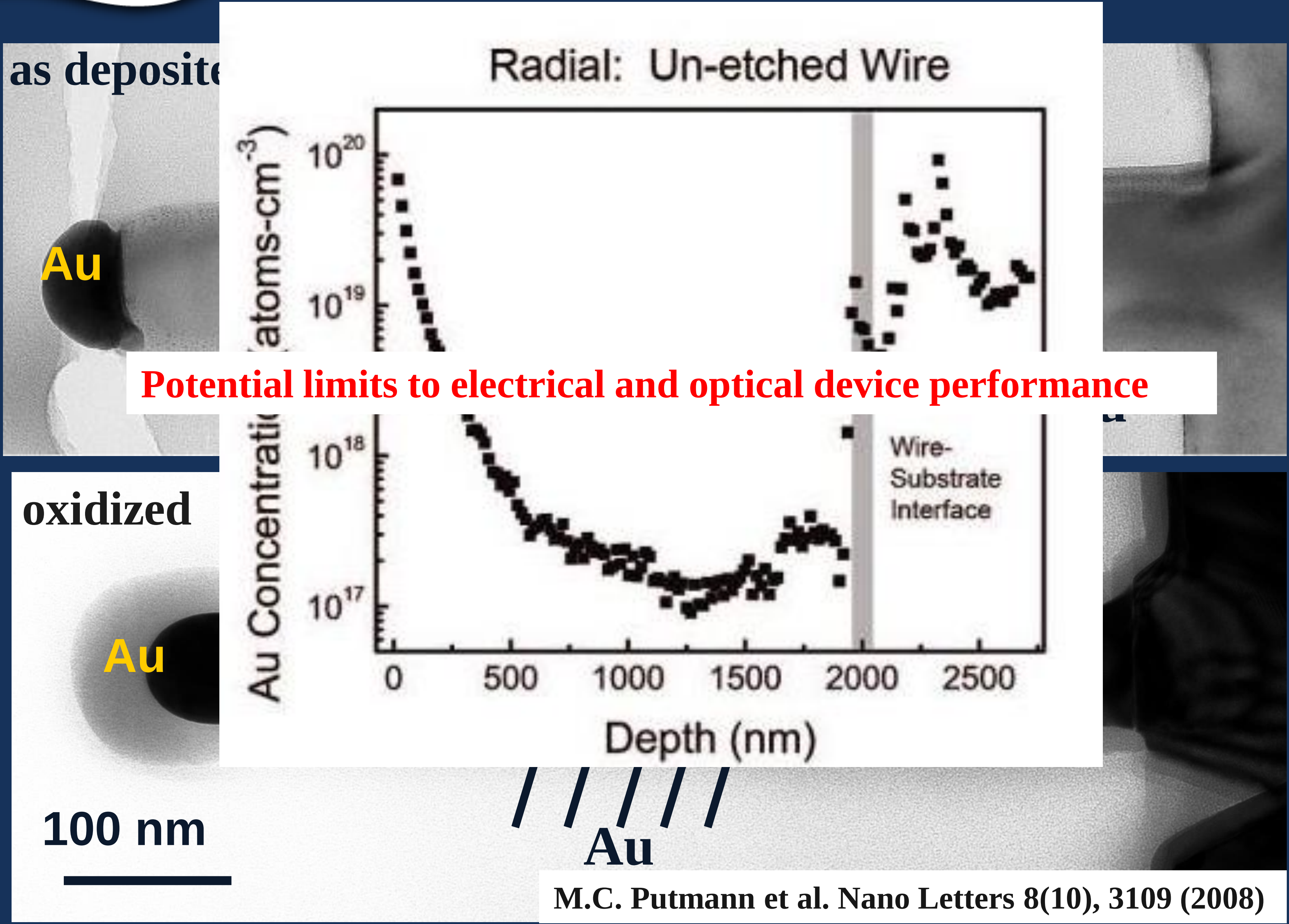
Bottom-up: Aluminum Catalyst





Wang, Y. , V. Schmidt , S. Senz , and U. Gösele, Nature Nanotechnology 1 (3) , p 186 (2006)
Allon I. Hochbaum, Rong Fan, Rongrui He, and Peidong Yang, Nano Lett., 5(3), 457(2005)

Problematic: Gold Contamination



Potential limits to electrical and optical device performance

M.C. Putmann et al. Nano Letters 8(10), 3109 (2008)

Direct Au implantation

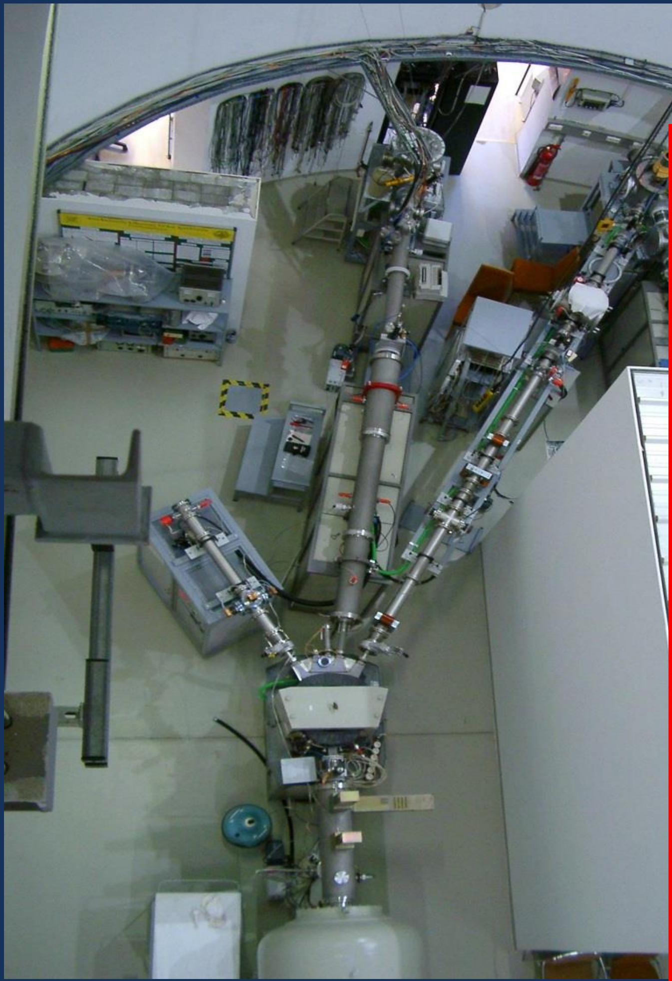
Bottom-up: Au Implantation

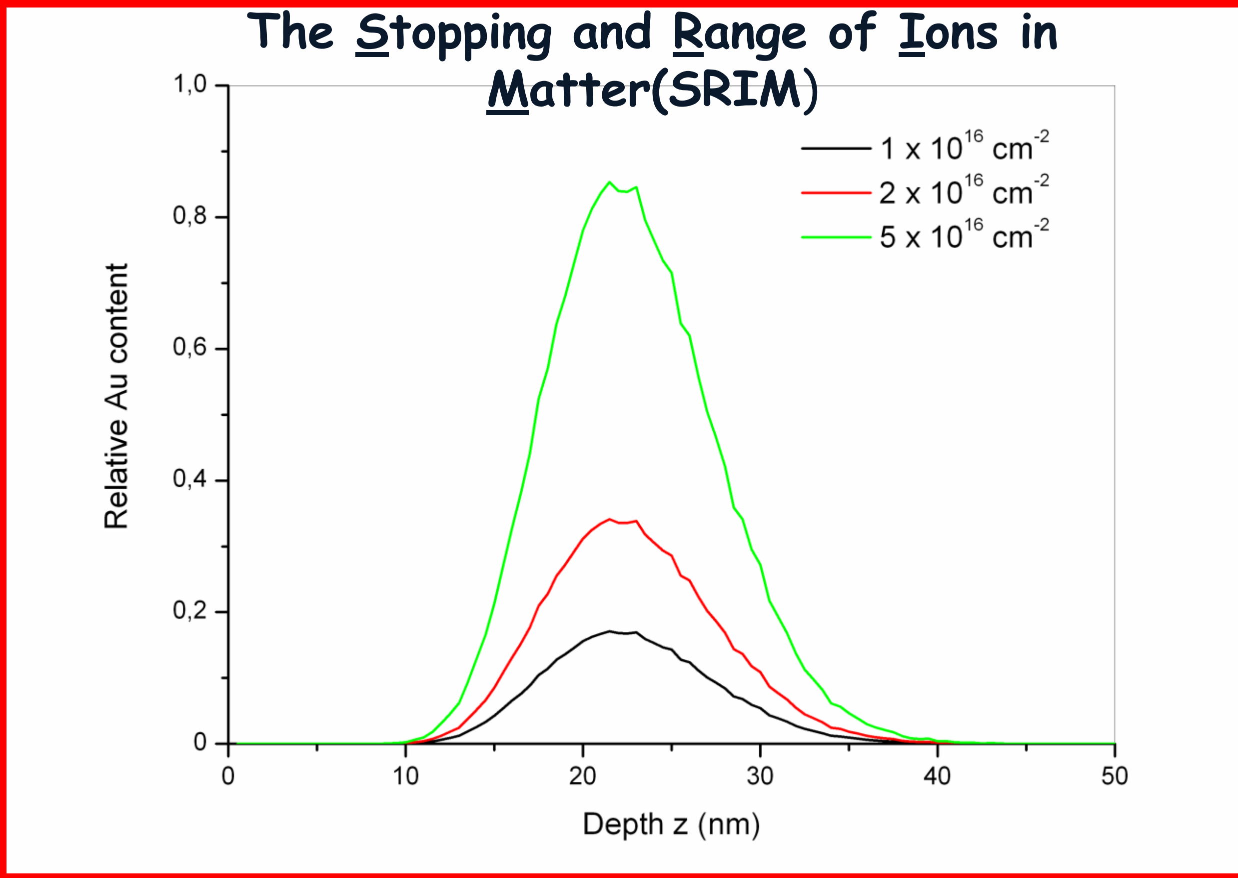
Energy: 30 keV

Temperature: RT and 350°C

Fluence: $1 \times 10^{15} \ldots 5 \times 10^{16}$ cm^{-2}

ROMEO 400 keV Implanter

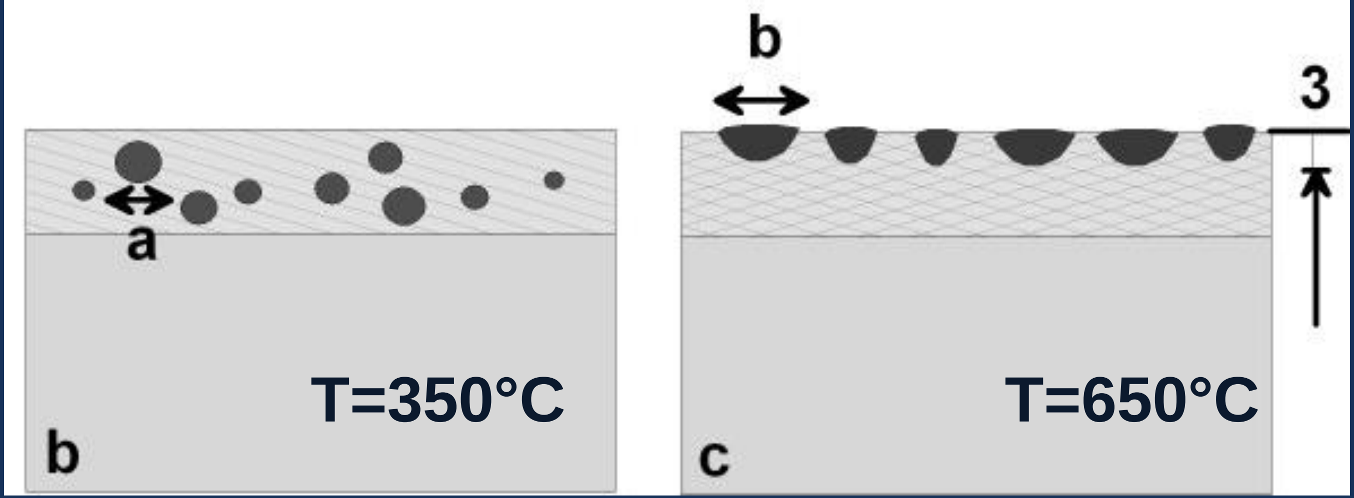




The Stopping and Range of Ions in Matter(SRIM)

Bottom-up: Au Implantation

RT



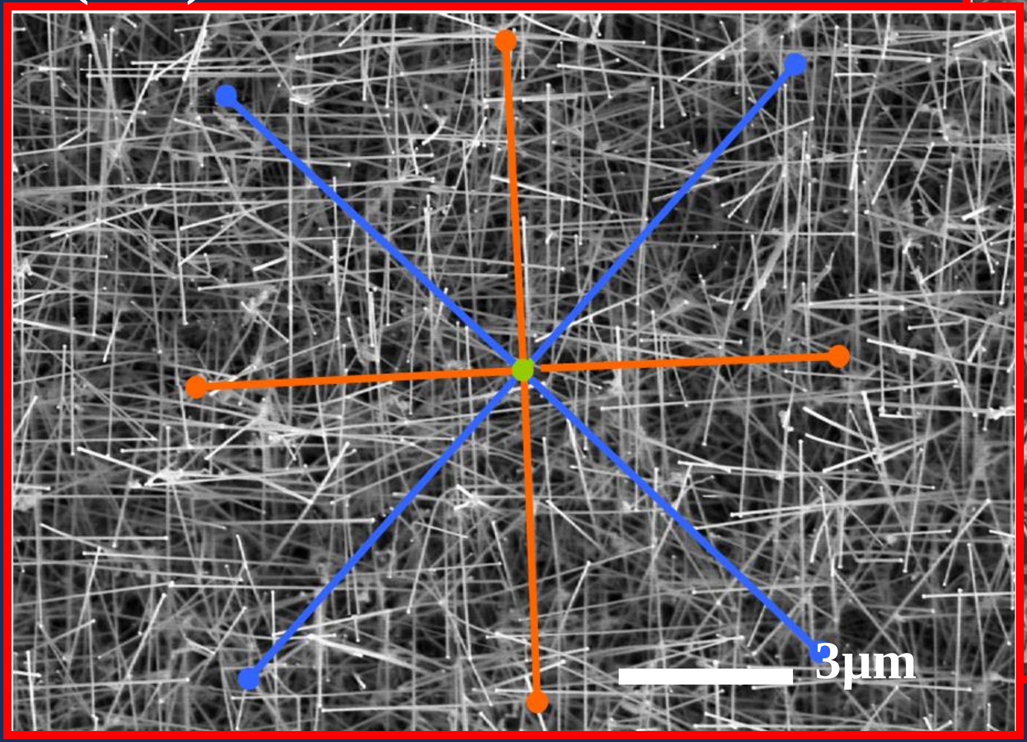
Th. Stelzner et al., Nanotechnology 17, 2895 (2006)

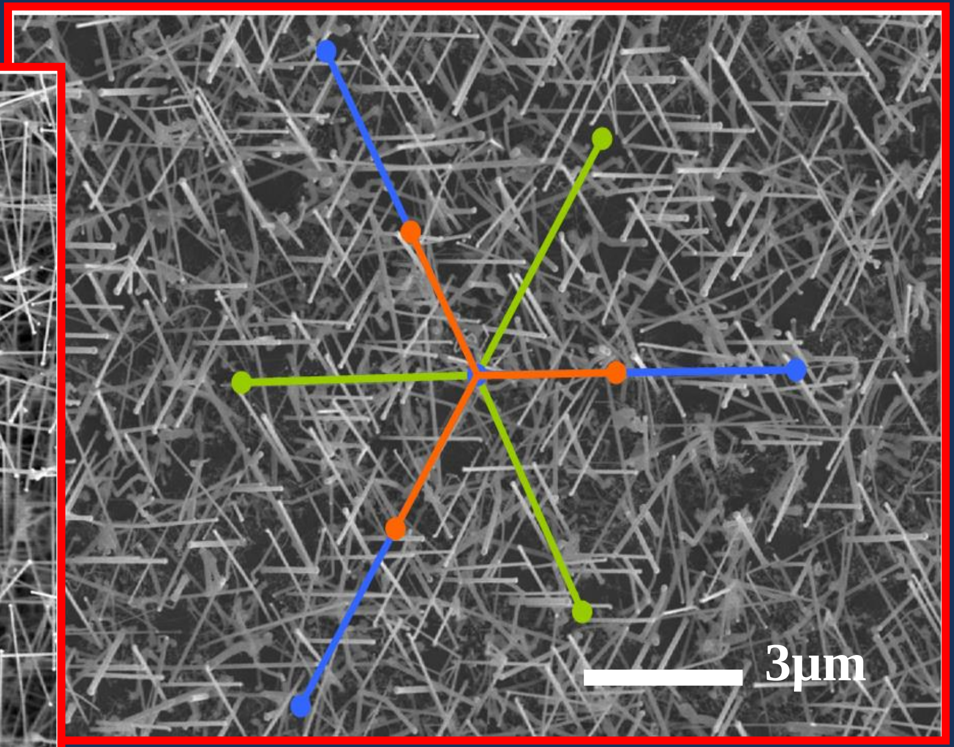
Bottom-up: Au Implantation

SiNWs CVD growth from implanted Au catalyst

Si(111)

Si(100)

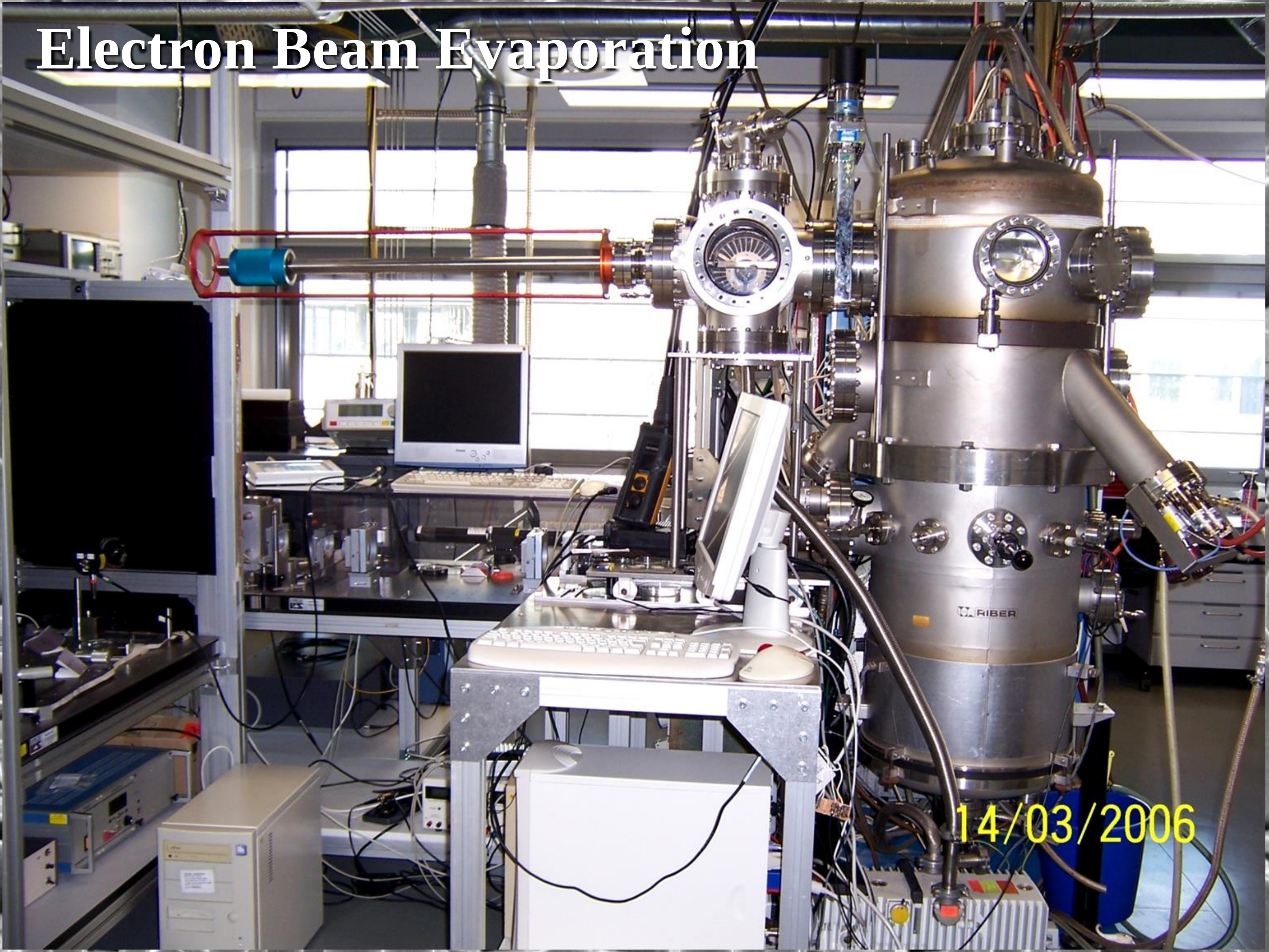




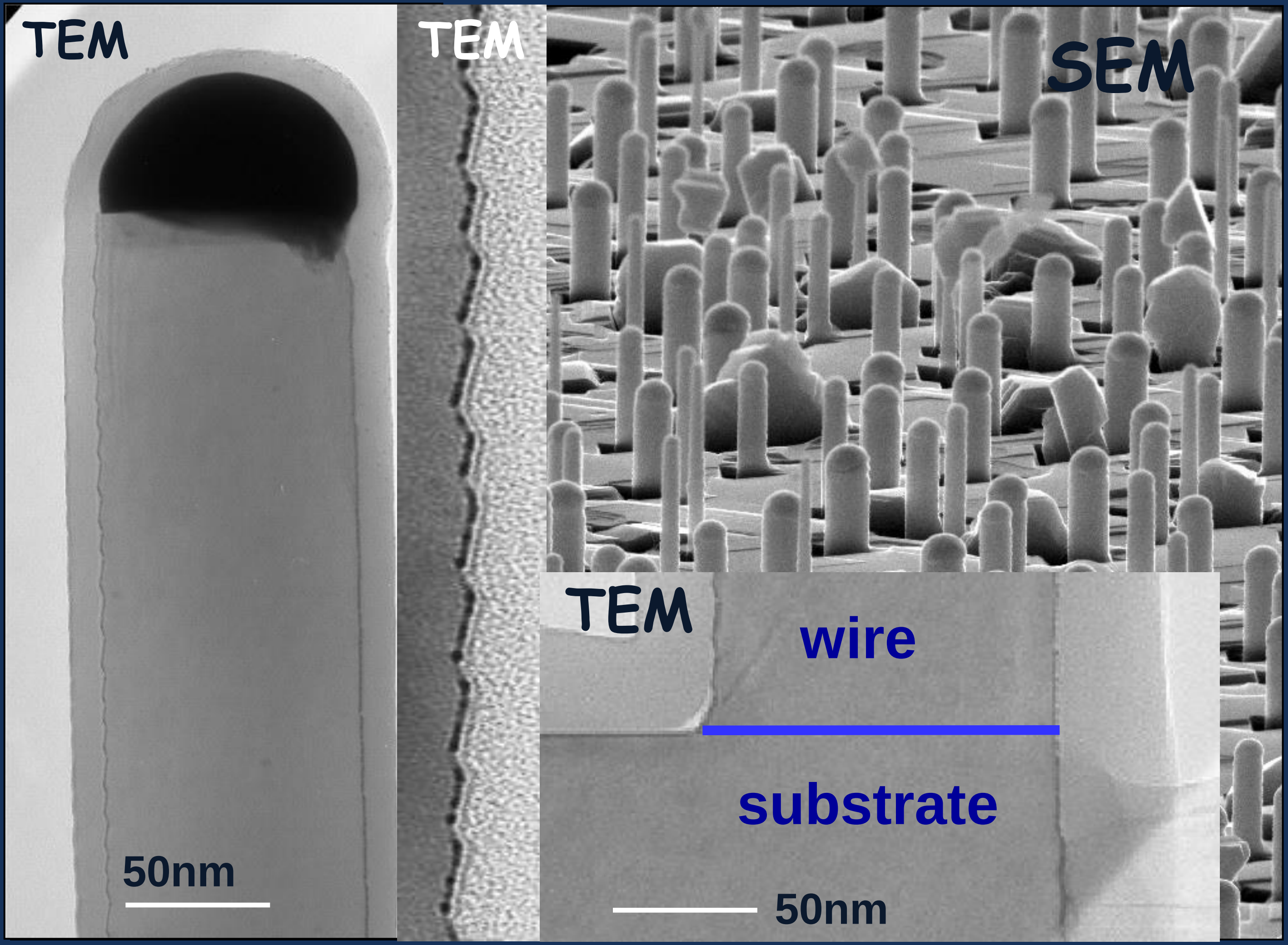
SEM micrographs

Bottom-up: PVD

Electron Beam Evaporation



Bottom-up: PVD



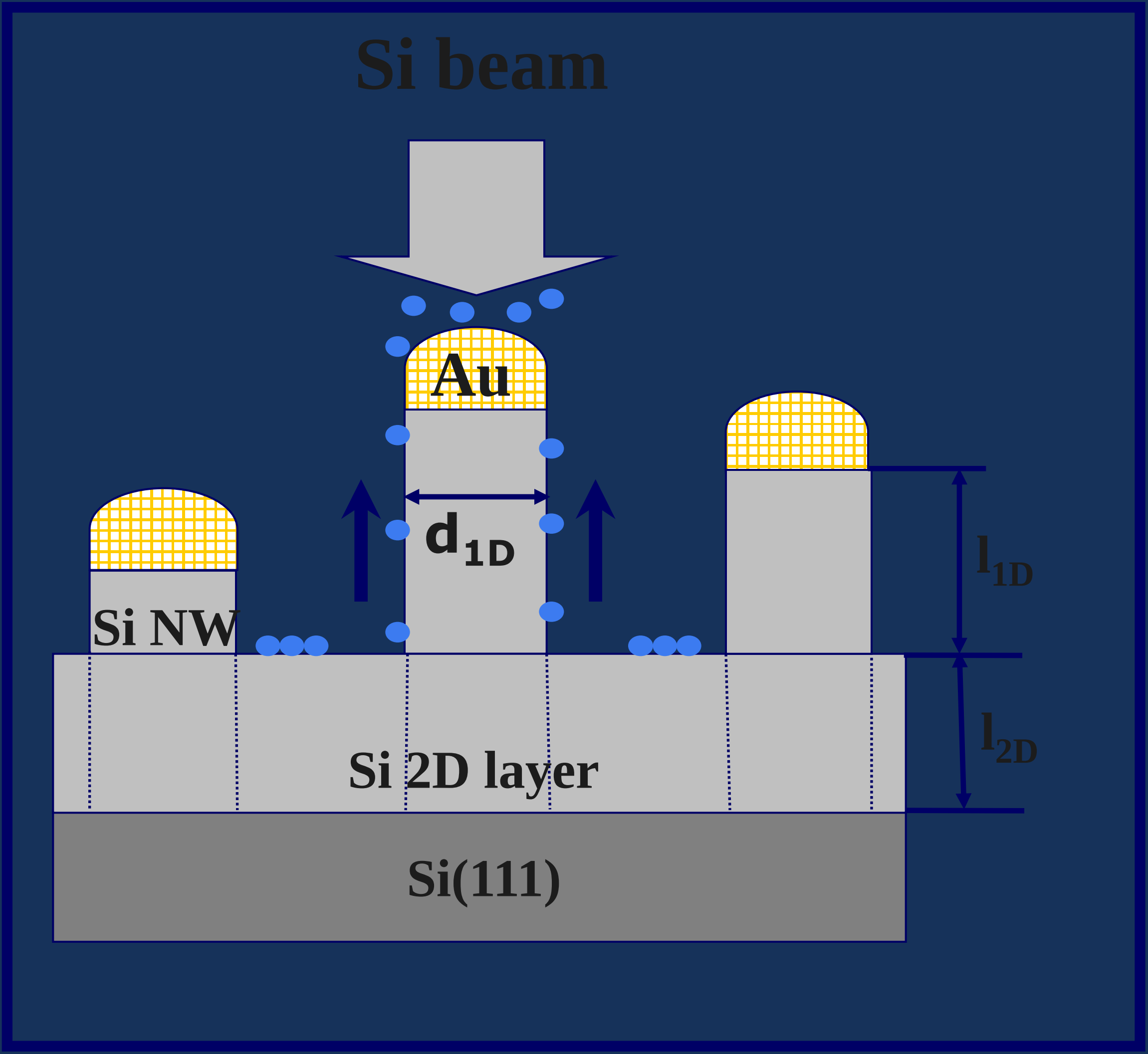
EBE

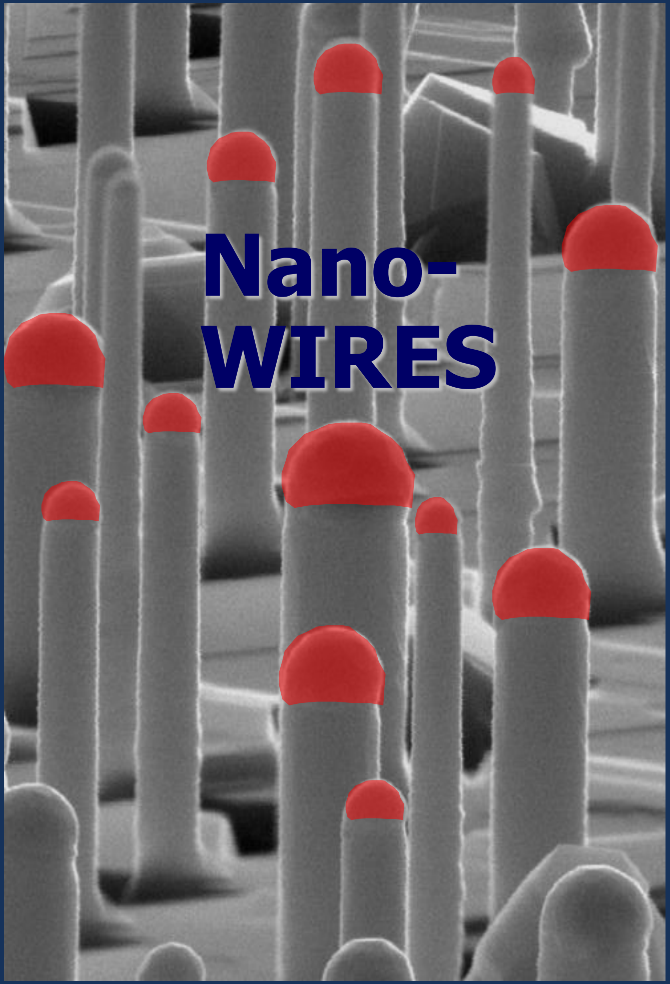
80mA
475°C
Si(111)
Au-1.2nm
1h

→ EBE NWs
II <111>

V. Sivakov et al. PSSa 203(15), 3692 (2006)
V. Sivakov et al., J. Cryst. Growth *300*, 288(2007)

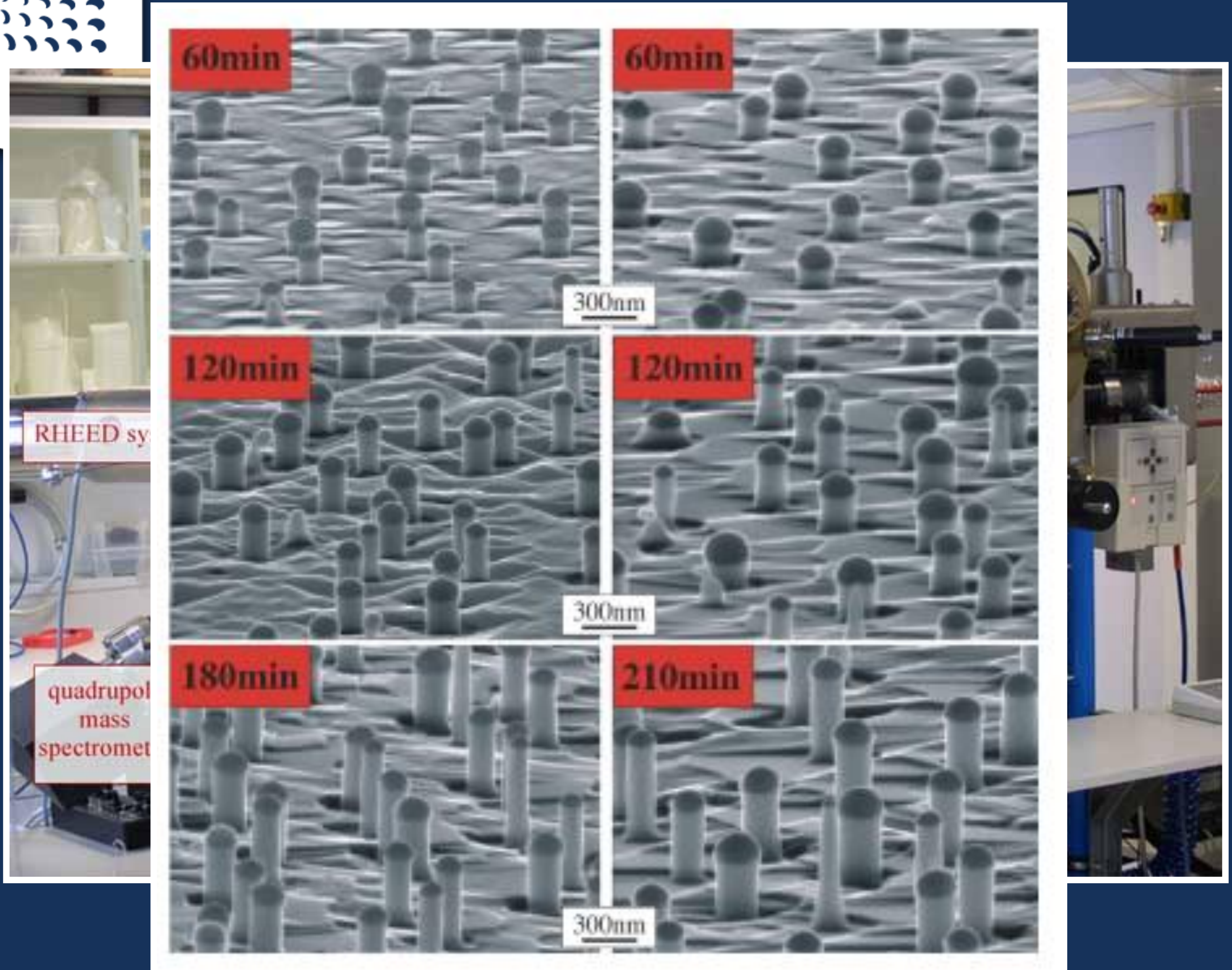
Bottom-up: PVD



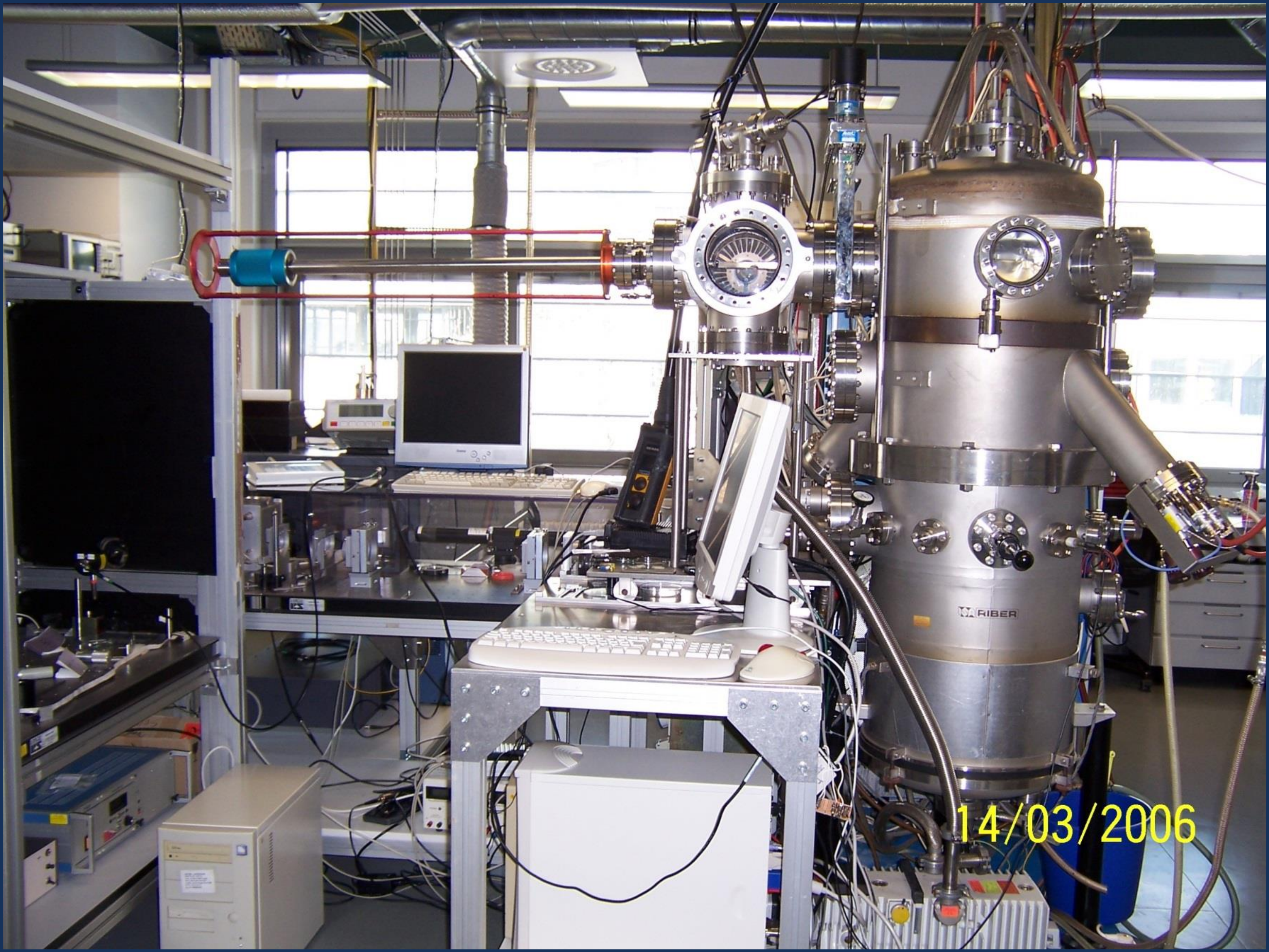


L. Schubert et al. APL 84, 4968 (2004)

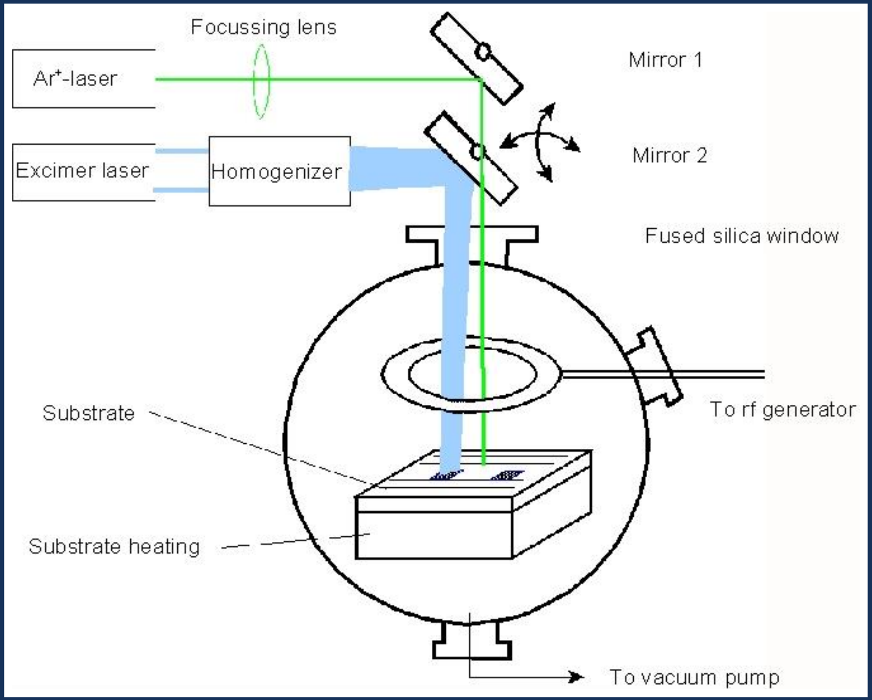
Bottom-up: PVD



Bottom-up: PVD



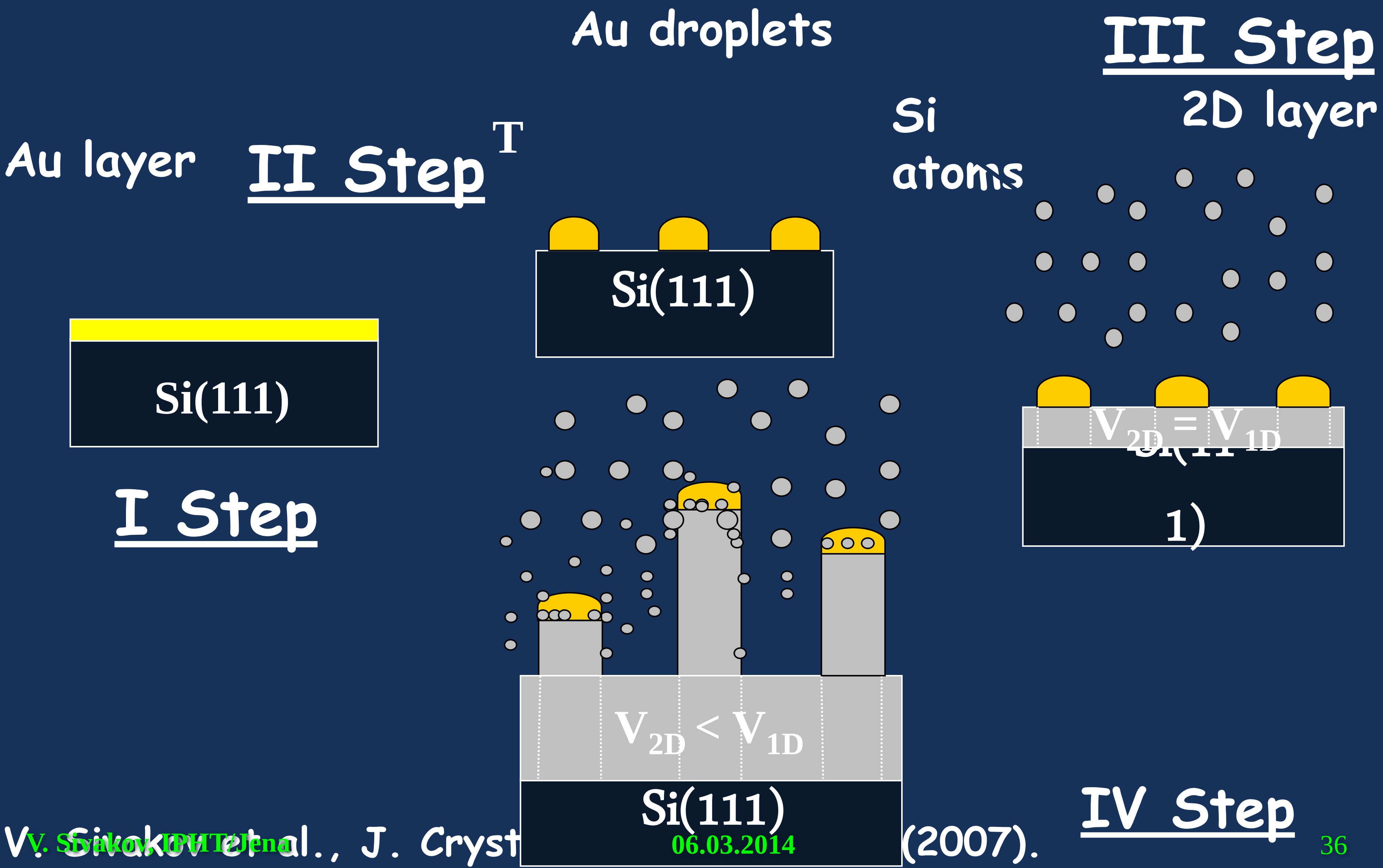
Bottom-up: PVD



Substrate: p-Si(111)
Au thickness: 0.6-2.4 nm
T_S: 450-550 °C
I_E: 30-80 mA
V: 1-100 nm/min
t: 5-240 min

V. Sivakov et al., Phys. Stat. Sol. A, 203(15), 3692 (2006).

Bottom-up: PVD



Au layer

I Step

Si(111)

II Step

T

Au droplets

Si(111)

$V_{2D} < V_{1D}$

Si(111)

III Step

Si atoms

2D layer

$V_{2D} = V_{1D}$

Si(11 1)

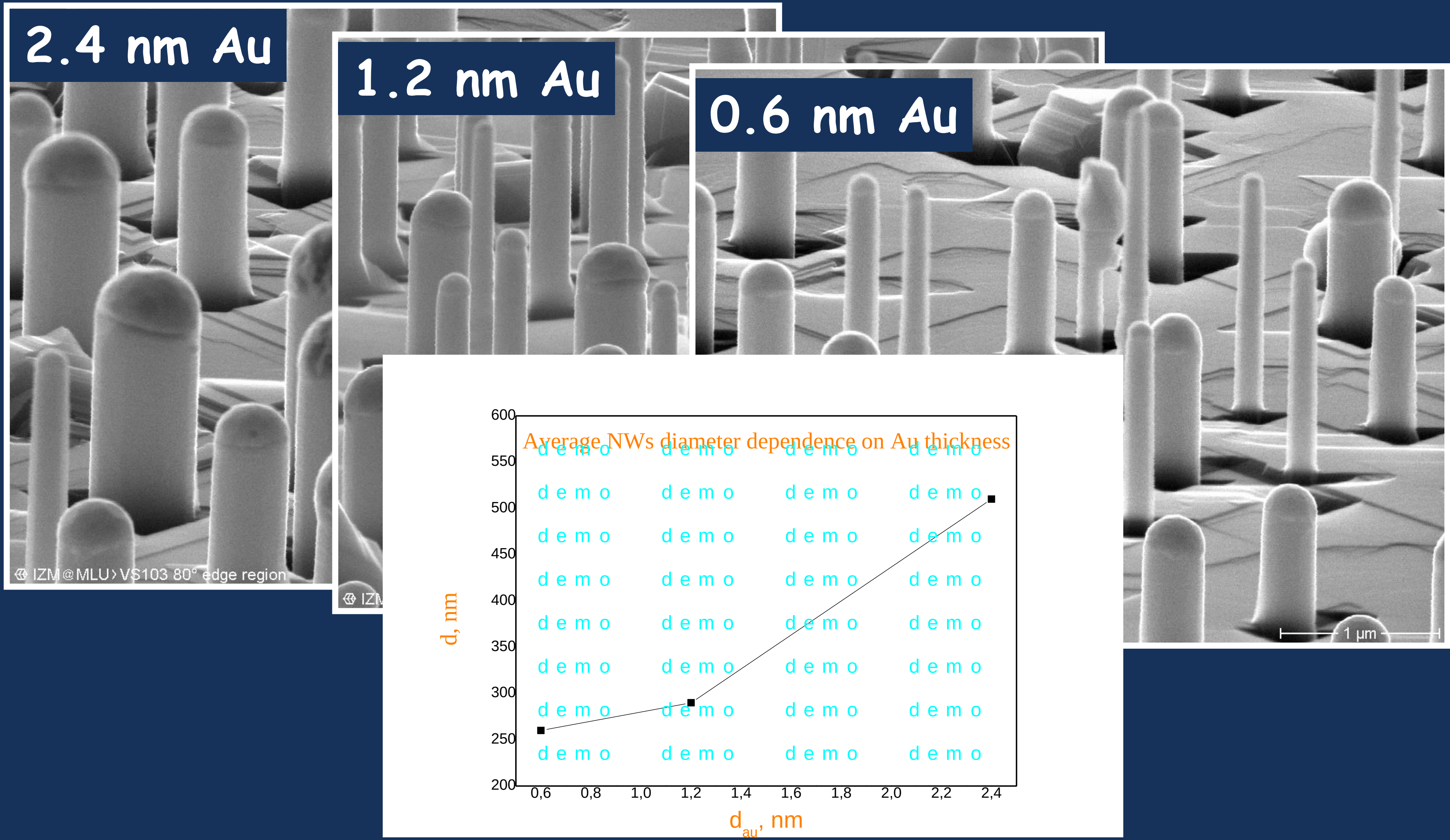
IV Step

V. Sivakov et al., J. Cryst (2007).

Bottom-up: PVD

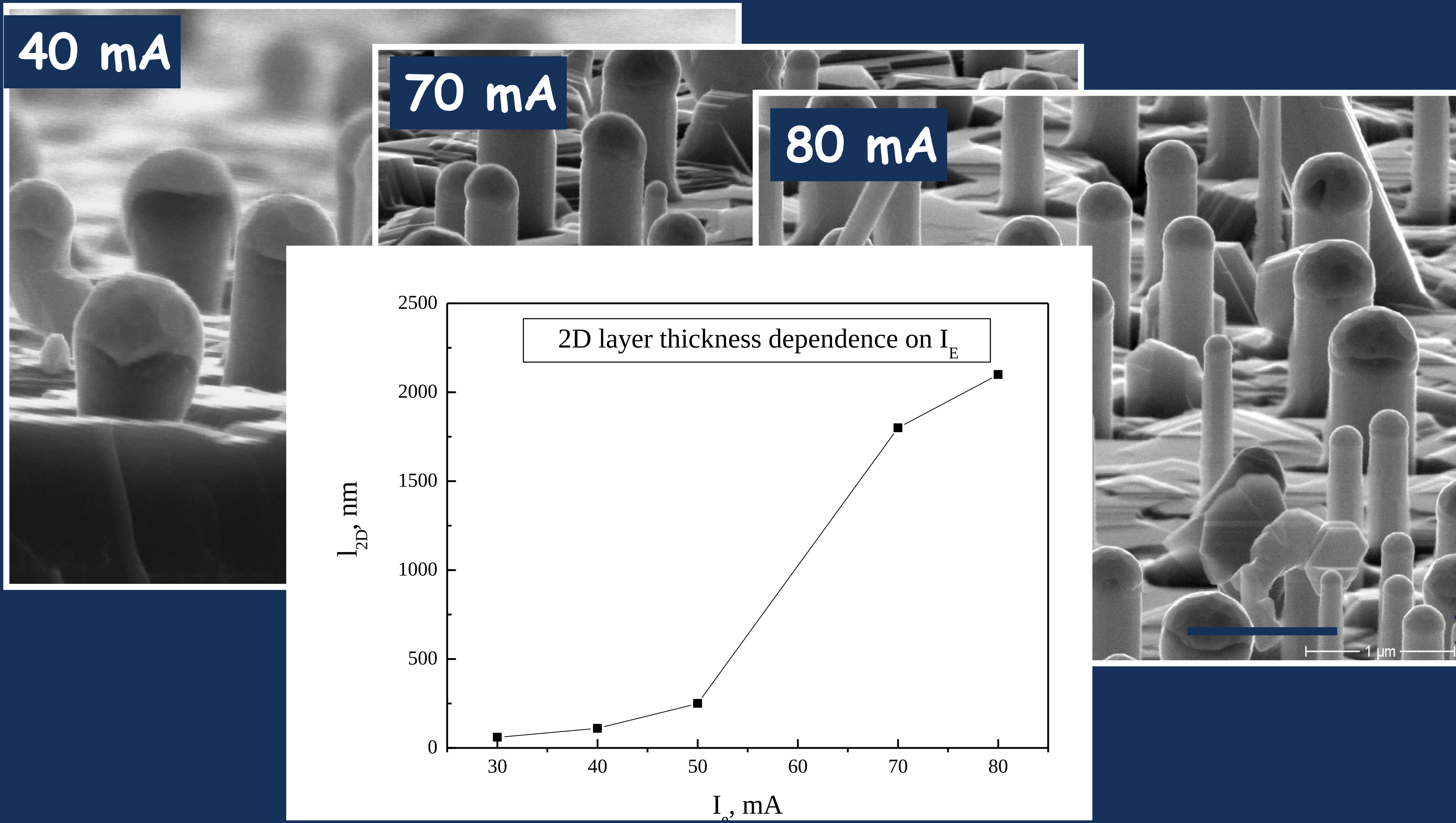
- **Si Nanowires (NWs) Growth Kinetic**
- -NWs diameter as a function of catalyst thickness
- -NWs length as a function of emission current
- -NWs length and diameter as a function of process temperature
- -NWs length as a function of NWs diameter
- -Ostwald ripening

Bottom-up: PVD



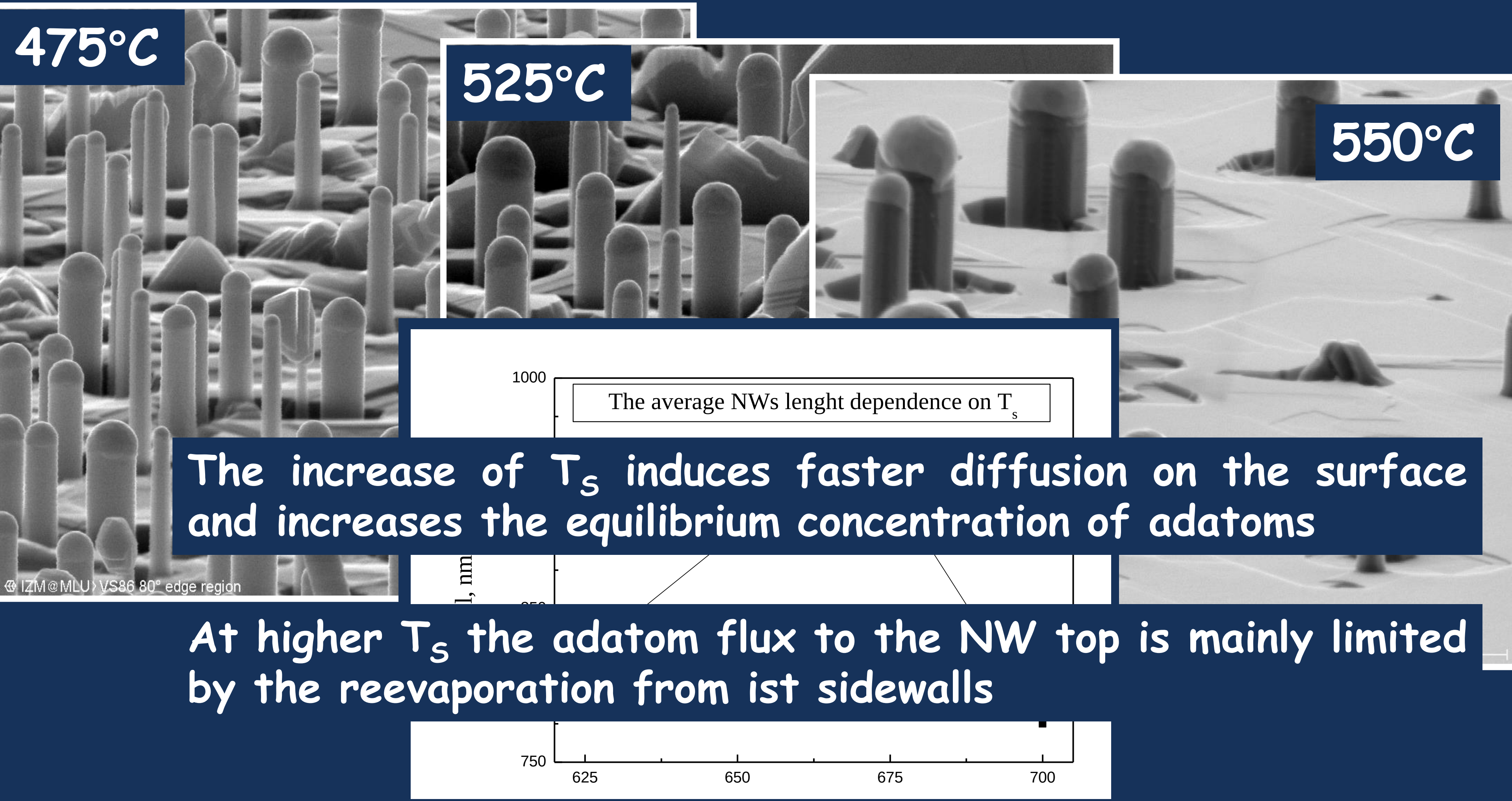
V. Sivakov et al., J. Cryst. Growth, 300, 288(2007).

Bottom-up: PVD



V. Sivakov et al., J. Cryst. Growth, 300, 288(2007).

Bottom-up: PVD

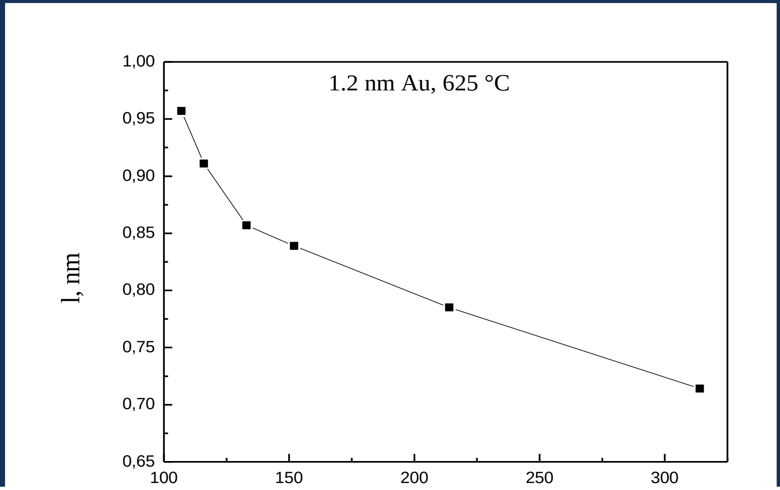


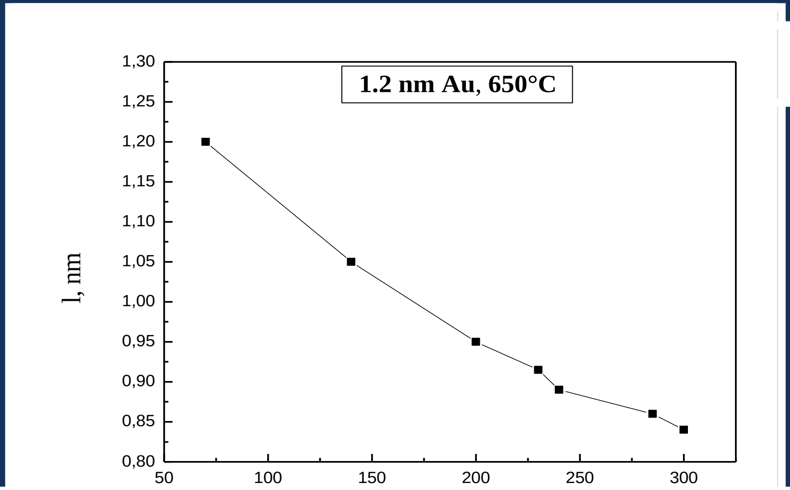
The increase of T_S induces faster diffusion on the surface and increases the equilibrium concentration of adatoms

At higher T_S the adatom flux to the NW top is mainly limited by the reevaporation from ist sidewalls

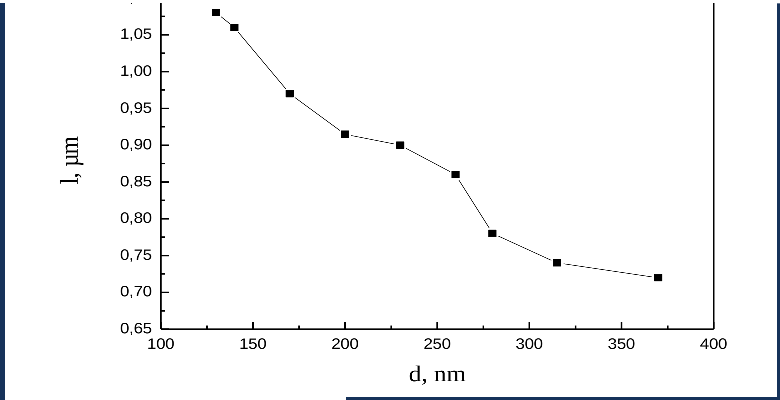
V. G. Dubrovskii et al., Physical Review E 73, 021603 (2006)

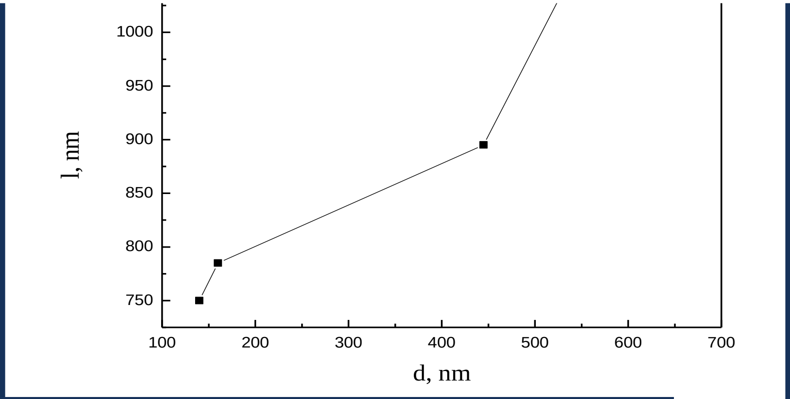
Bottom-up: PVD





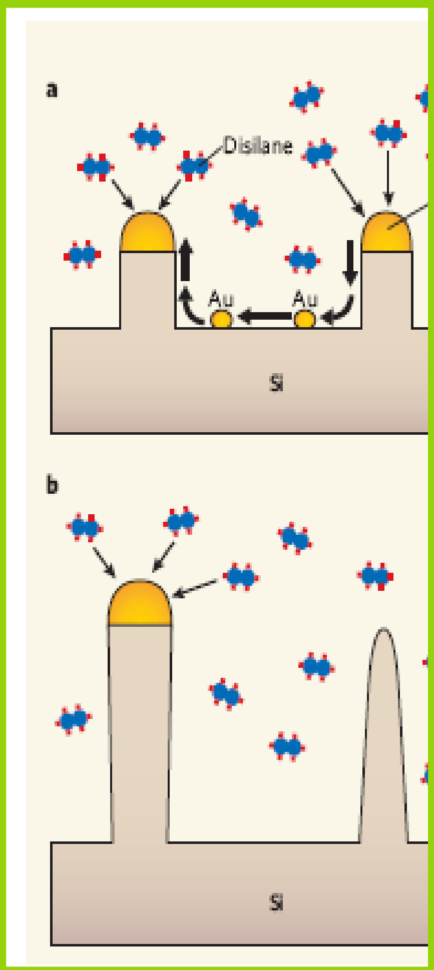
For the CVD growth by the VLS mechanism whiskers with larger diameter grow faster those with a smaller diameter due to the Gibbs-Thomson effect discussed by Givargizov.

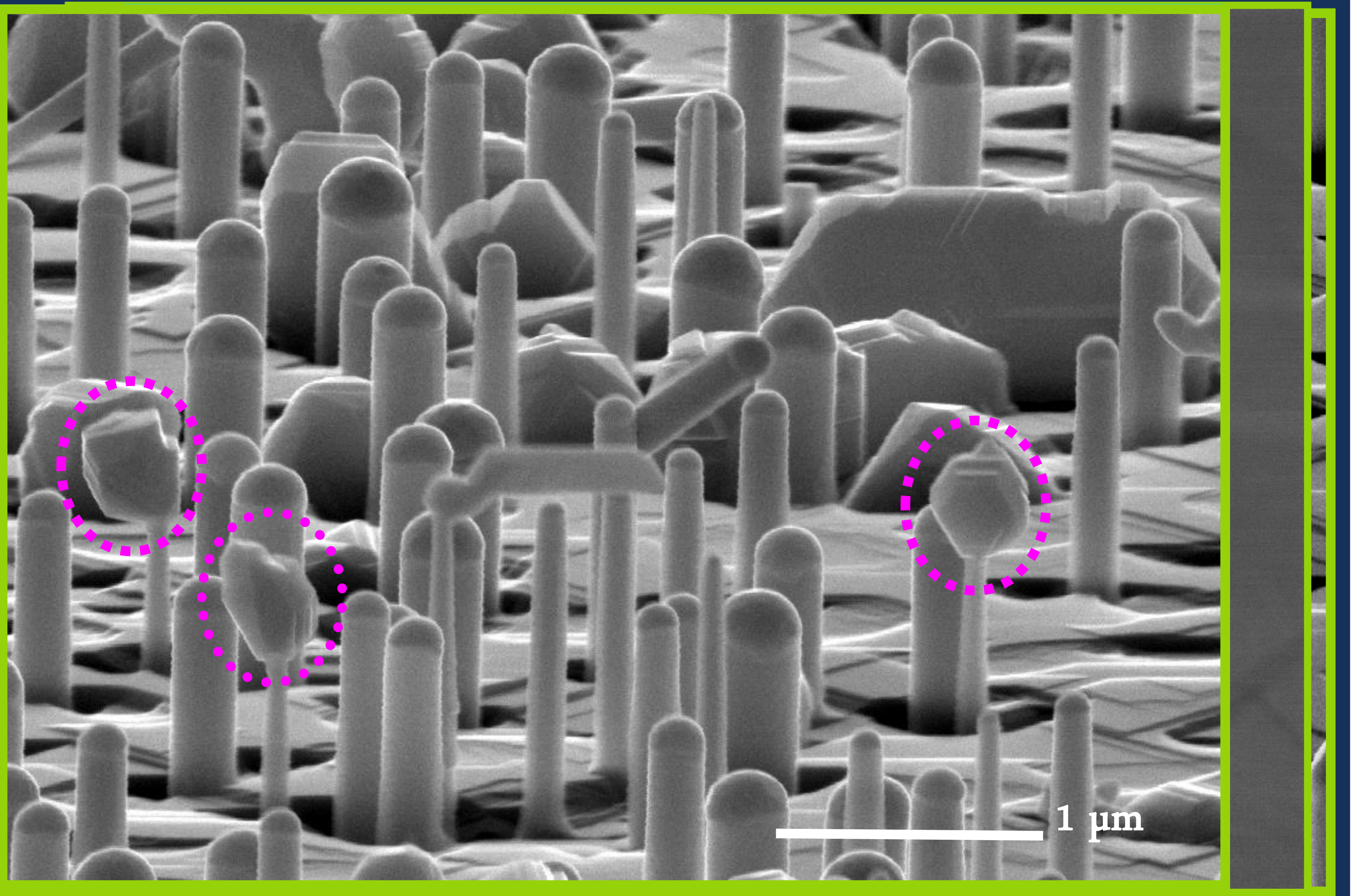




V. Sivakov et al., J. Cryst. Growth, 300, 288(2007).

Bottom-up: PVD



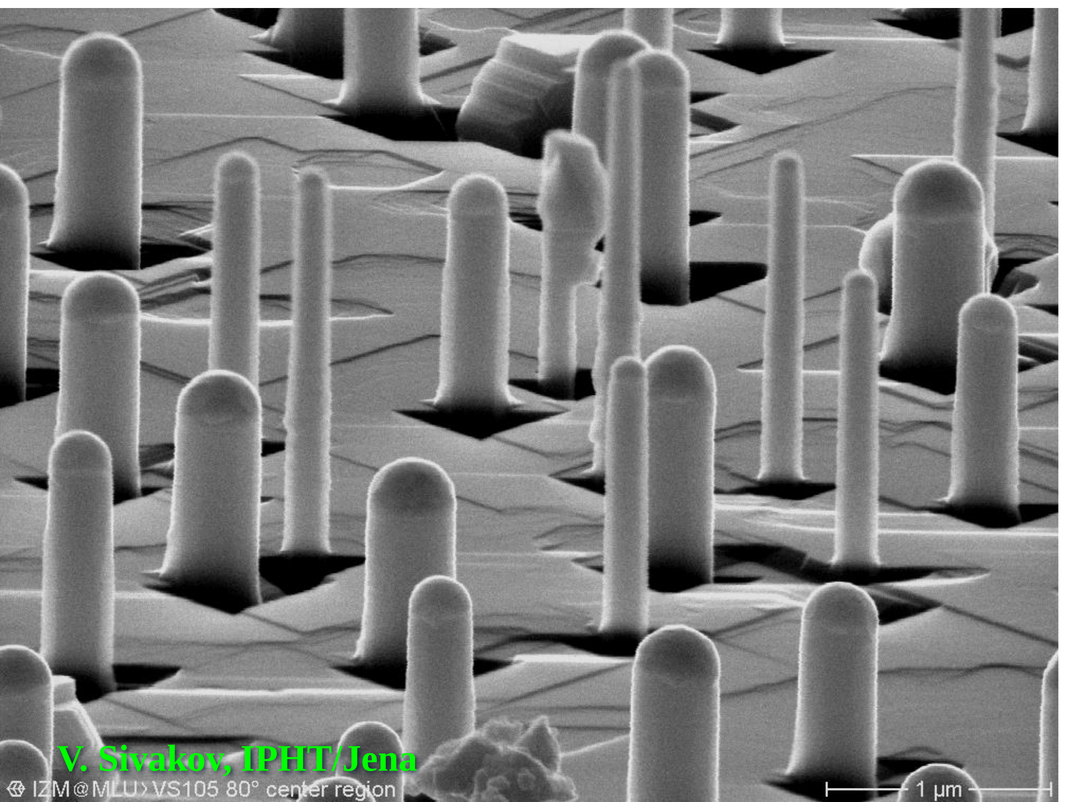


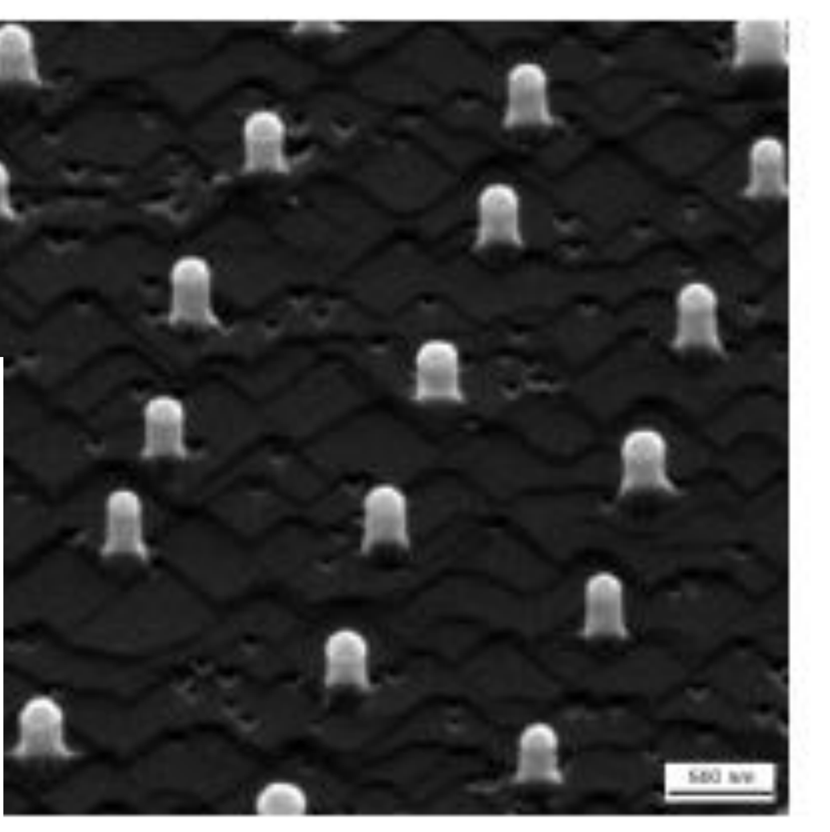
J. B. Hannon, S. Kodambaka, F. M. Ross, and R. M. Tromp, *Nature*, DOI: 10.1038/nature04574 (2006)

U. Gösele, *Nature*, DOI: 10.1038/nature04609 (2006)

Bottom-up: PVD

EBE, 1h
$\Delta L_{1D} \approx 1500$ nm



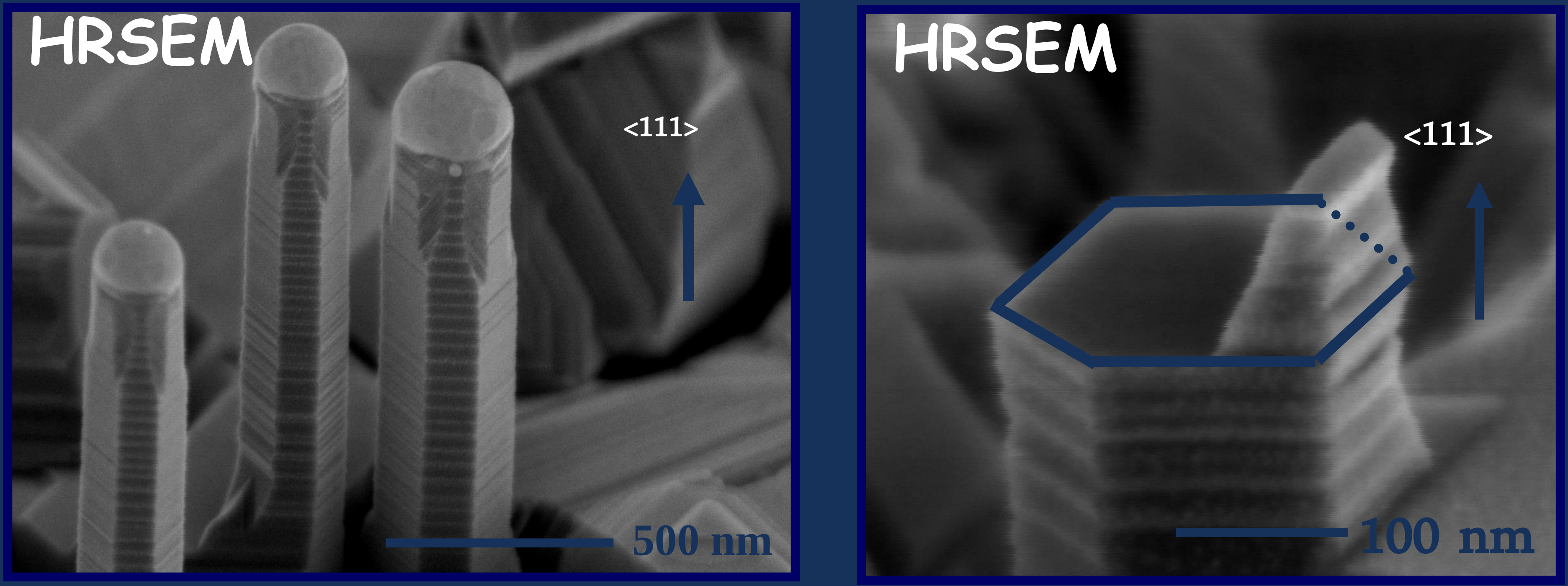


MBE, 36 min
$\Delta L_{1D} \approx 250$ nm

Bottom-up: PVD

Silicon NWs Facetting

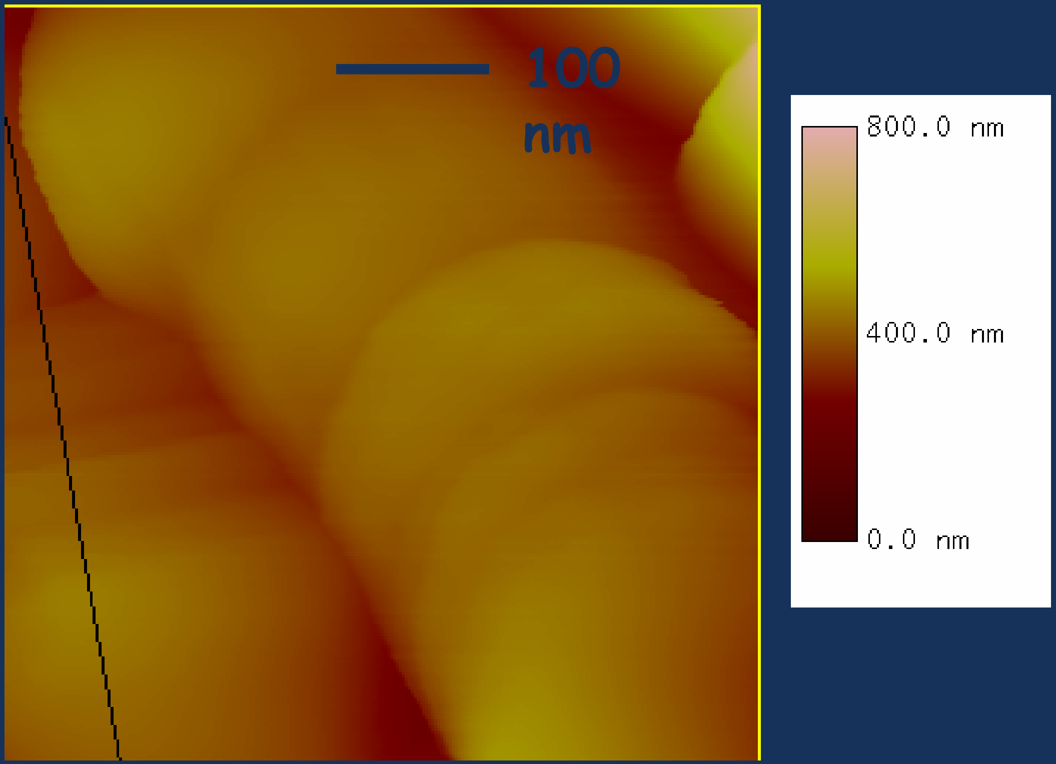
Bottom-up: PVD

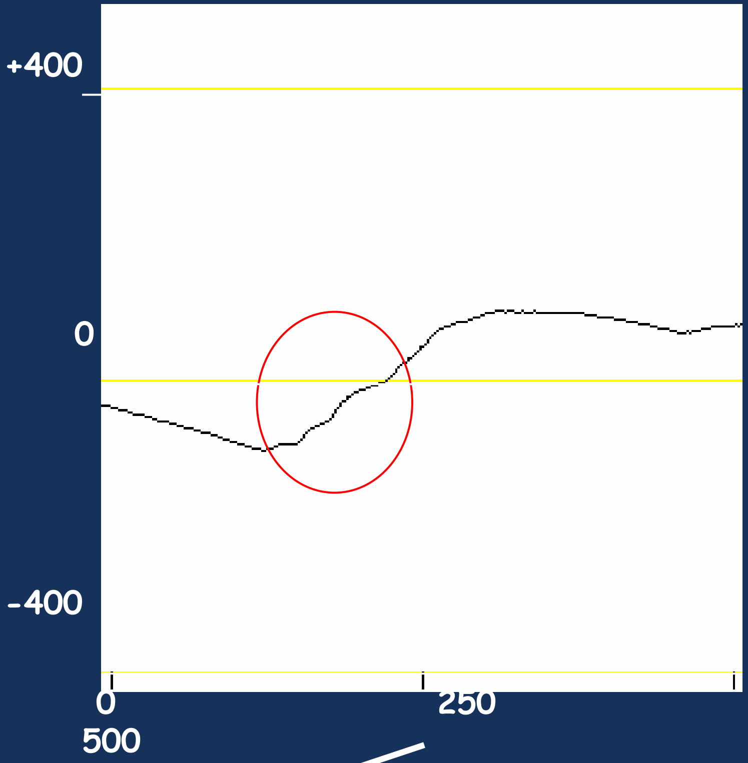


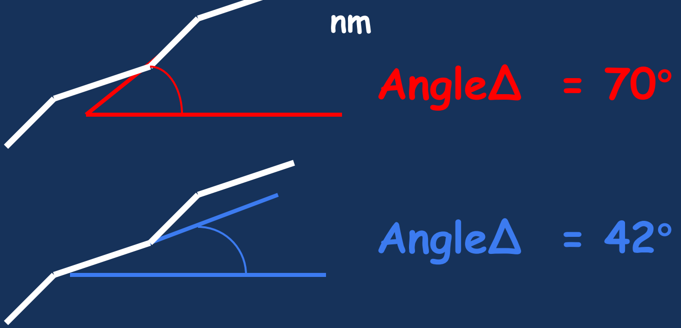
HRSEM micrographs of Si NWs grown by EBE on Si(111) at 550°C for 1h at emission current 80 mA and Au thickness of 1.2 nm. The faceting along three sides of Si NWs is clearly visible in (a) and (b). The growth direction is <111>.

V. Sivakov et al., MRS Fall Meeting, 11.27 – 12.01. 2006, Boston USA.

Bottom-up: PVD







Approximate Angle of the side facets = 28°

(111) (113)

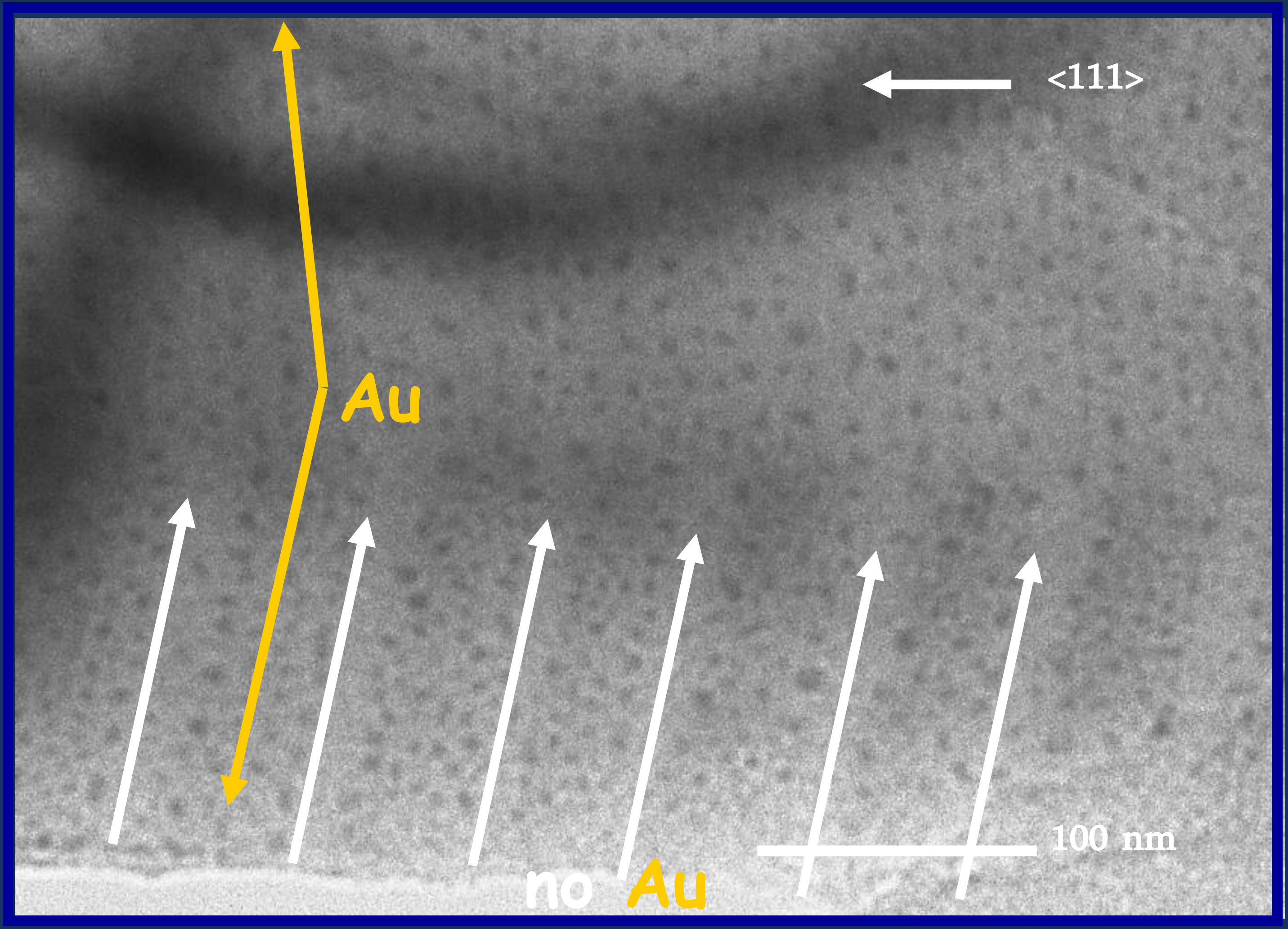
V. Sivakov et al., DPG Conference, 03.26 - 03.30, 2007, Regensburg, Germany.

Bottom-up: PVD

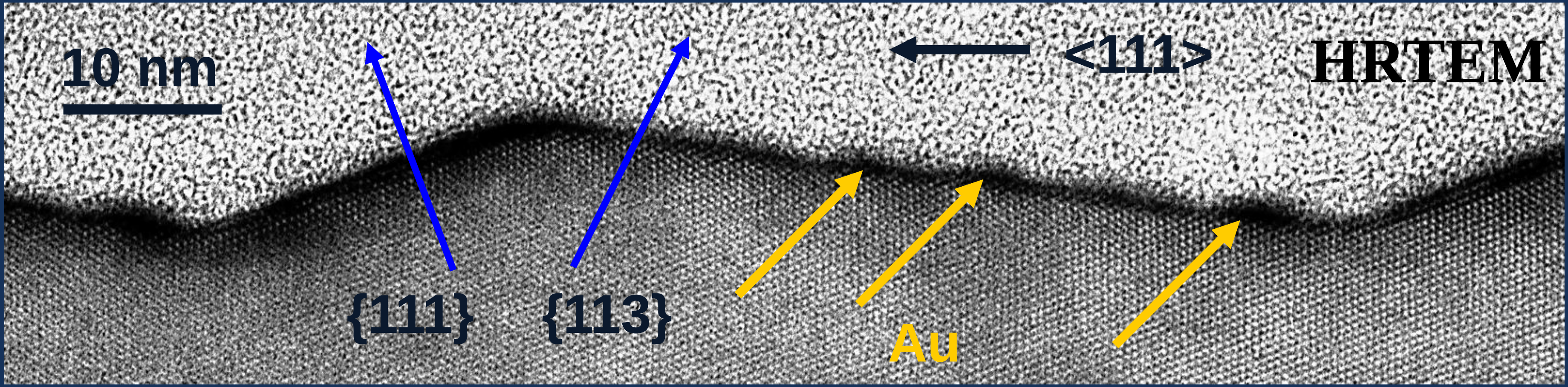
HRTEM

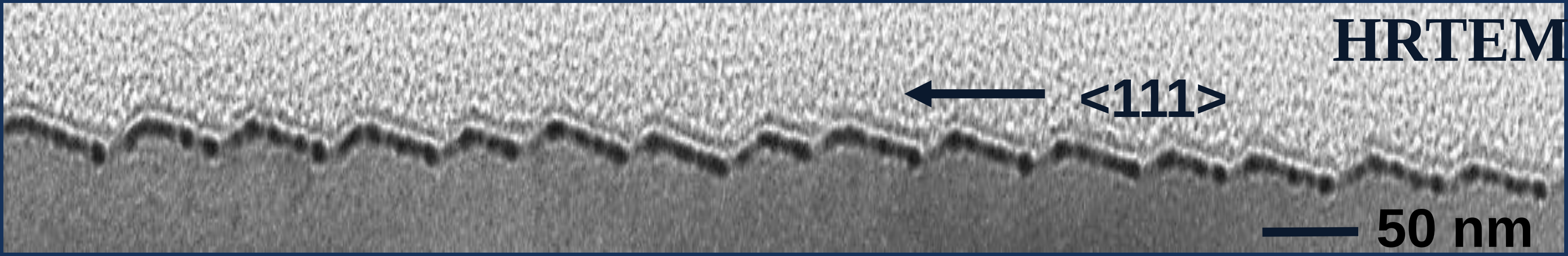
EBE

T = 550°C
60 min
Si(111)
80mA



Bottom-up: PVD

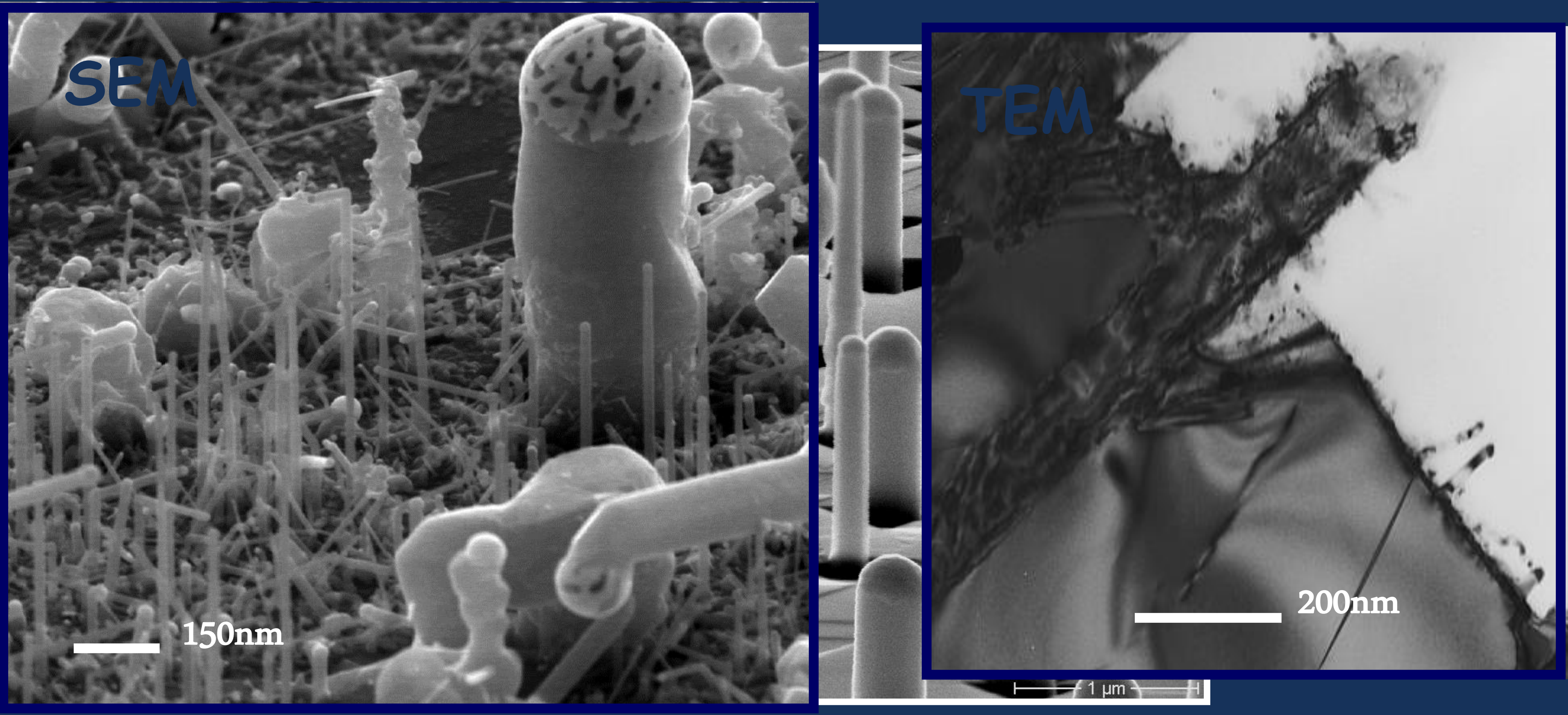




V. Sivakov et al., MRS Fall Meeting 2006, Boston USA.
V. Sivakov et al., Nanotechnology, 20, 405607 (2009) .

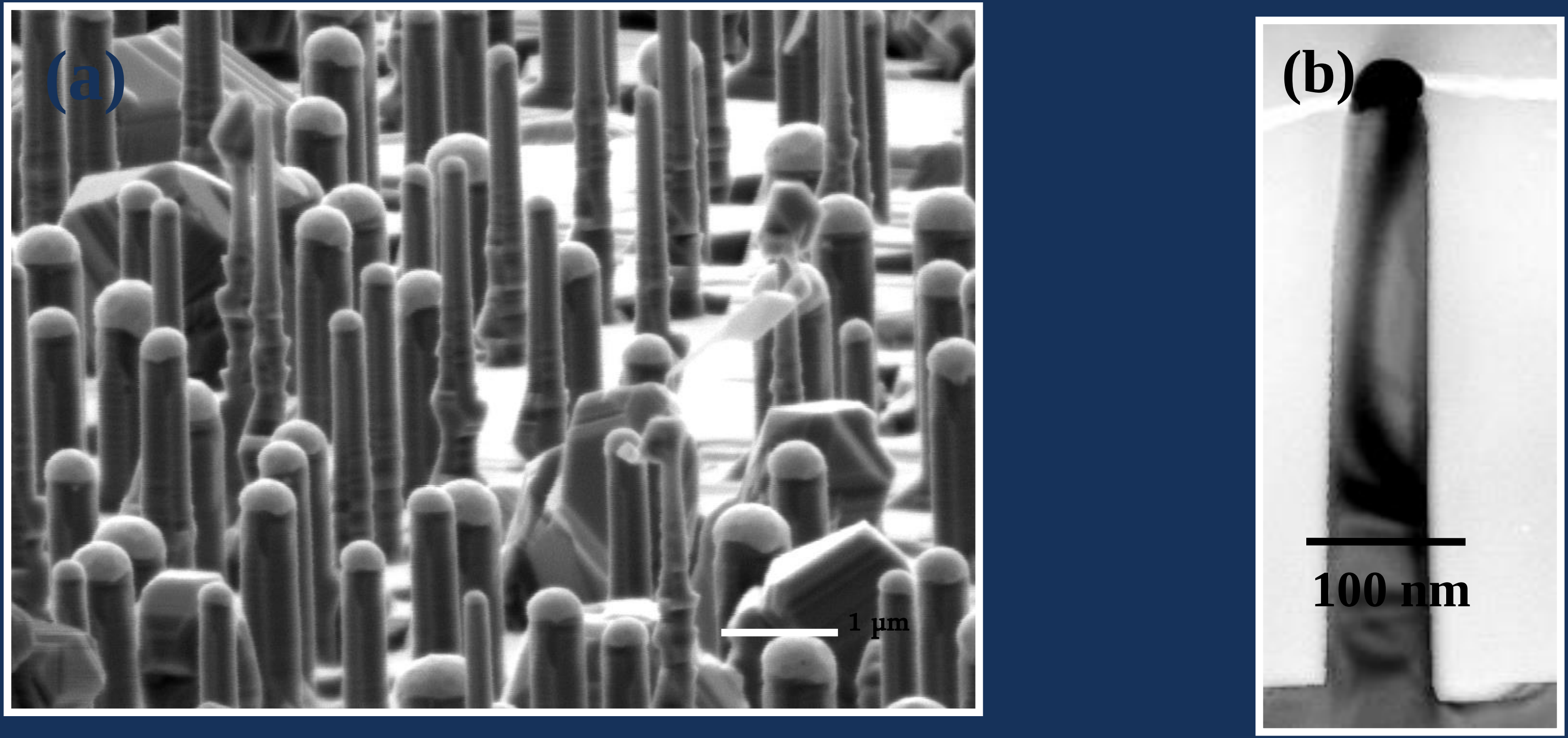
Gold Migration@Oxidation of Si NWs

Oxidation of Si NWs



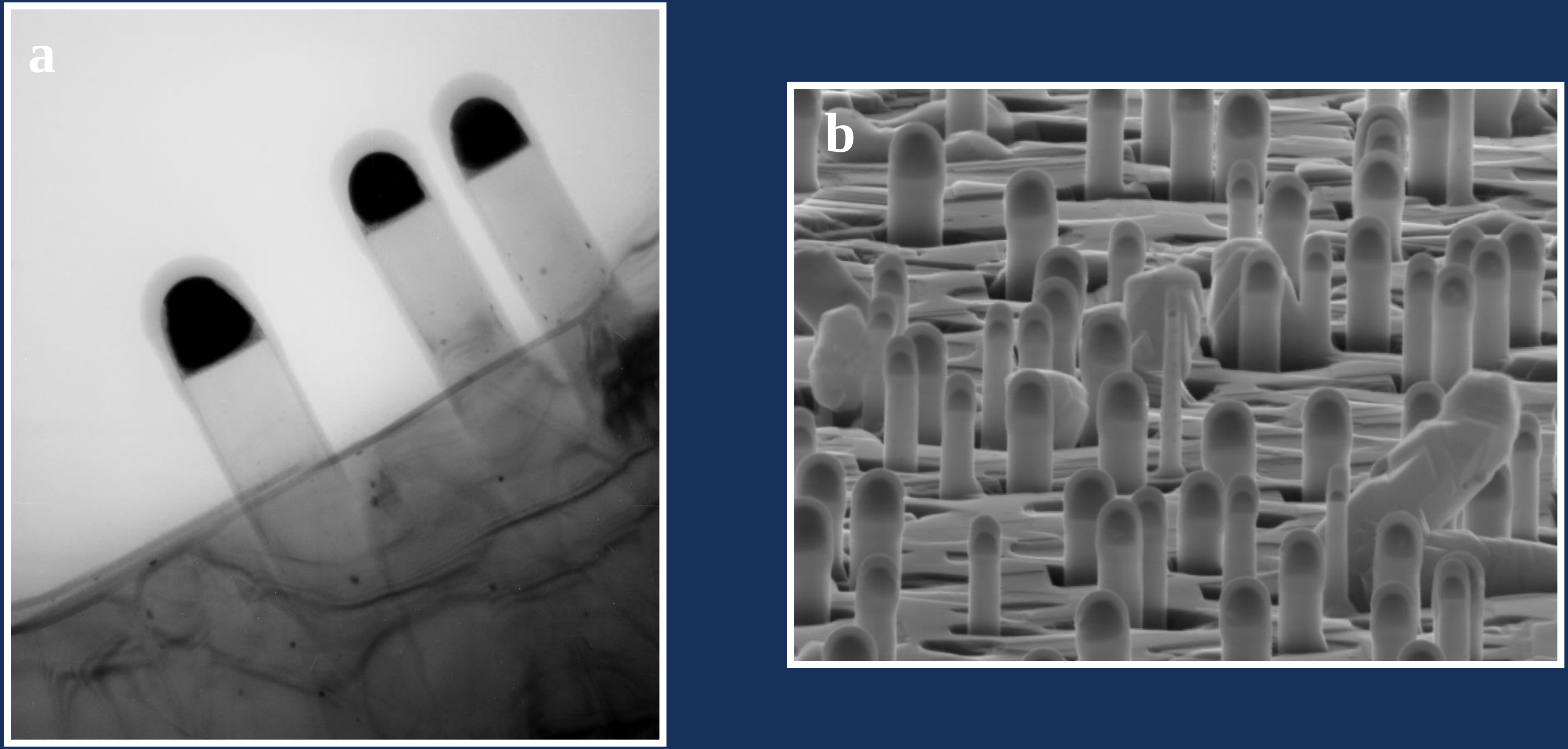
CVD on EBE

Oxidation of Si NWs



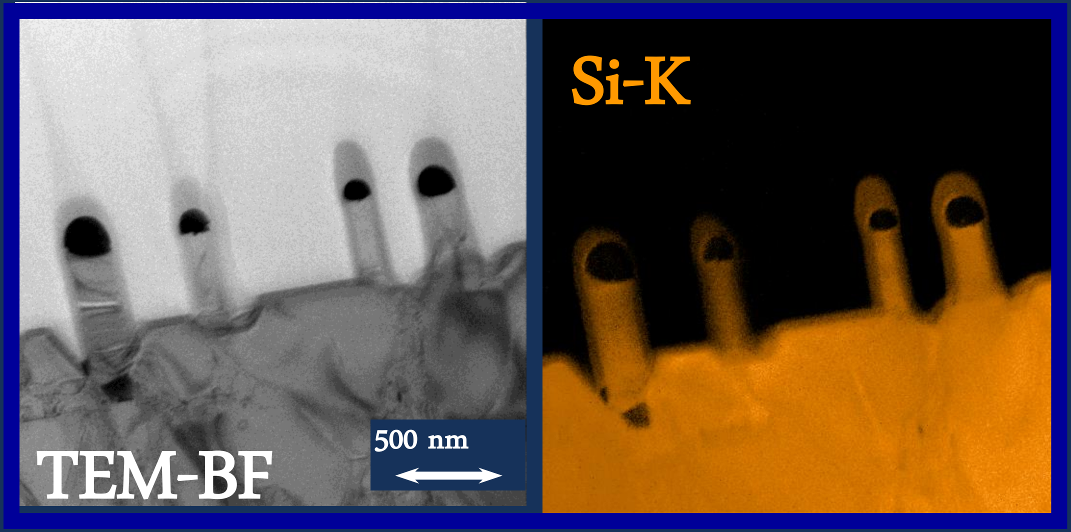
Electron microscopy micrographs of the Si NWs grown by EBE on Si(111) at 700°C for 1h at emission current 80 mA and Au thickness of 1.2 nm: (a) scanning electron microscopy (SEM) image; (b) transmission electron microscopy (TEM) image.

Oxidation of Si NWs



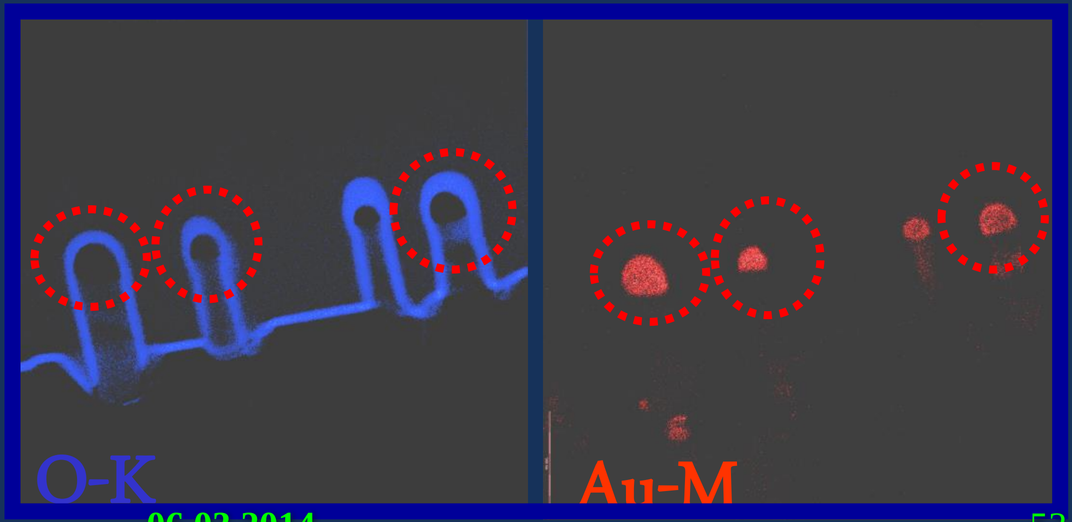
Electron microscopy micrographs of the Si NWs annealed in air at 800 °C for 1h: (a) TEM image; (b) SEM image.

Oxidation of Si NWs



Electron energy loss spectrosc. (EELS) & Energy-filtered TEM

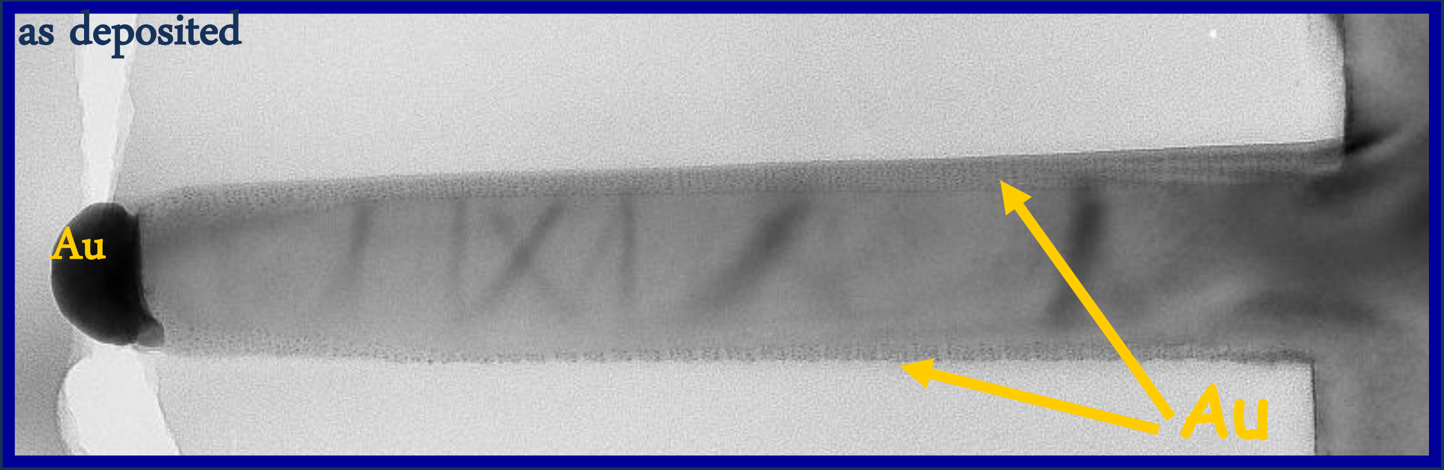
Elemental distributions
in the region of Si
nanowires
on Si(111) in cross-section
(Growth by EBE)



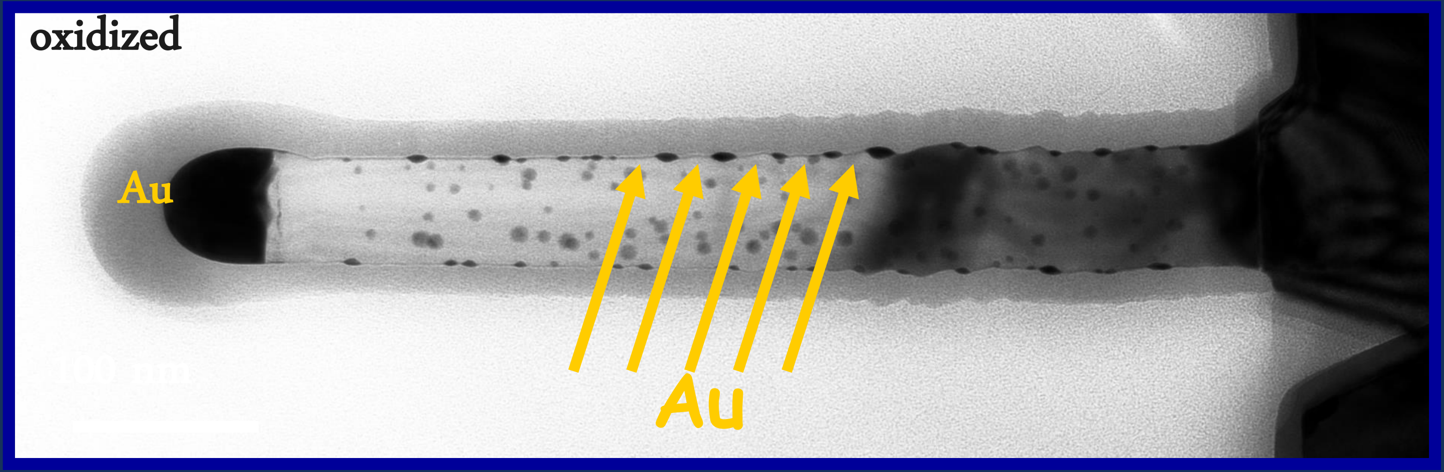
Oxidation of Si NWs

EBE

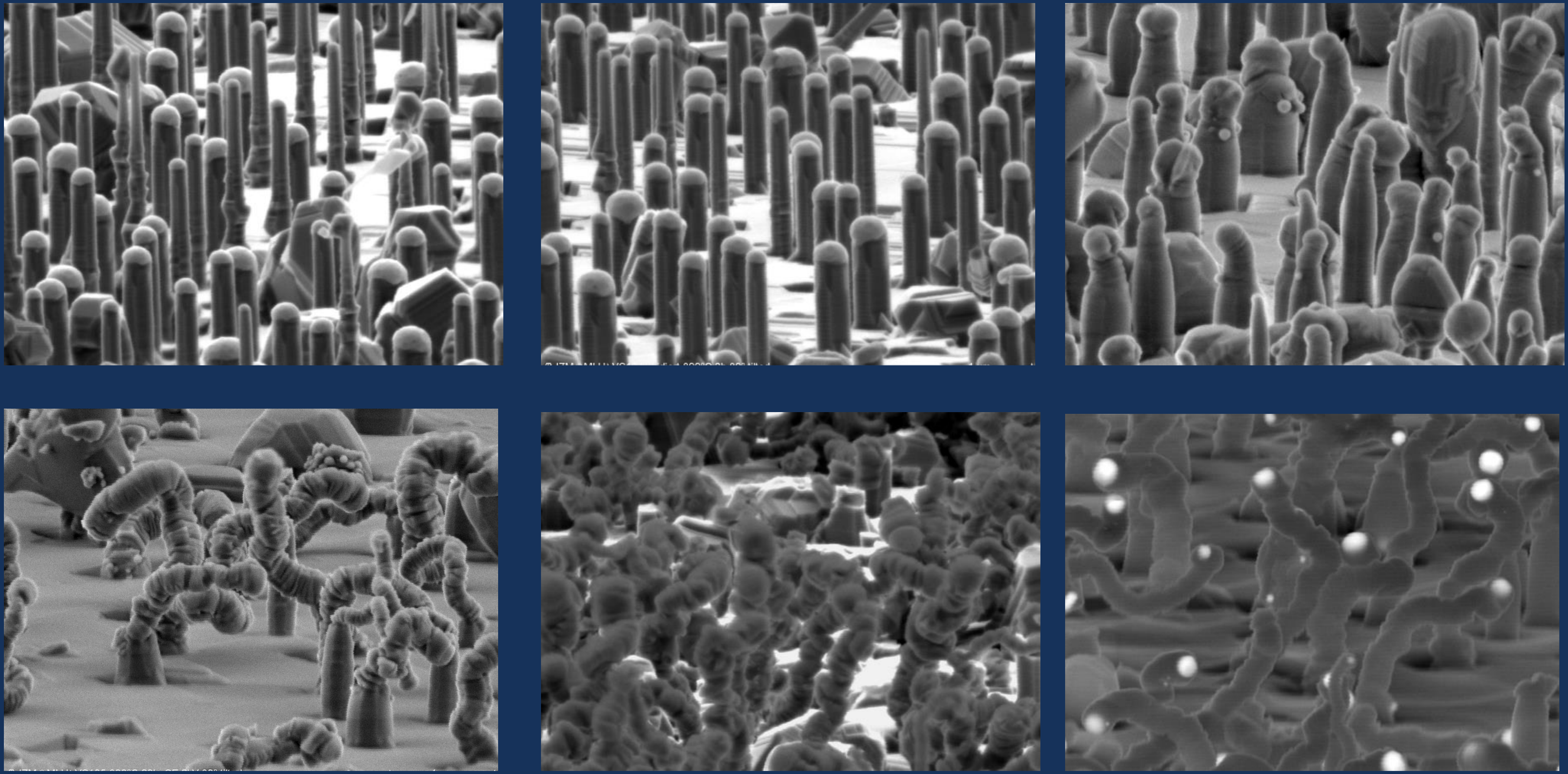
T = 550°C
60 min
Si(111)
80mA



T_{ox} = 800°C
60 min

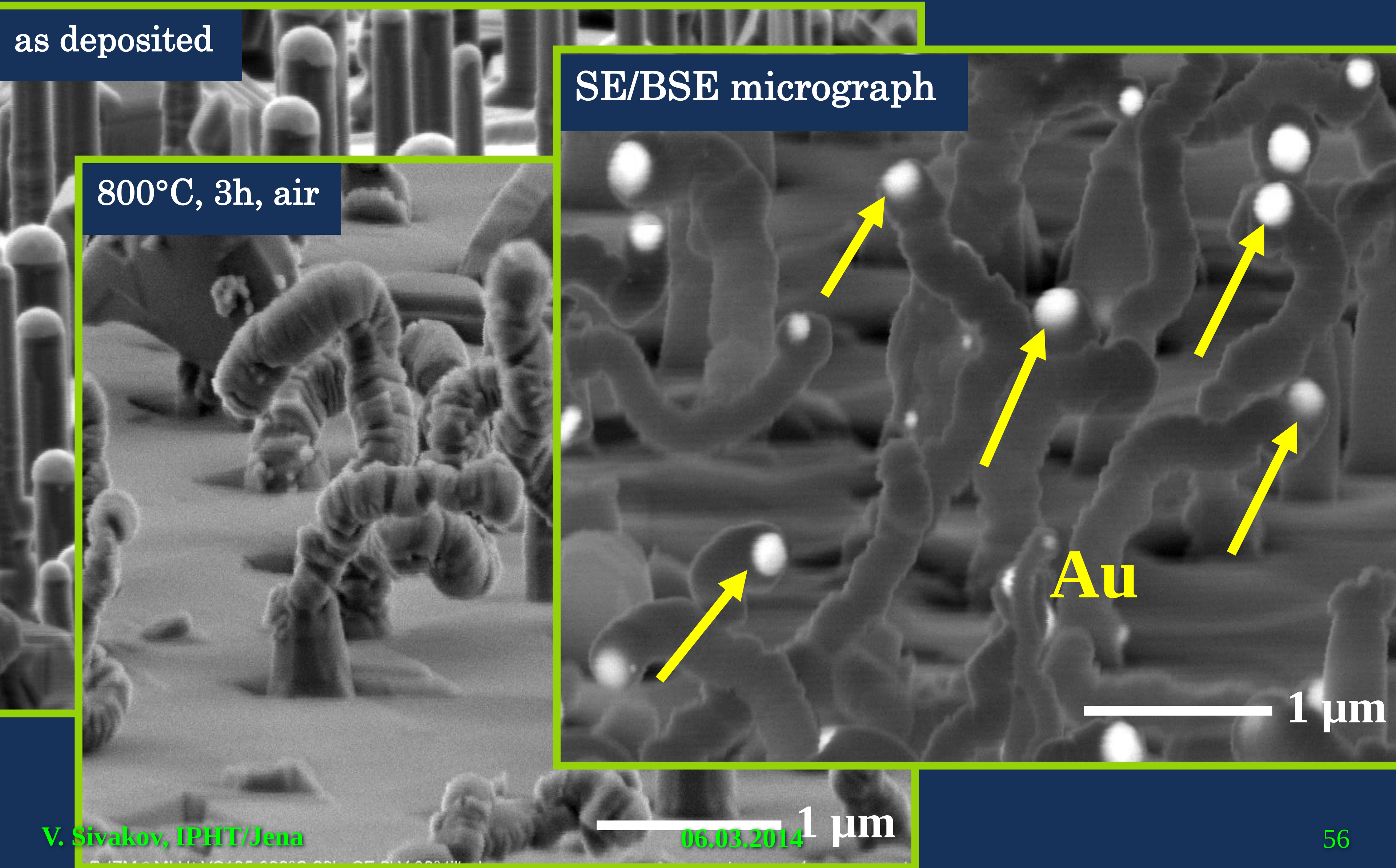


Oxidation of Si NWs

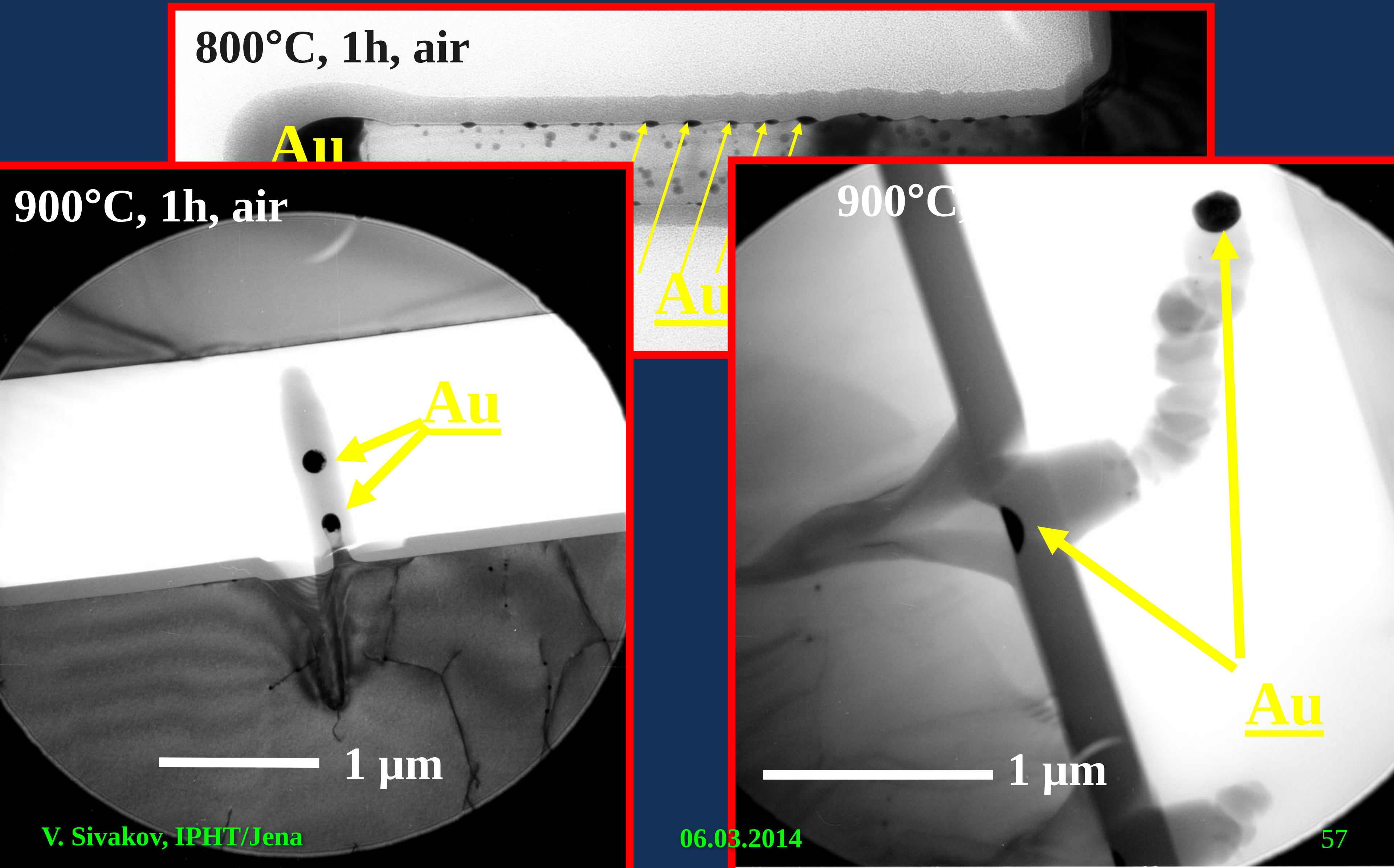


SEM cross section micrographs of the silicon nanowires heat treated at oxidative atmosphere for: (a) 0h, as deposited; (b) 300 °C, 3 h; (c) 500 °C, 3h; (d) 800 °C, 3h; (e) 900 °C, 3h; (f) Au EDX mapping of the sample heat treated at 900 °C.

Oxidation of Si NWs



Oxidation of Si NWs



Oxidation of Si NWs

It is well known [1] that when O_2 reacts with Si surfaces two processes can occur:

(i) ***passive oxidation***, at low *T* and high O_2 partial pressures (pO_2, which results in the formation of SiO_2 through the reaction

$Si+O_2 \rightarrow SiO_2$ (1)

(ii) ***active oxidation***, at high *T* and low pO_2, which results in the etching of the Si surface by the formation of volatile SiO via the reaction

(iii) SiO can be released by the decomposition of the SiO_2 layer at the Si/SiO_2 interface through the reaction

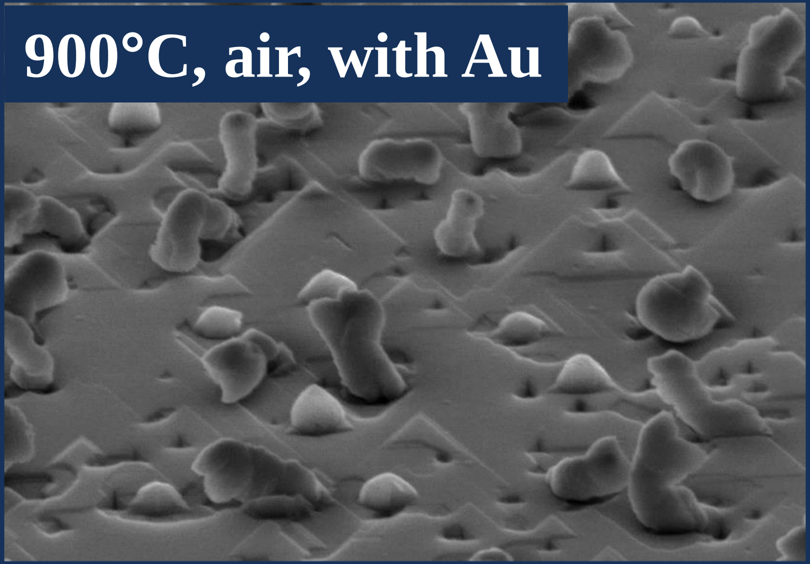
$Si+SiO_2 \rightarrow 2SiO$ (3)

This reaction is also known to occur at high *T* and low pO_2 and generate voids in thin SiO_2 layers [2].26 The equilibrium SiO partial pressure associated with this reaction is quite high at T = 900 C (pSiO ~ 10^{-3} Torr),[1] and thus this reaction can also be a parallel source of volatile SiO.

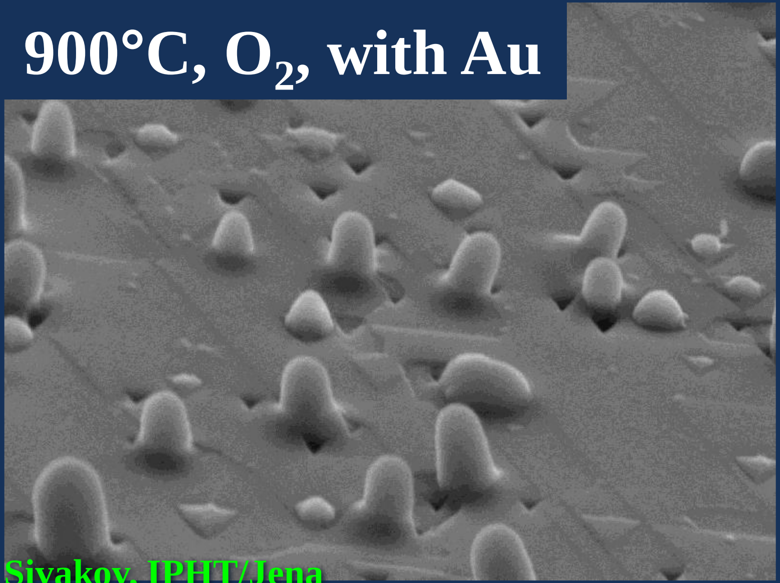
[1]. J.J.Landers and J.Morrison, *J. Appl. Phys.* 33, 2089 (1962).
[2]. R.T romp, G.W .Rublof f, P.Balk, and F.K.LeGoues, *Phys. Rev. Lett.* 55, 2332 (1985).

Oxidation of Si NWs

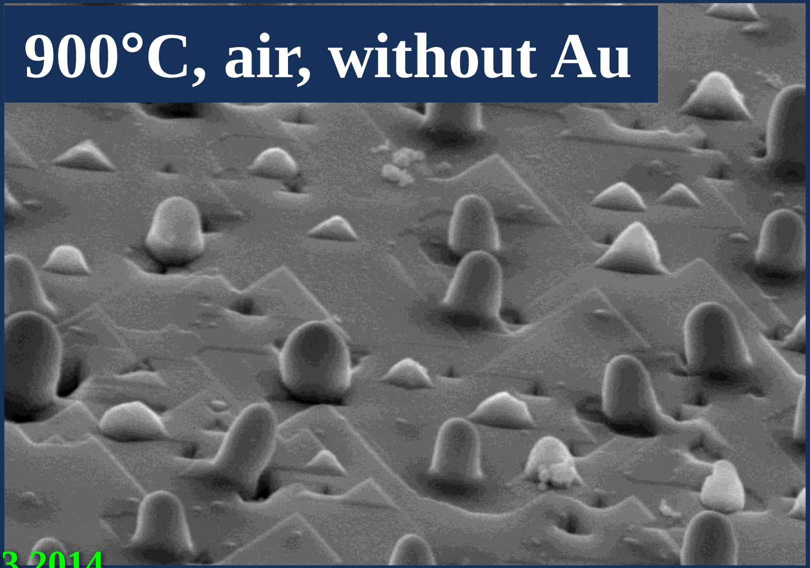
as deposited



900°C, air, with Au

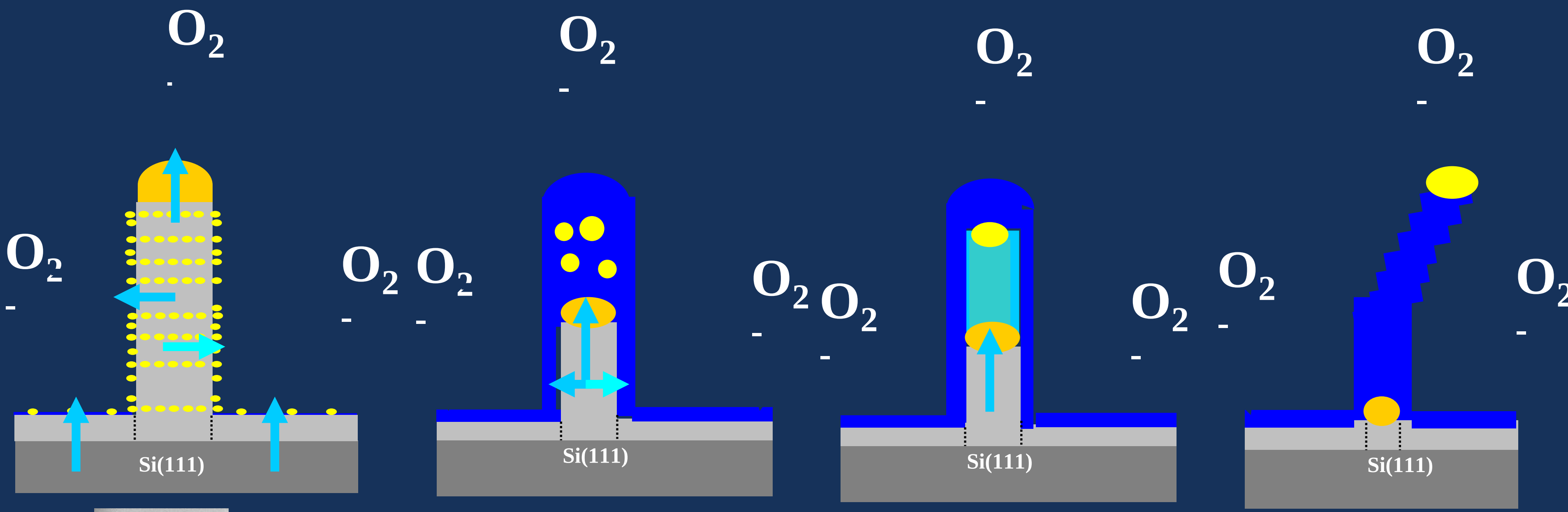


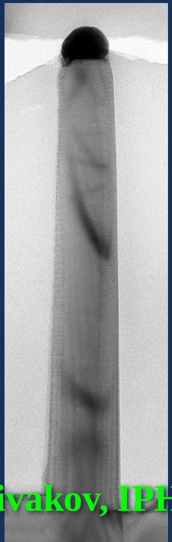
900°C, O_2, with Au

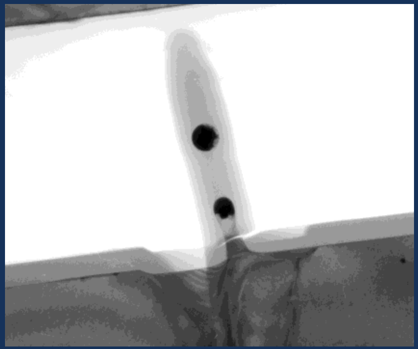


900°C, air, without Au

Oxidation of Si NWs

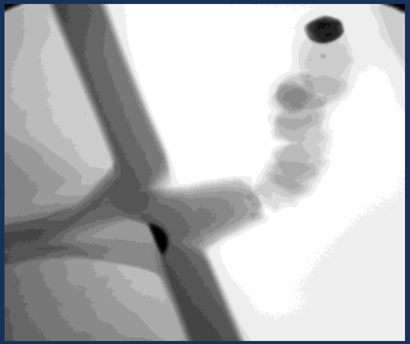






$Si+SiO_2 \rightarrow 2SiO$?????

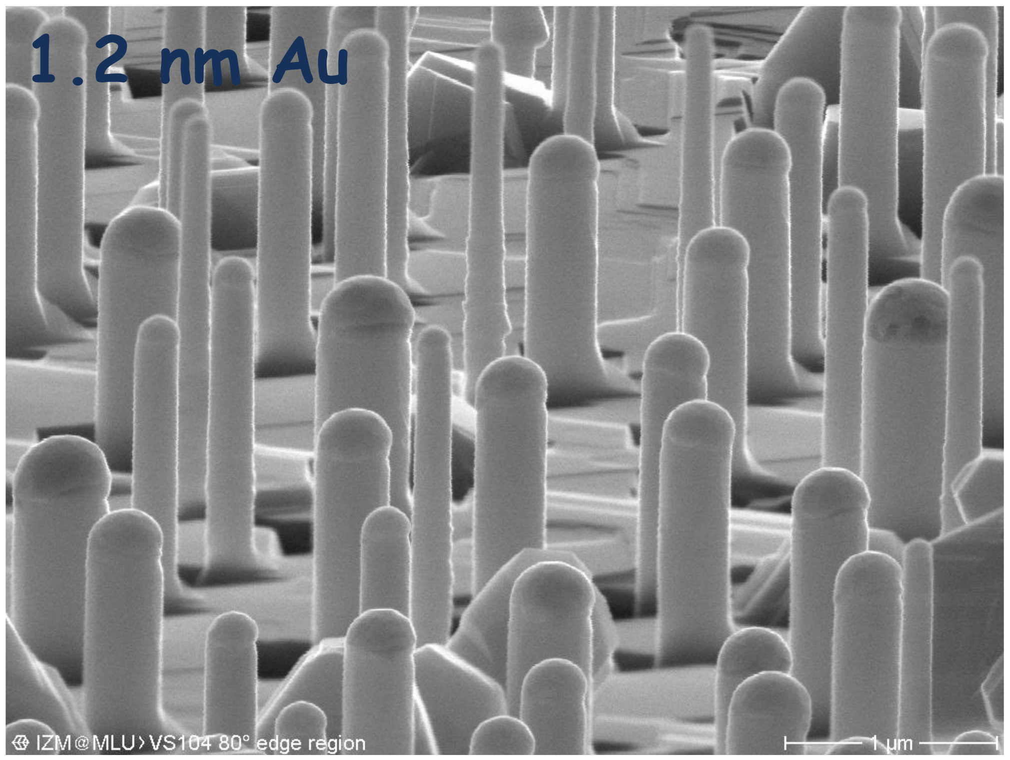
900°C



$2SiO \rightarrow Si+SiO_2$???

900°C, 10^{-3} Torr

Oxidation of Si NWs



SERS@TERS

M. Becker, V. Sivakov et al., NanoLett. 7(1), 75(2007).

Electronic Devices

Implantation of p- and n-dopands

1D Nanosensors

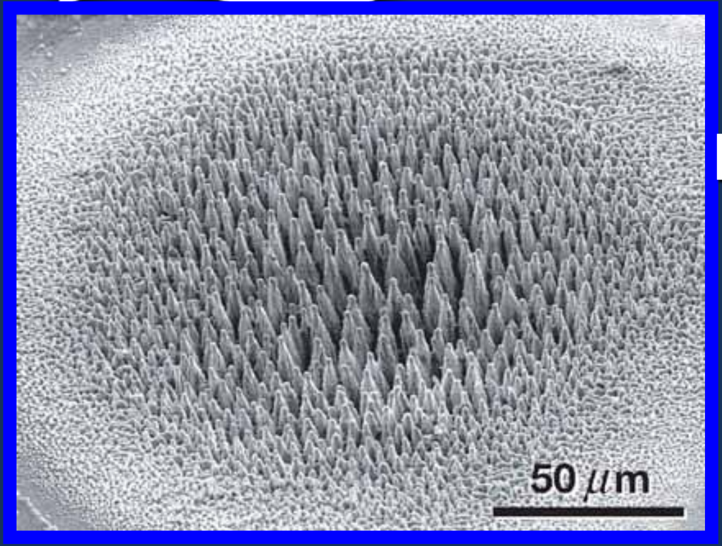
Outline

1. Bottom-up (VLS) Technology
2. **Application and Problematic of VLS NWs**
3. Top-down vs Bottom-up
4. NWs a Key for Novel Devices

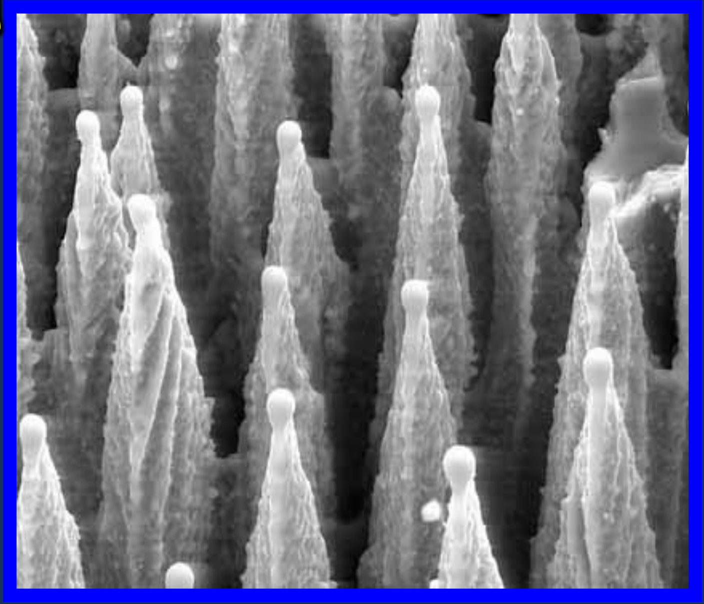
Disadvantages of Bottom-Up/VLS Process

- Expensive, Many Steps Process
- Contamination by Catalyst
- Difficulties by Epitaxy Realization
- Defects in Single Crystal (twins)
- Arrays Realization Difficulties

Motivation



BLACK SILICON



Electronic Imaging & Signal Processing DOI: 10.1117/2.2200812.0002

Black silicon is ready to revolutionize photoelectronics

Mark Crawford

The light-absorption properties of this accidentally discovered material promise sweeping advances from cameras to solar cells.

Black silicon moves out of the laboratory

OLE • December 2008 • optics.org/ole

A new photonic material could have significant advantages for detection, imaging andpower-generation applications

Motivation

Harvard University and SiOnyx Partner to Commercialize Black Silicon

Harvard University's Office of Technology Development (OTD) and SiOnyx, Inc. today announced that SiOnyx has exclusively licensed Harvard's portfolio of black silicon patents.

Black silicon, a novel laser implant technique that radically alters the photonic properties of semiconductor devices, was discovered by Harvard's Eric Mazur, Balkanski Professor of Physics and Applied Physics, who holds a joint appointment in the Faculty of Arts and Sciences (FAS) and the School of Engineering and Applied Sciences (SEAS).

A highly light-absorbent material, black silicon absorbs nearly twice the visible light of regular silicon and detects infrared light that is normally invisible to silicon based devices, a capability that allows for dramatic performance enhancements in applications ranging from simple light detection to advanced digital imaging and solar energy.

In consideration for licensing the patents, Harvard has received an equity position in SiOnyx and will receive downstream royalties. SiOnyx also recently raised $11 million in funding from Harris & Harris, Polaris Venture Partners and RedShift Ventures.

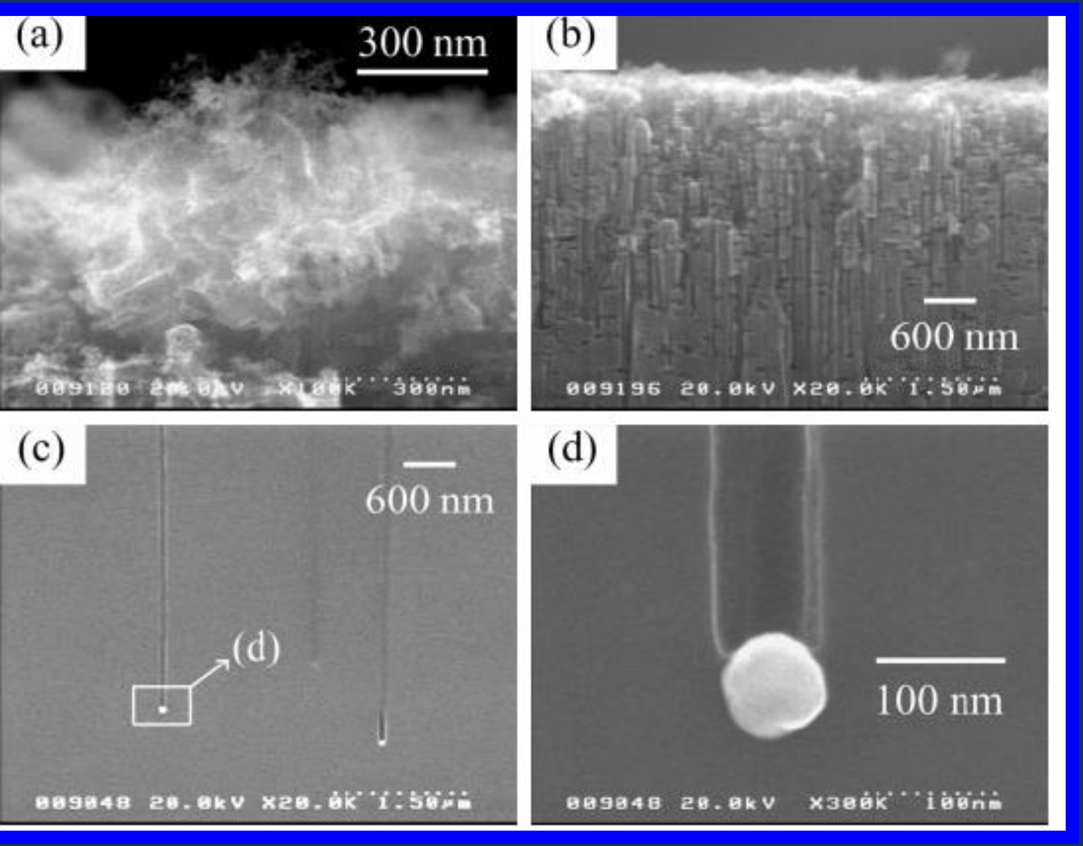
Is it possible to realize such nanostructures by chemical methods?

M-Si-HF Interaction
M= Pt, Au, Ag

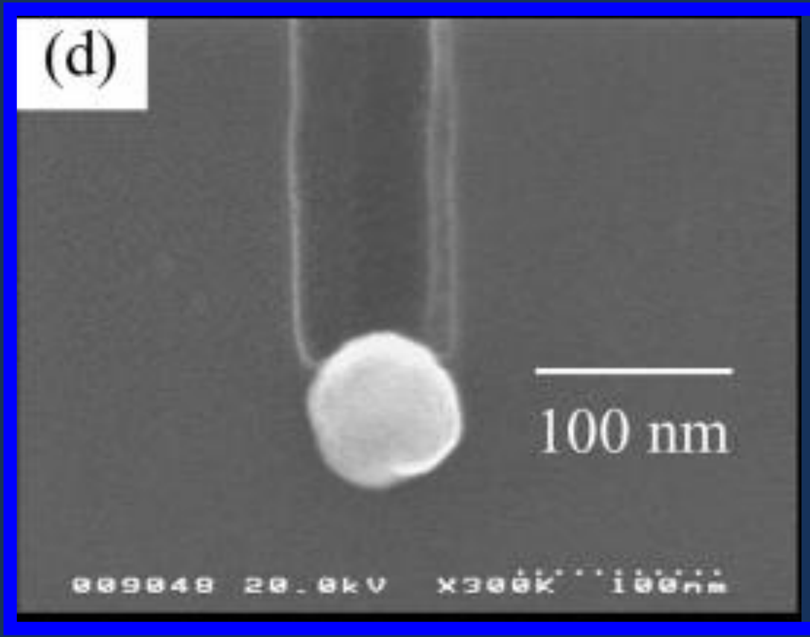
Boring Deep Cylindrical Nanoholes in Silicon Using Silver Nanoparticles as a Catalyst

K. Tsujino, M. Matsumura

Silicon shows unique electrochemical properties in solutions containing hydrofloric acid. Cylindrical holes electrochemically formed in silicon in these solutions have recently attracted much attention due to their possible applications in photonic crystals, micromachining, etc.



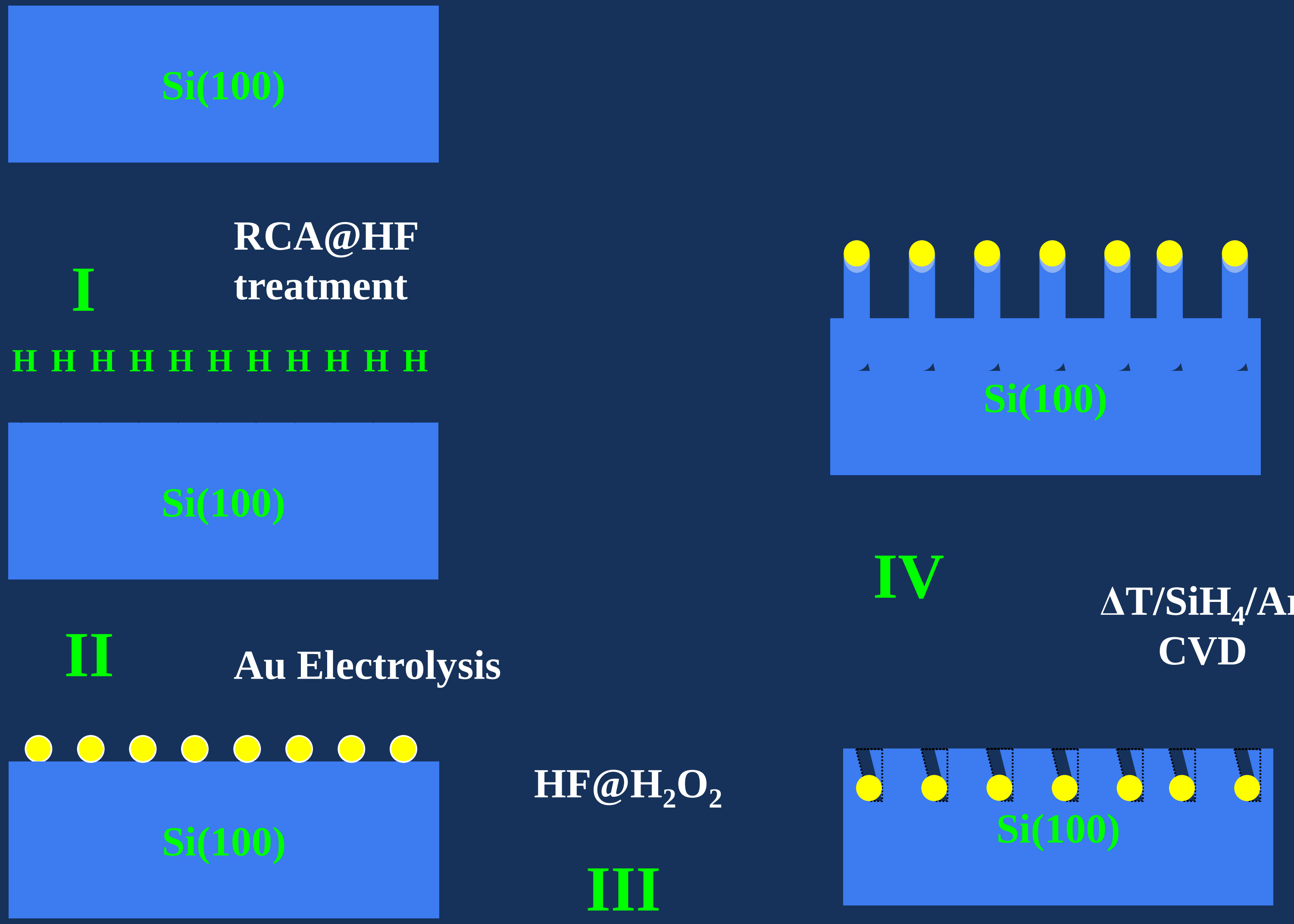
Etching Solution
50% HF+30%H_2O_2



Adv. Mater. 8(18), 17(2005)

Au-Si-HF Interaction

Arrays formation procedure



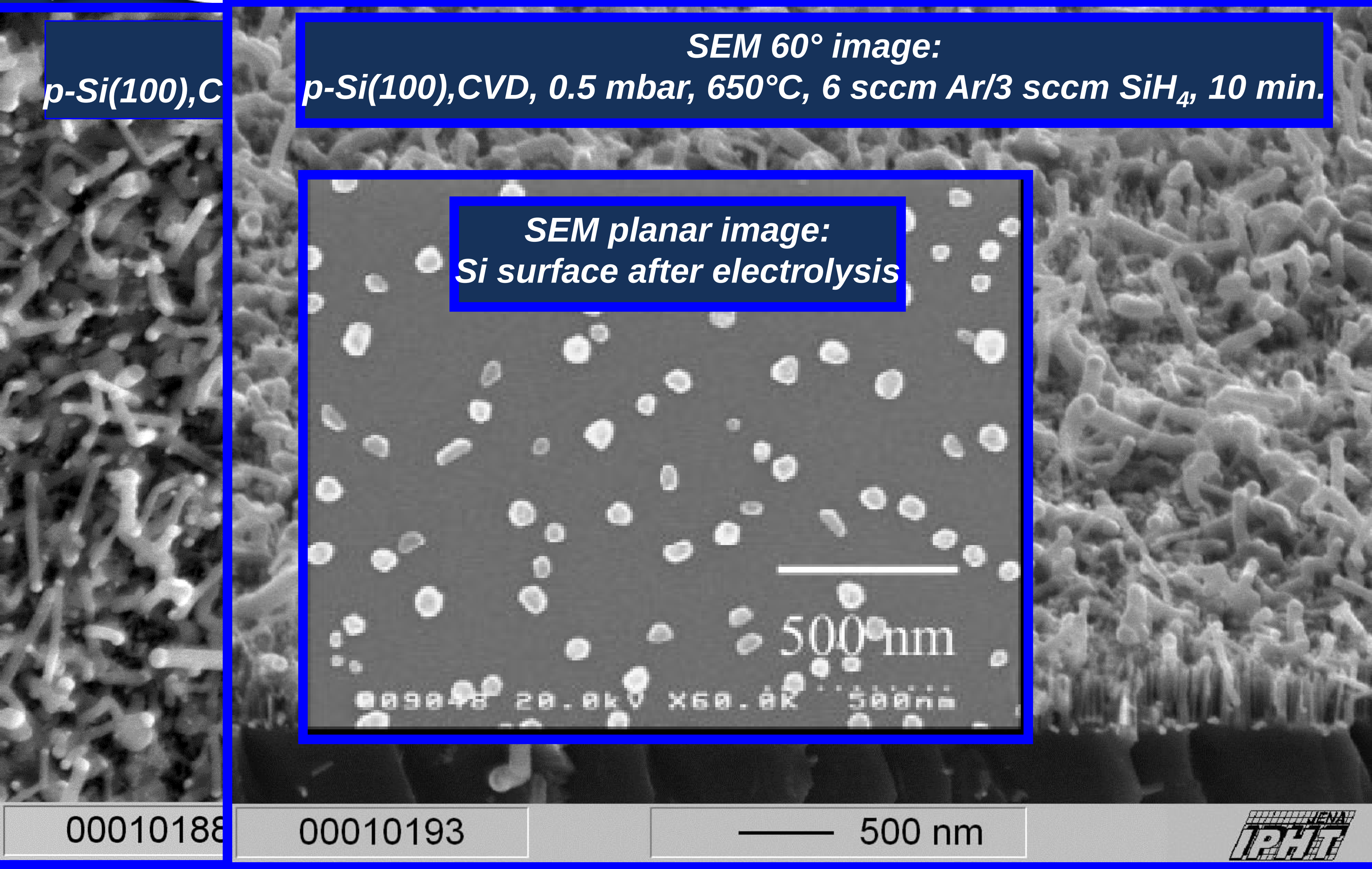
I RCA@HF treatment

II Au Electrolysis

III HF@H_2O_2

IV $\Delta T/SiH_4/Ar$ CVD

Au-Si-HF Interaction



p-Si(100),C

SEM 60° image:

p-Si(100),CVD, 0.5 mbar, 650°C, 6 sccm Ar/3 sccm SiH_4, 10 min.

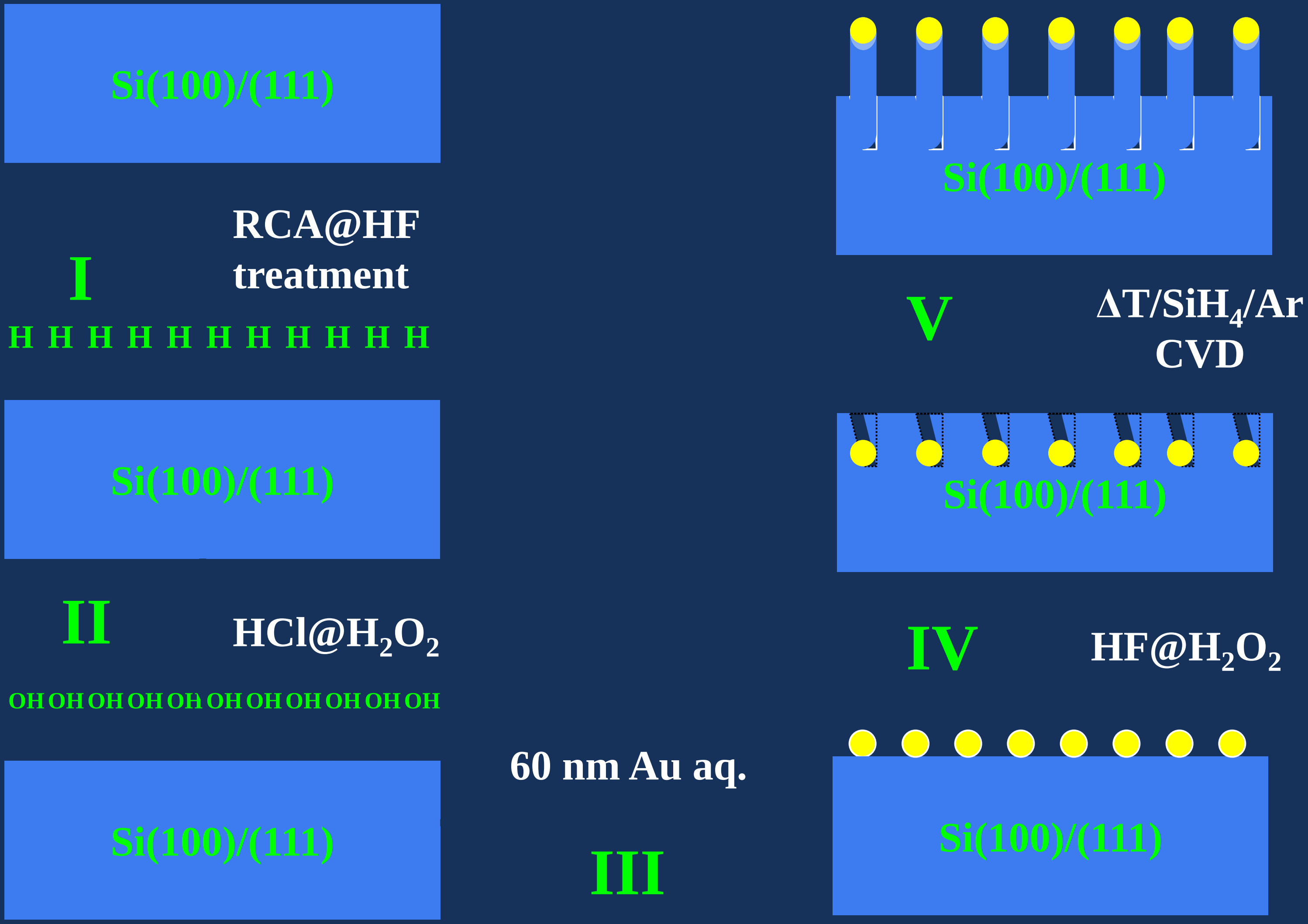
SEM planar image:

Si surface after electrolysis

$Au_{colloid}$-Si-HF Interaction

Arrays formation procedure:

Gold Colloids



Si(100)/(111)

I

RCA@HF treatment

H H H H H H H H H H H

Si(100)/(111)

II

HCl@H_2O_2

OH OH OH OH OH OH OH OH OH OH OH

Si(100)/(111)

60 nm Au aq.

III

Si(100)/(111)

IV

HF@H_2O_2

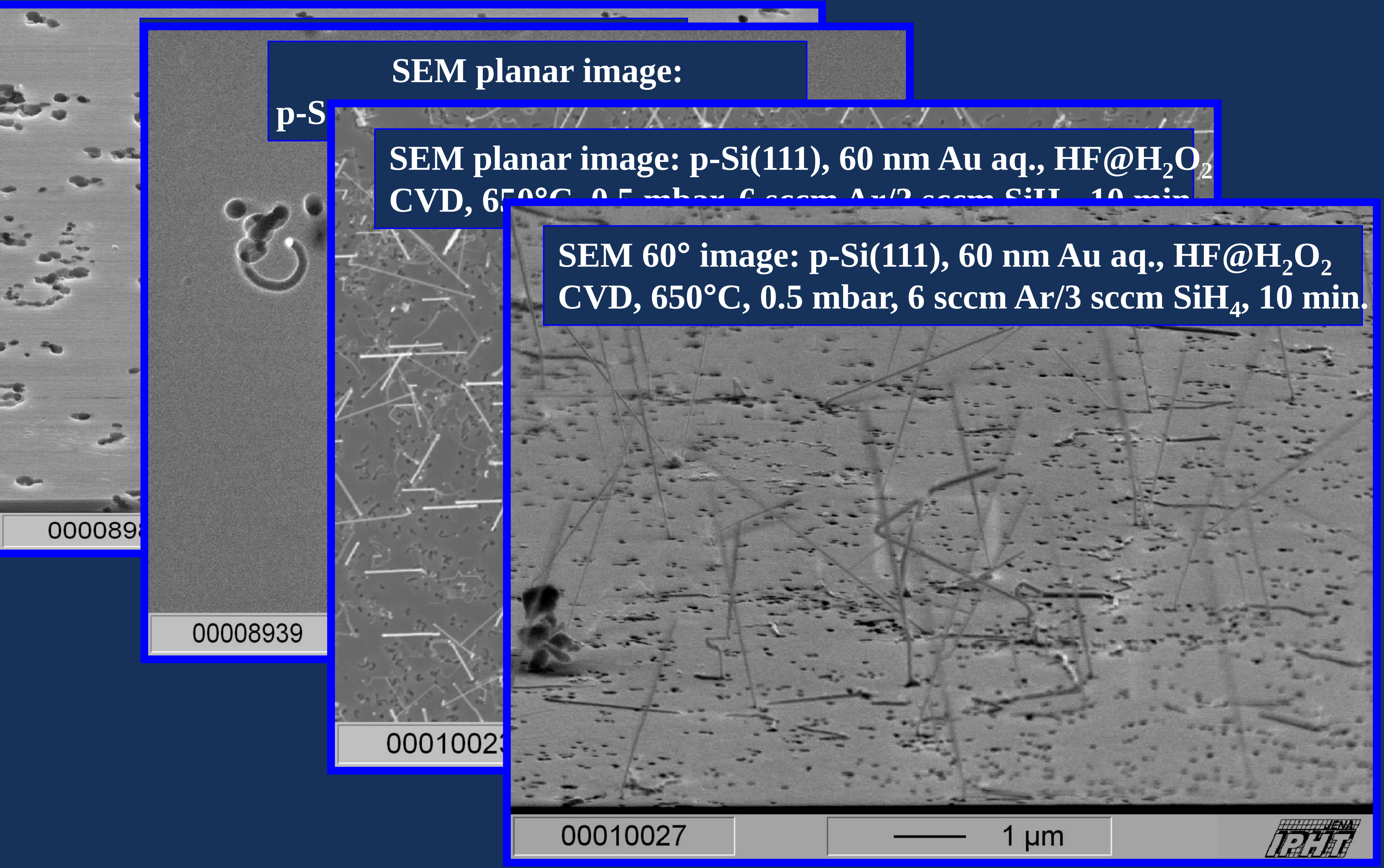
Si(100)/(111)

V

ΔT/SiH_4/Ar CVD

Si(100)/(111)

$Au_{colloid}$-Si-HF Interaction



SEM planar image:

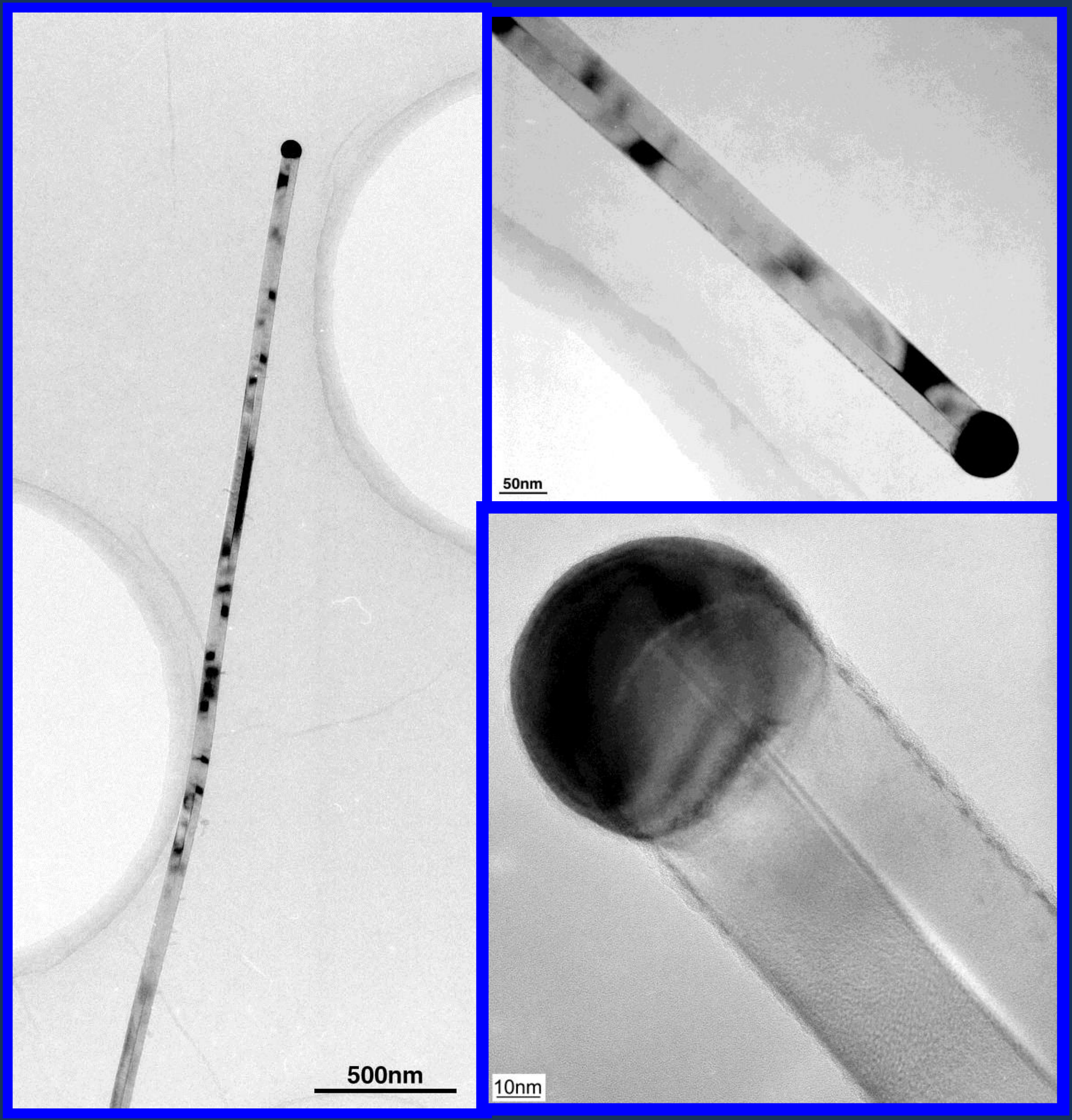
p-S

SEM planar image: p-Si(111), 60 nm Au aq., HF@H_2O_2

CVD, 65

SEM 60° image: p-Si(111), 60 nm Au aq., HF@H_2O_2
CVD, 650°C, 0.5 mbar, 6 sccm Ar/3 sccm SiH_4, 10 min.

$Au_{colloid}$-Si-HF Interaction



TEM: Si NWs

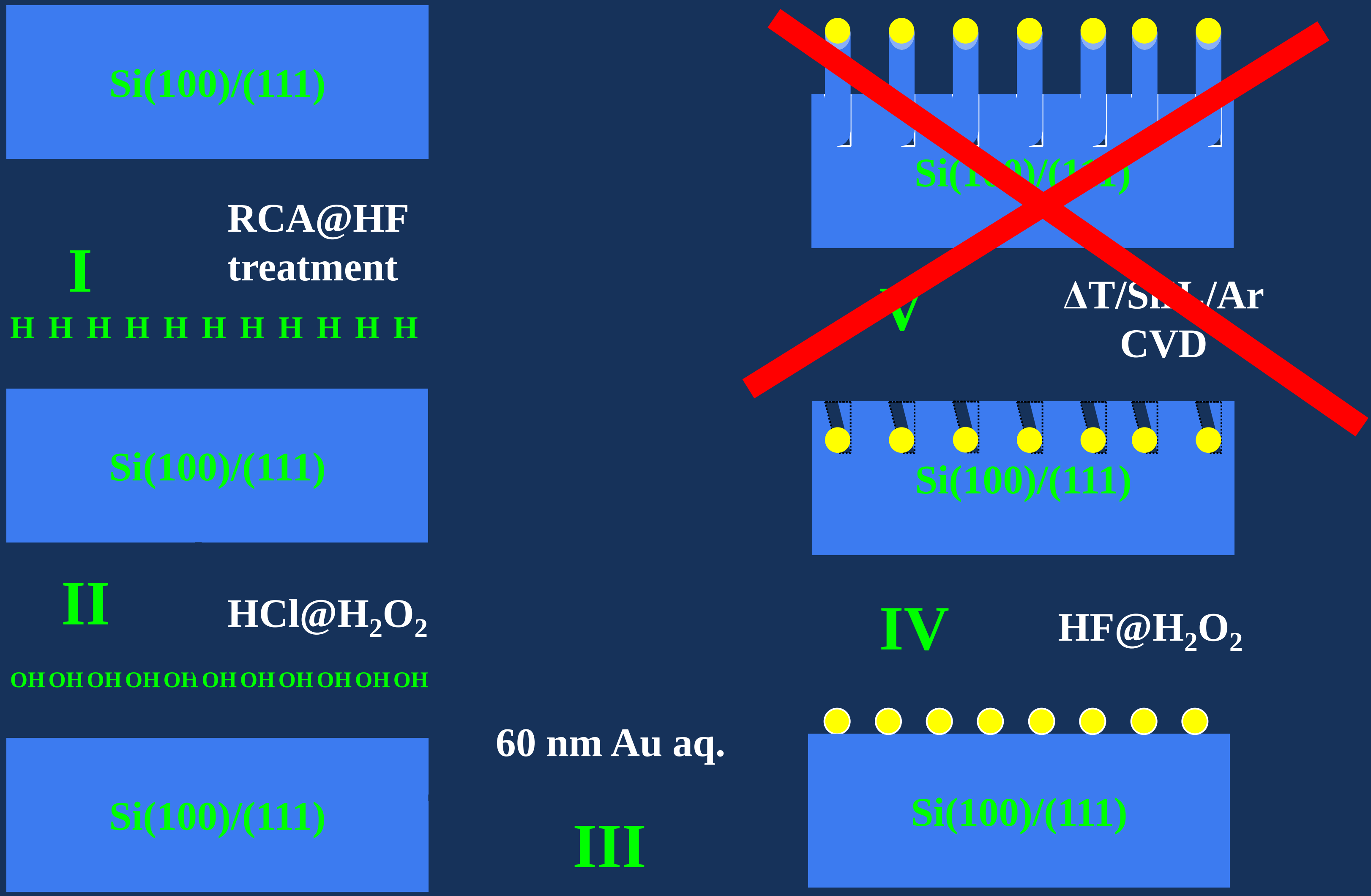
TEM: cross section

All NWs have twins!!!

$Au_{colloid}$-Si-HF Interaction

Arrays formation procedure:

Gold Colloids



Si(100)/(111)

I

RCA@HF treatment

H H H H H H H H H H H

Si(100)/(111)

II

$HCl@H_2O_2$

OH OH OH OH OH OH OH OH OH OH OH

Si(100)/(111)

60 nm Au aq.

III

Si(100)/(111)

IV

$HF@H_2O_2$

Si(100)/(111)

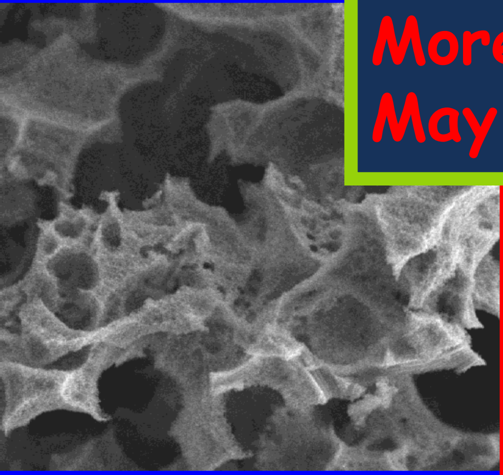
~~V~~

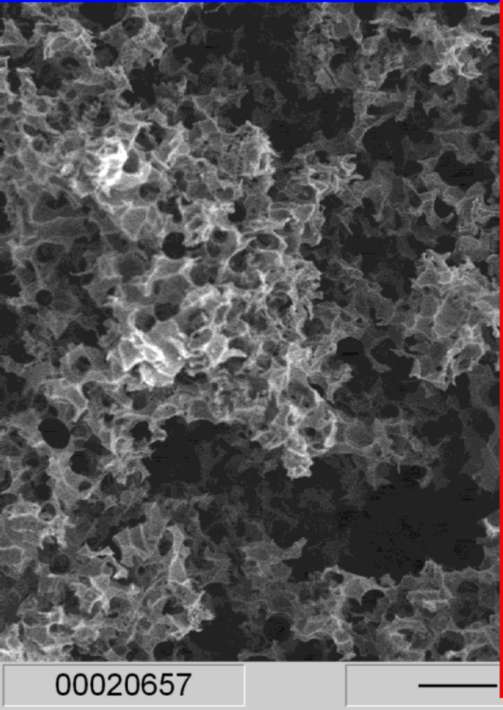
~~ΔT/SiH_4/Ar CVD~~

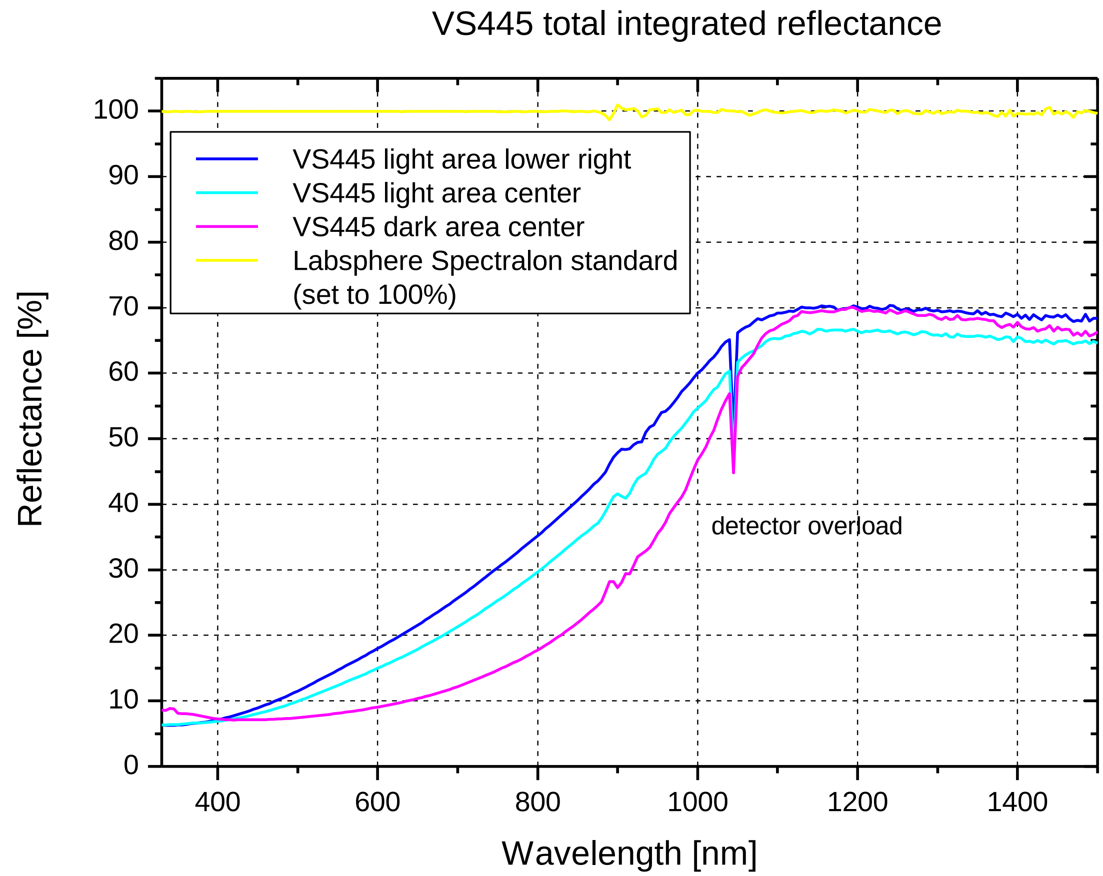
~~Si(100)/(111)~~

M-Si-HF Interaction
M= Pt, Au, Ag

More optic investigations are required!!!
May be photonic crystal properties???



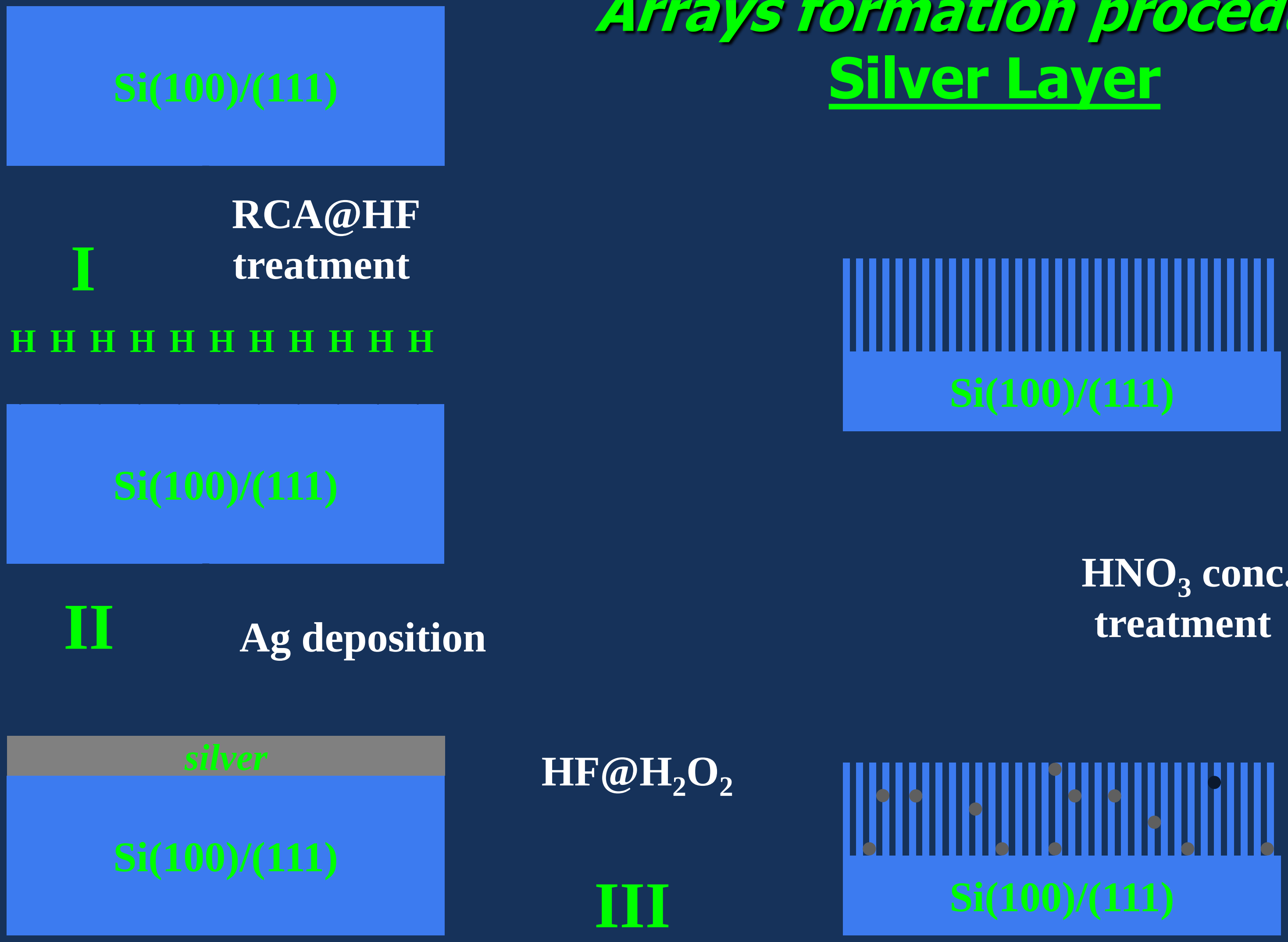



VS445 total integrated reflectance

Ag-Si-HF Interaction

Arrays formation procedure:

Silver Layer



I **RCA@HF treatment**

II **Ag deposition**

HF@H_2O_2

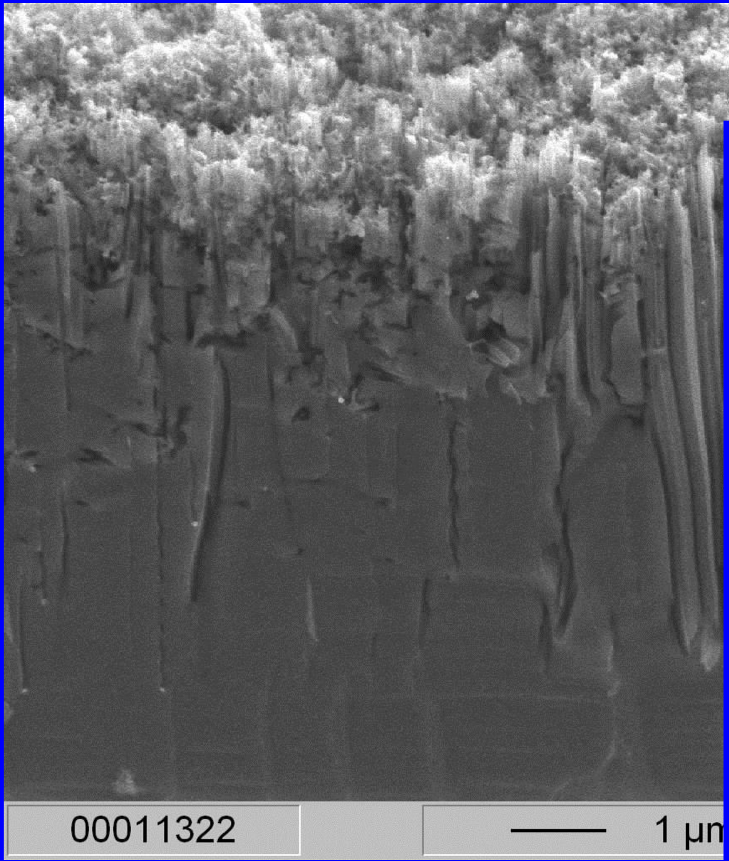
III

HNO_3 conc. treatment

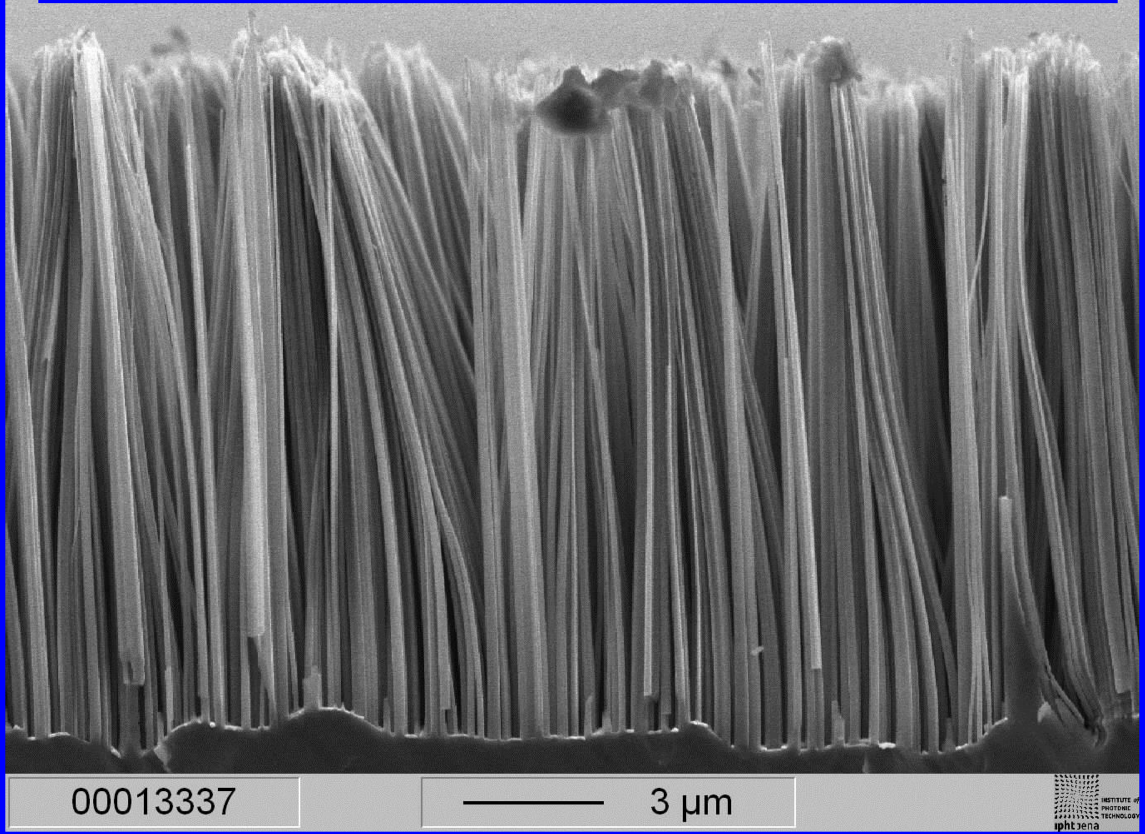
Preparation of silver layers by Dr. H. Schneidewind is gratefully acknowledged

Ag-Si-HF Interaction

SEM image:
25 nmAg//Si(111) treatment for 0.5h in HF/H_2O_2

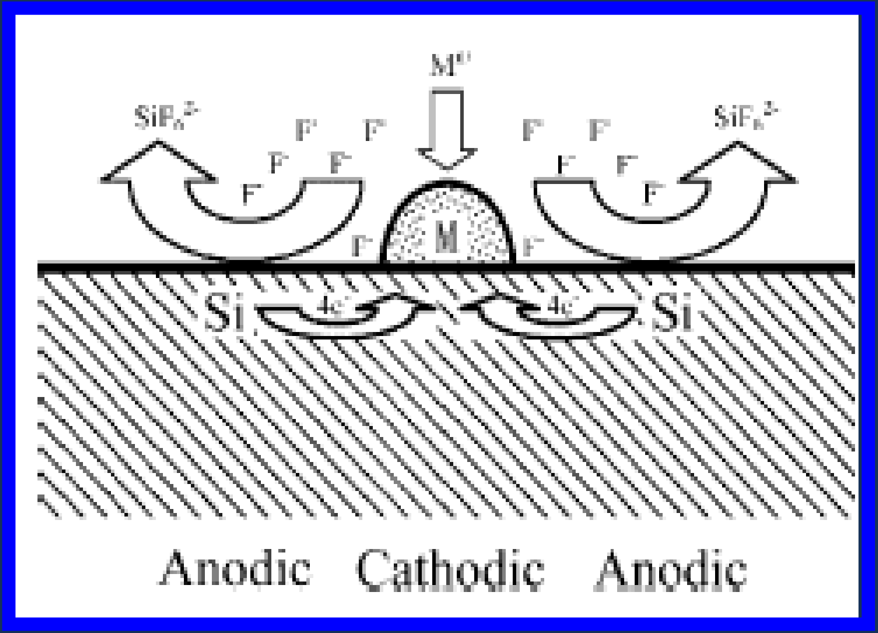


SEM image:
20nmAg//Si(111) treatment for 0.5h in HF/H_2O_2



$AgNO_3$-Si-HF Interaction

Growth Mechanism of SiNW Arrays



$$4Ag^+ \text{ (aq.)} + Si^0 \text{ (s)} + 6F^- \text{ (aq)} \rightarrow 4Ag^0\text{(s)} + SiF^{2-}_6 \text{ (aq.)}$$

K. Peng et.al., *Adv. Funct. Mater.*, 13(2), 127(2003)

$AgNO_3$-Si-HF Interaction

Arrays formation procedure:

Silver Nitrate

Si(100)/(111)

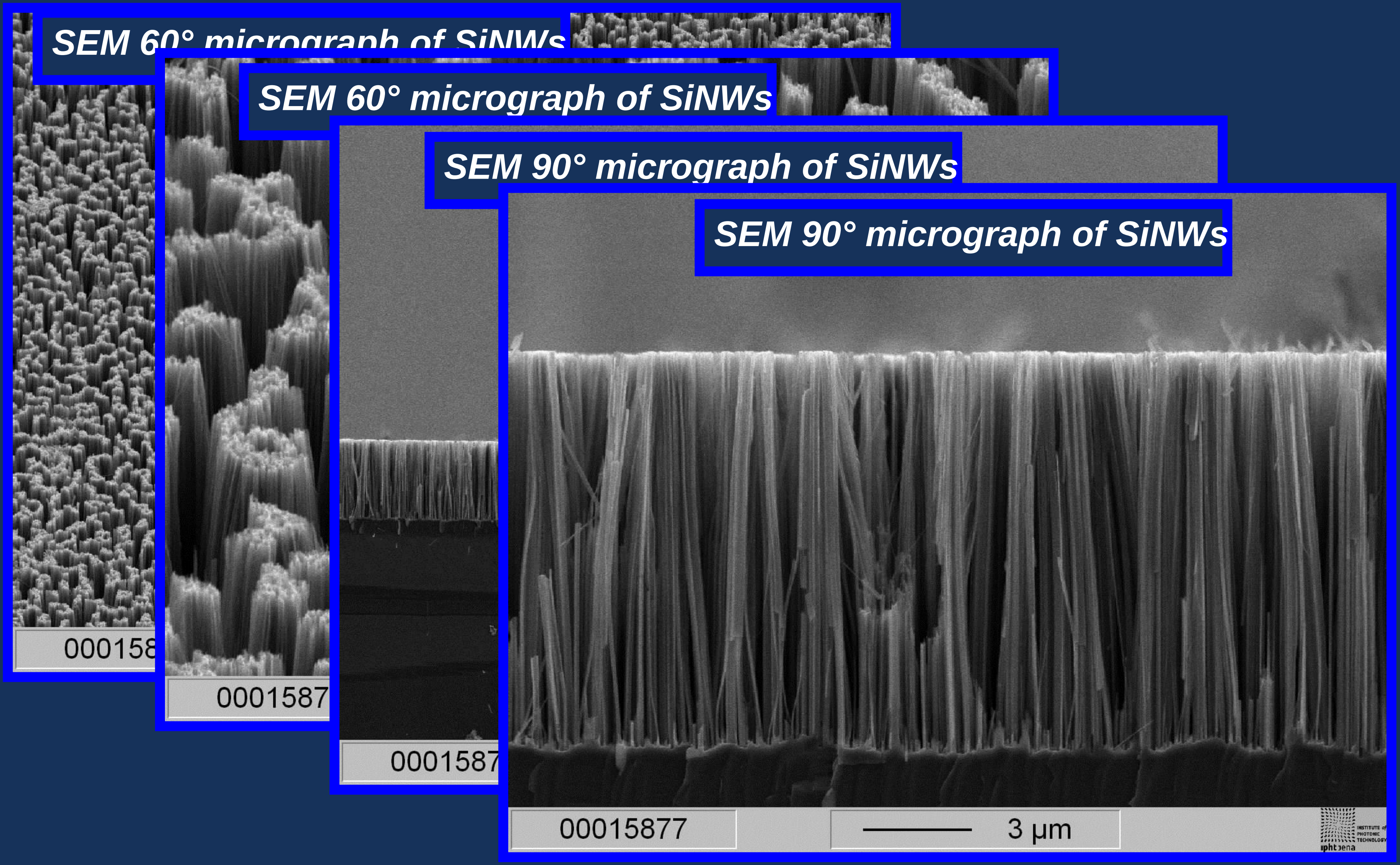
Si(100)/(111)

RCA@HF treatment

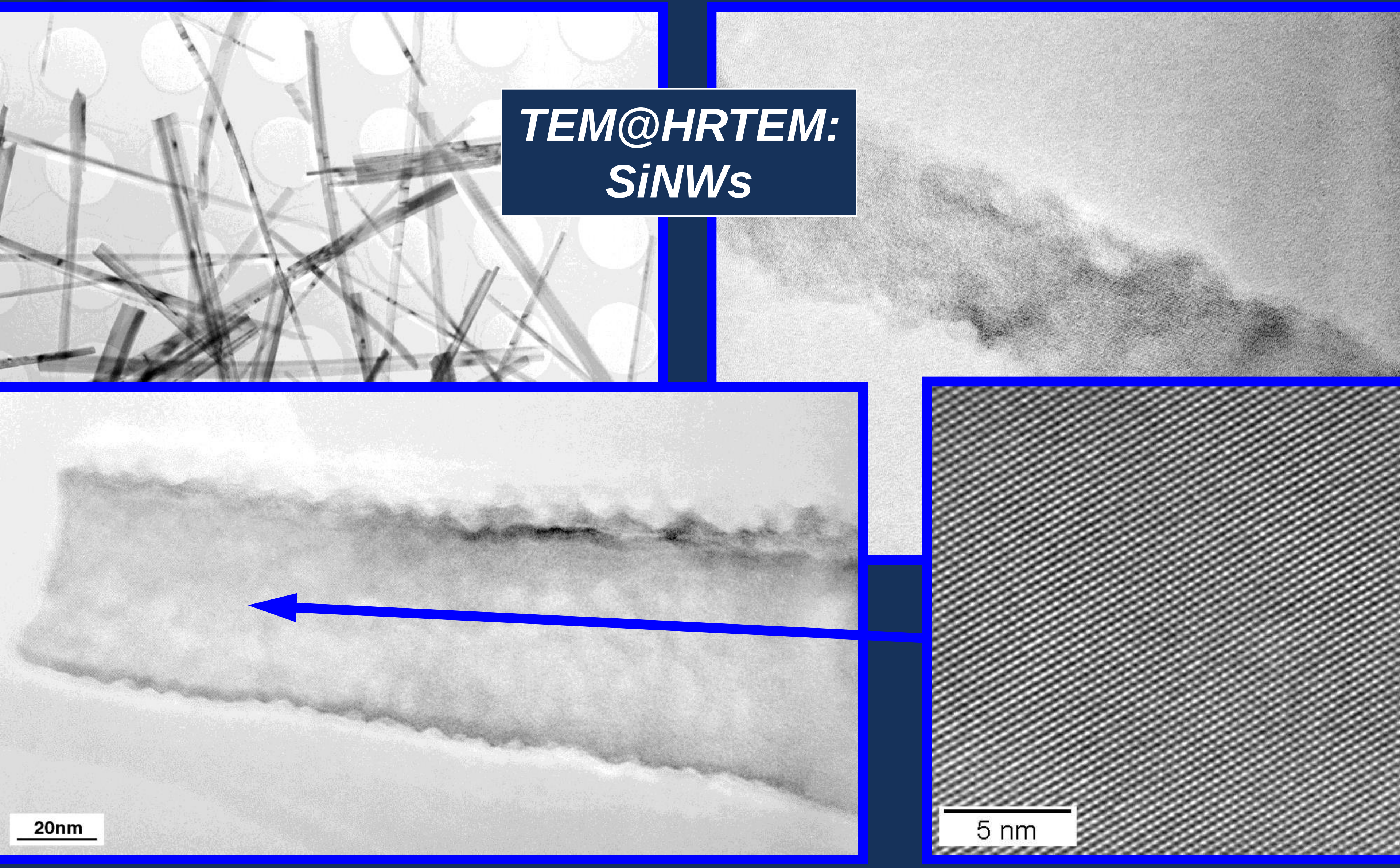
HNO_3 conc. treatment

$AgNO_3$/HF treatment

AgNO$_3$-Si-HF Interaction

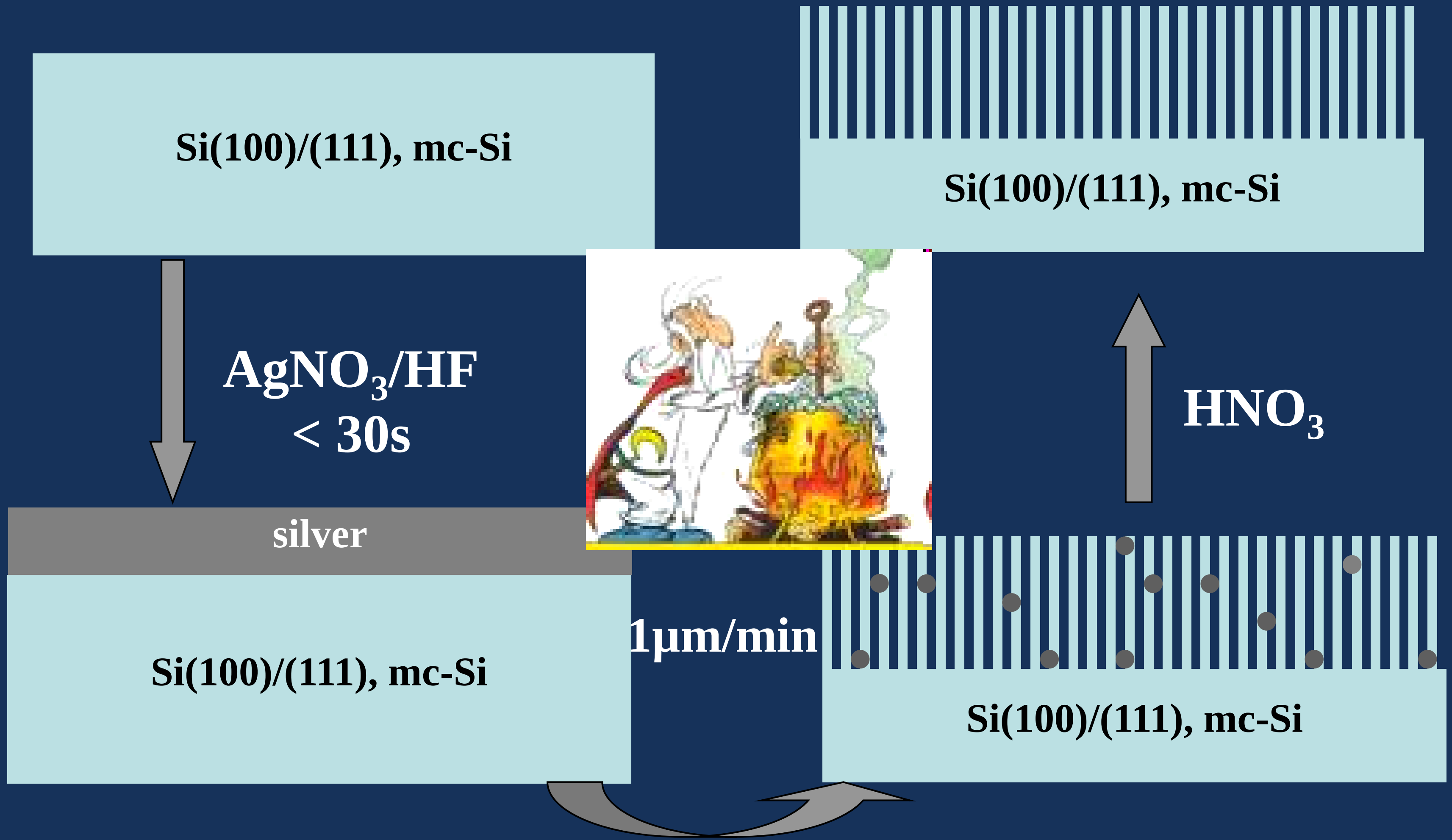


AgNO$_3$-Si-HF Interaction



TEM@HRTEM: SiNWs

Top-down: Wet-Chemical Etching



Si(100)/(111), mc-Si

$AgNO_3/HF$
< 30s

silver

Si(100)/(111), mc-Si

1µm/min

H_2O_2/HF

Si(100)/(111), mc-Si

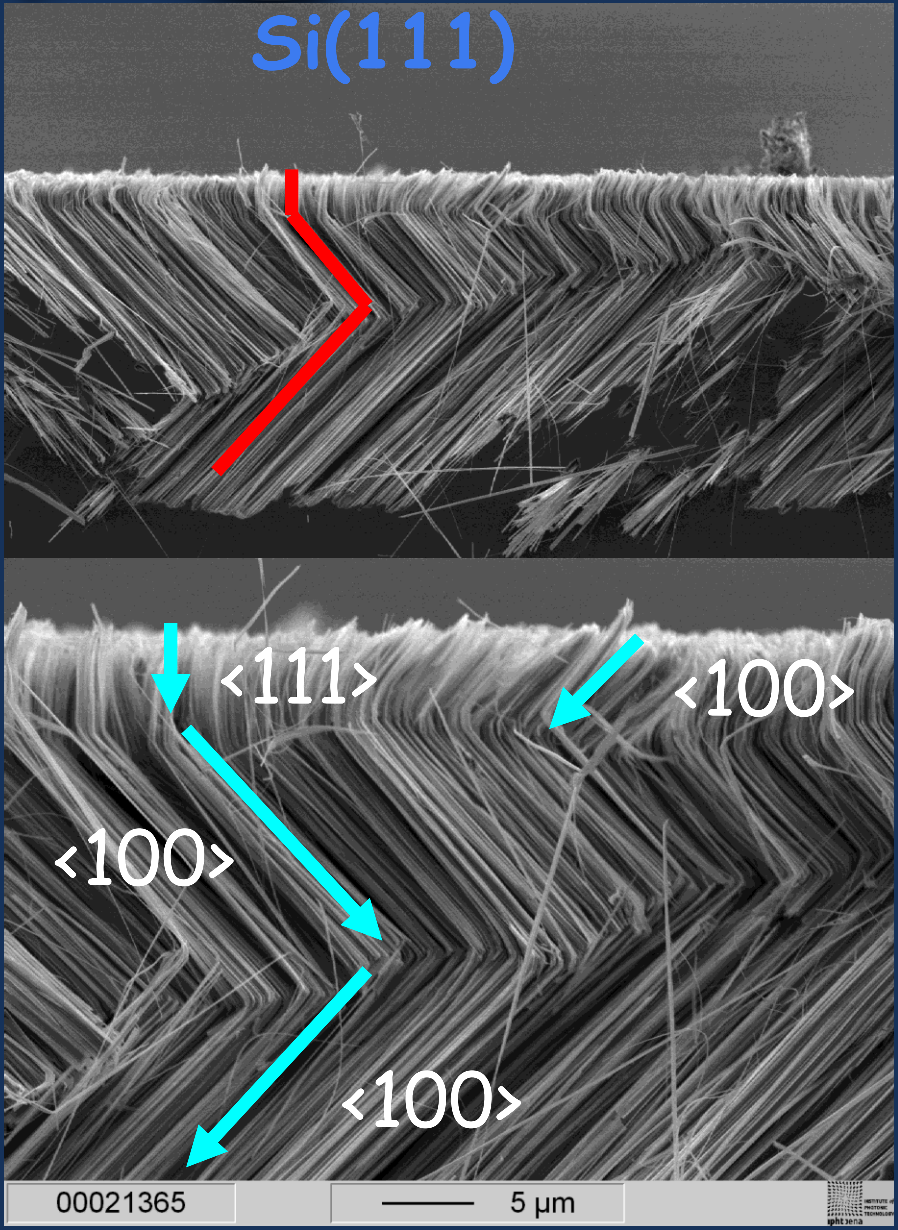
HNO_3

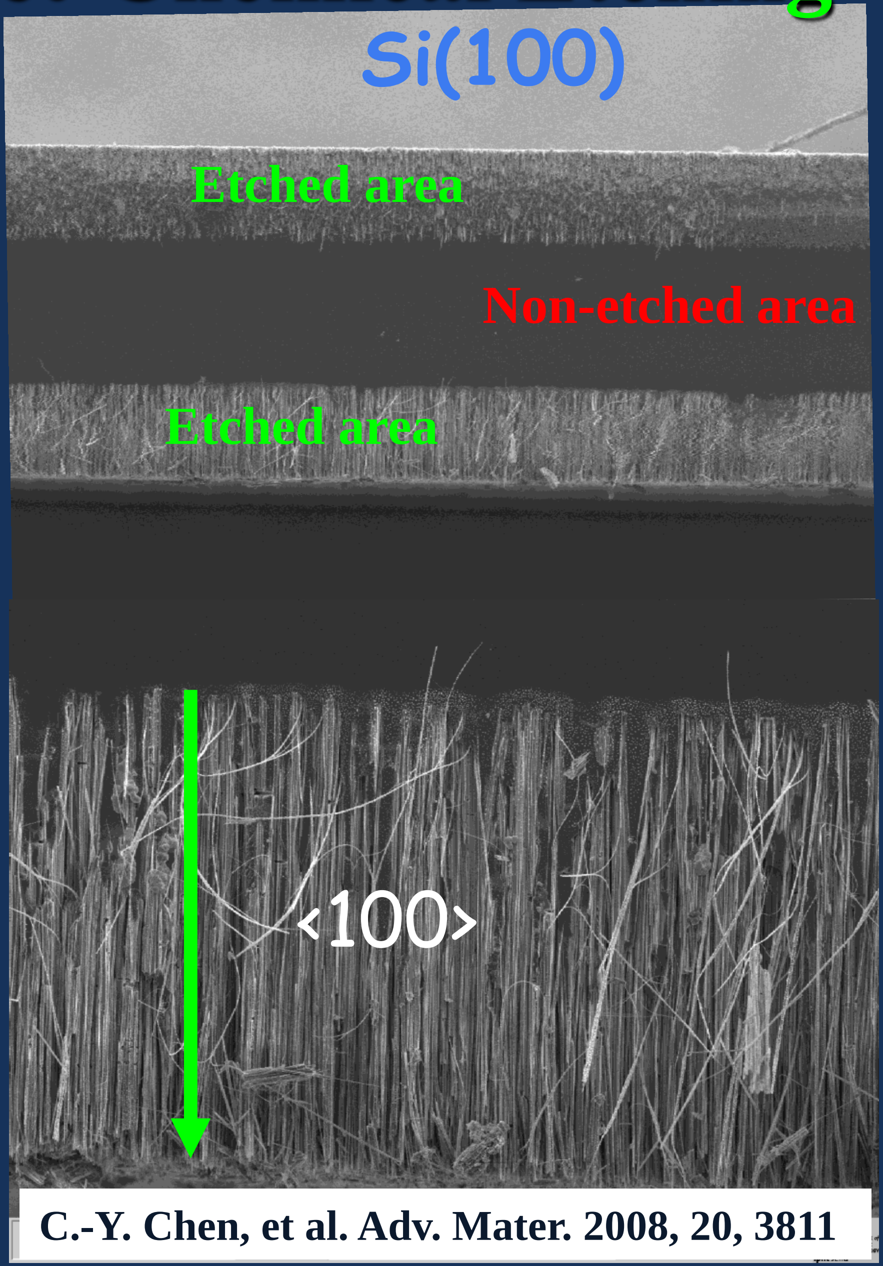
Si(100)/(111), mc-Si

V. A. Sivakov et al., J. Phys. Chem. C*114*, 3798–3803 (2010)

V. Sivakov et al., Intech "Nanowires - Fundamental Research", ISBN 978-953-307-327-9, p45 (2011)

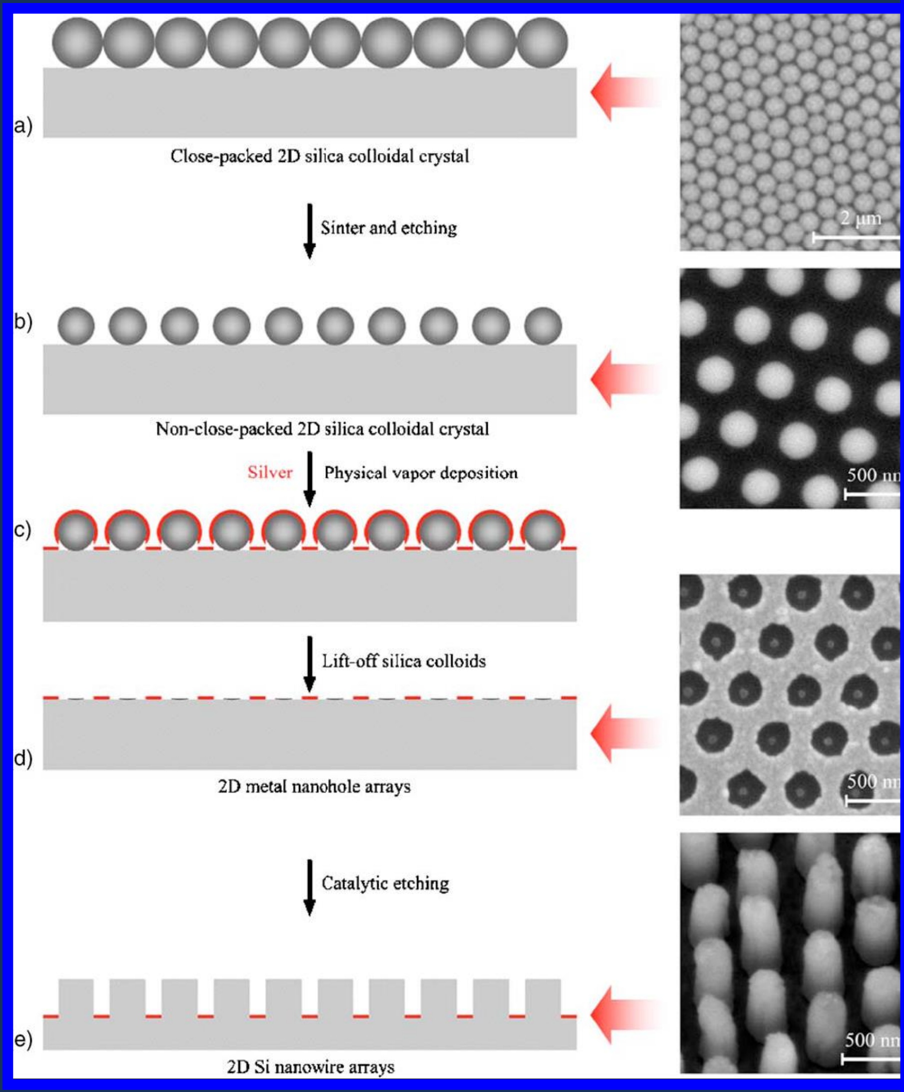
Top-down: Wet-Chemical Etching

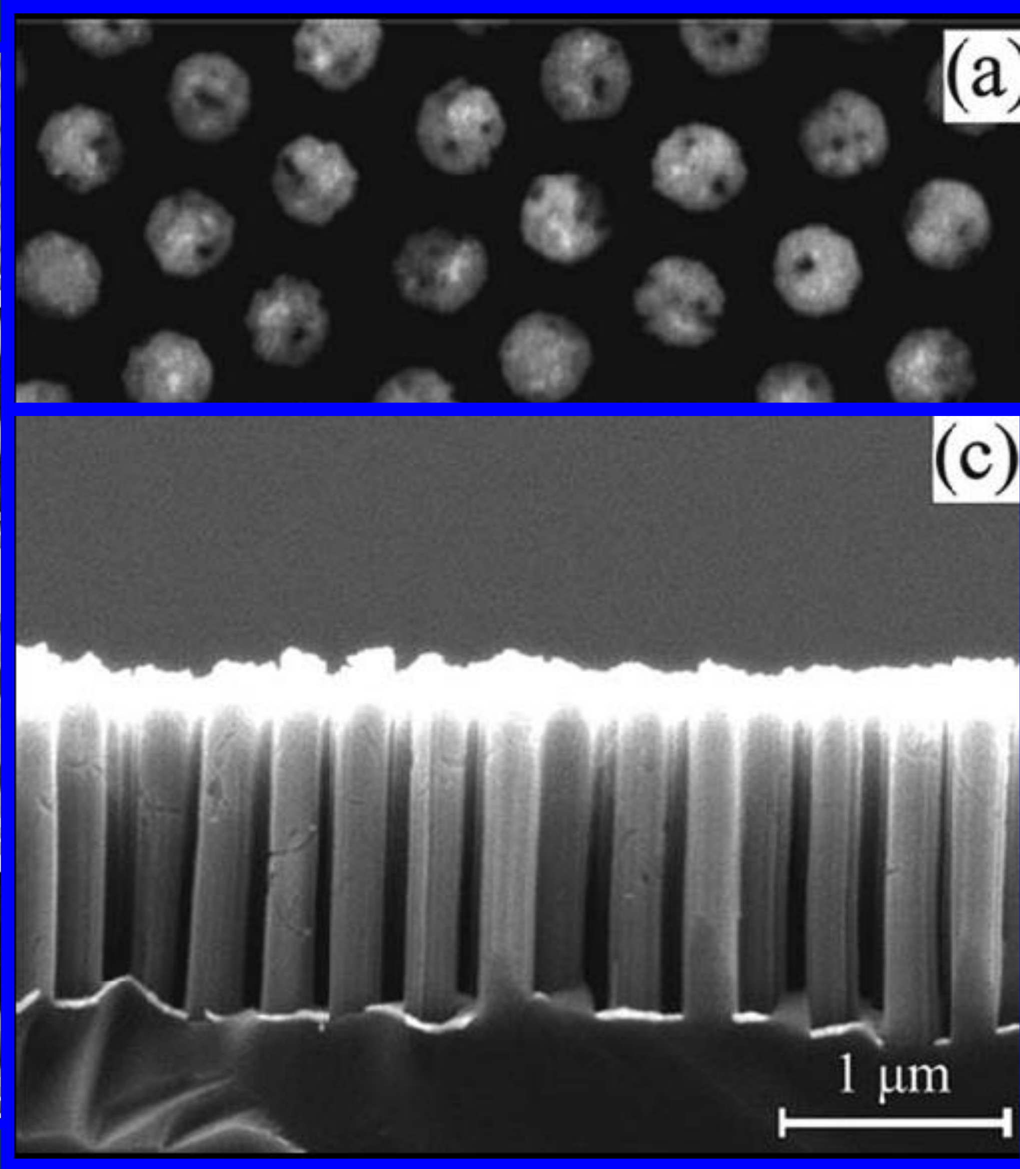




C.-Y. Chen, et al. Adv. Mater. 2008, 20, 3811

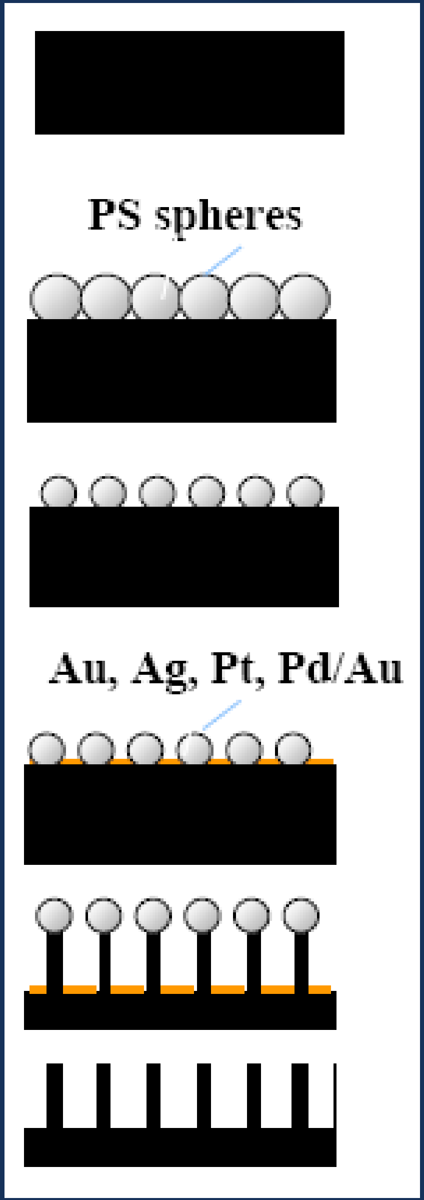
Ag-Si-HF Interaction





K. Peng, M. Zhang, A. Lu, R. Zhang and S.-T. Leea, Appl. Phys. Lett., 90, 163123 (2007).

Top-down: Wet-Chemical Etching



Substrate : n or p-type Si (100) wafers

Formation of hexagonal array of PS spheres: Ø 0.2µm to 4 mm

Reduction of the size and fixation of PS spheres:
RIE (O2 plasma) + Heat treatment

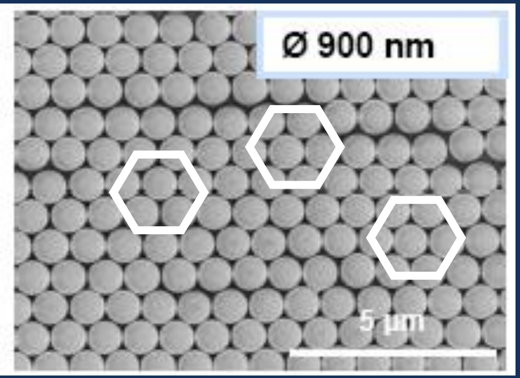
Deposition of metal catalyst:

Etching of Si nanowire arrays

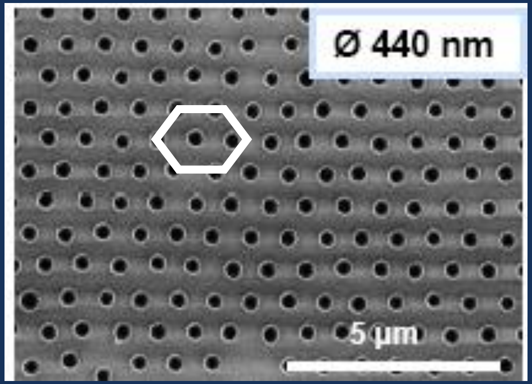
Removal of PS spheres and metal

Top-down: Wet-Chemical Etching

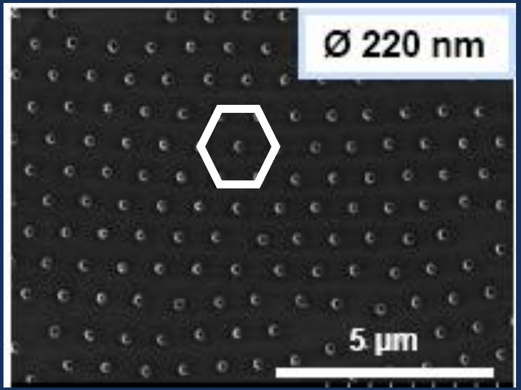
0 min, RIE

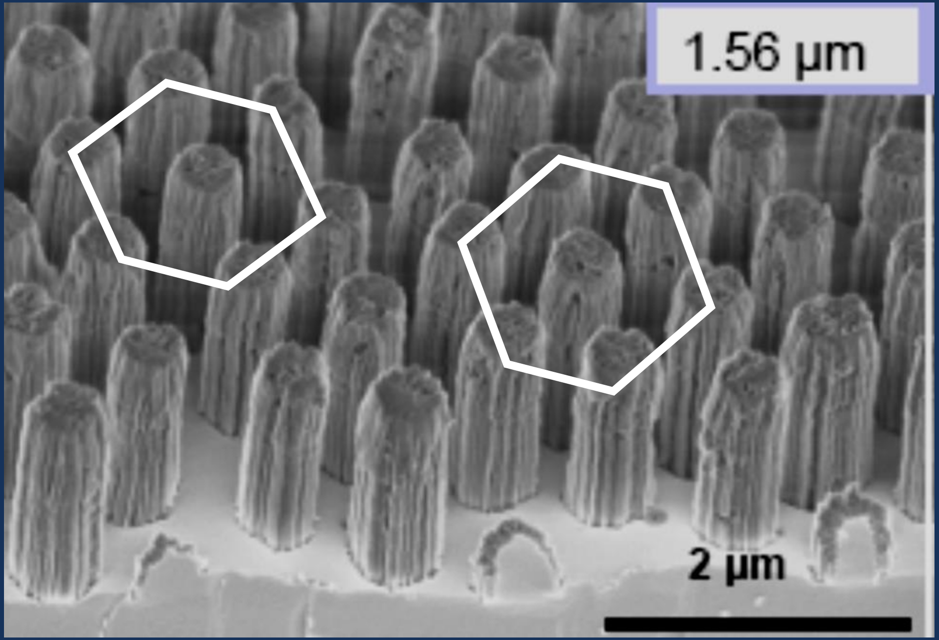


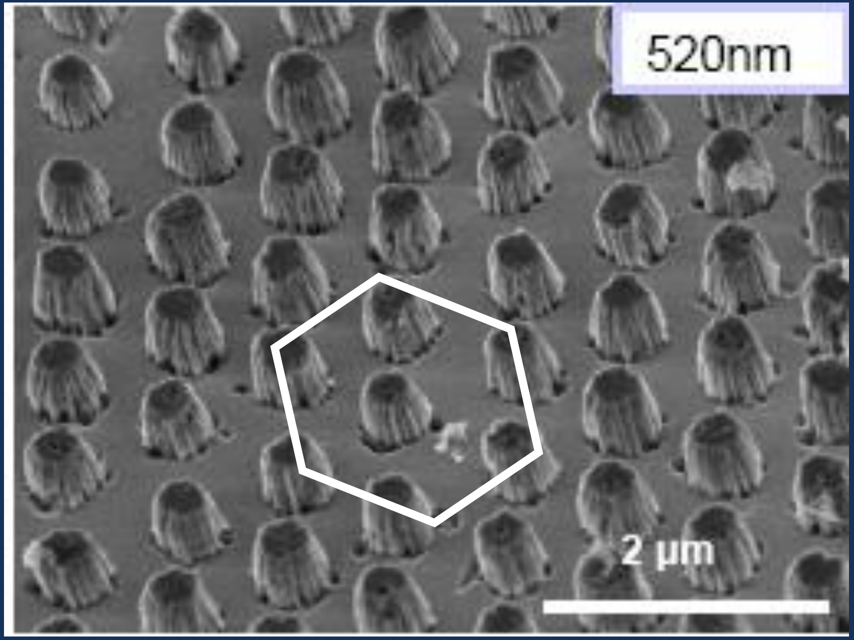
5 min, RIE



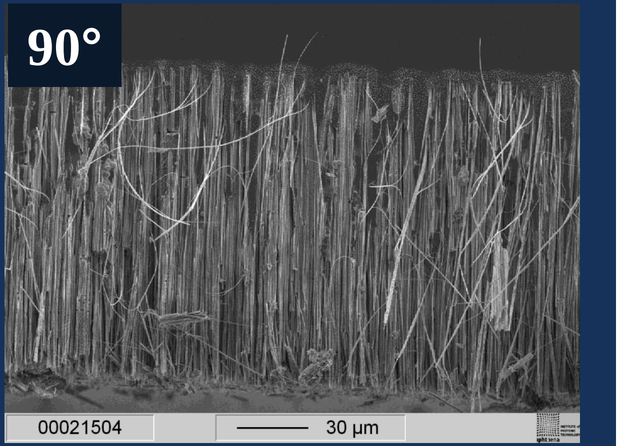
8 min, RIE

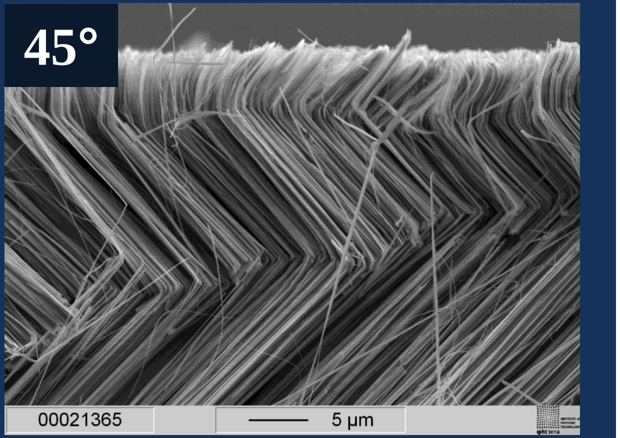


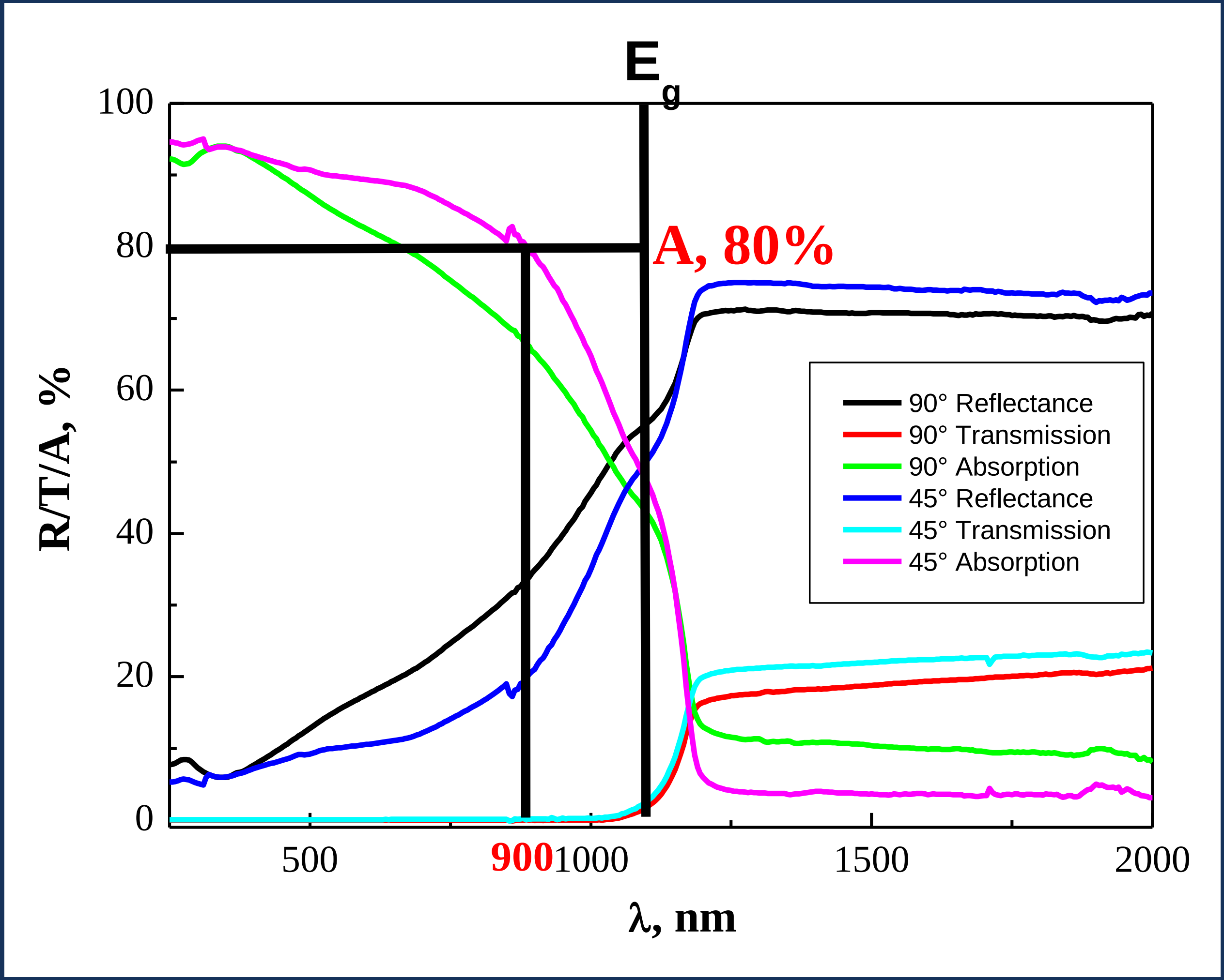




Top-down: Wet-Chemical Etching







V. Sivakov et al., Nano Lett. 9, 1549 (2009).

V. A. Sivakov et al., J. Phys. Chem. C, *114*, 3798–3803 (2010)

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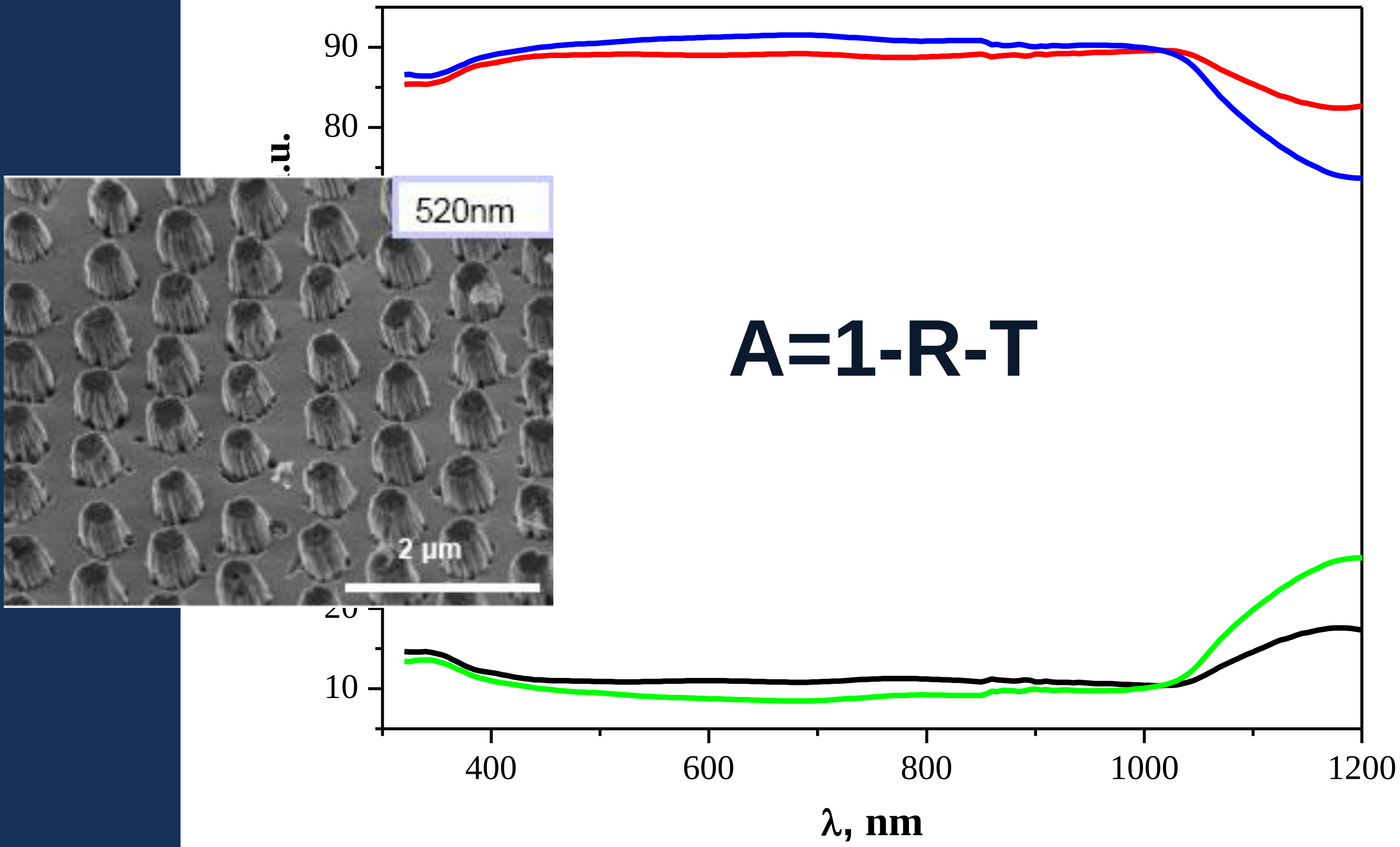
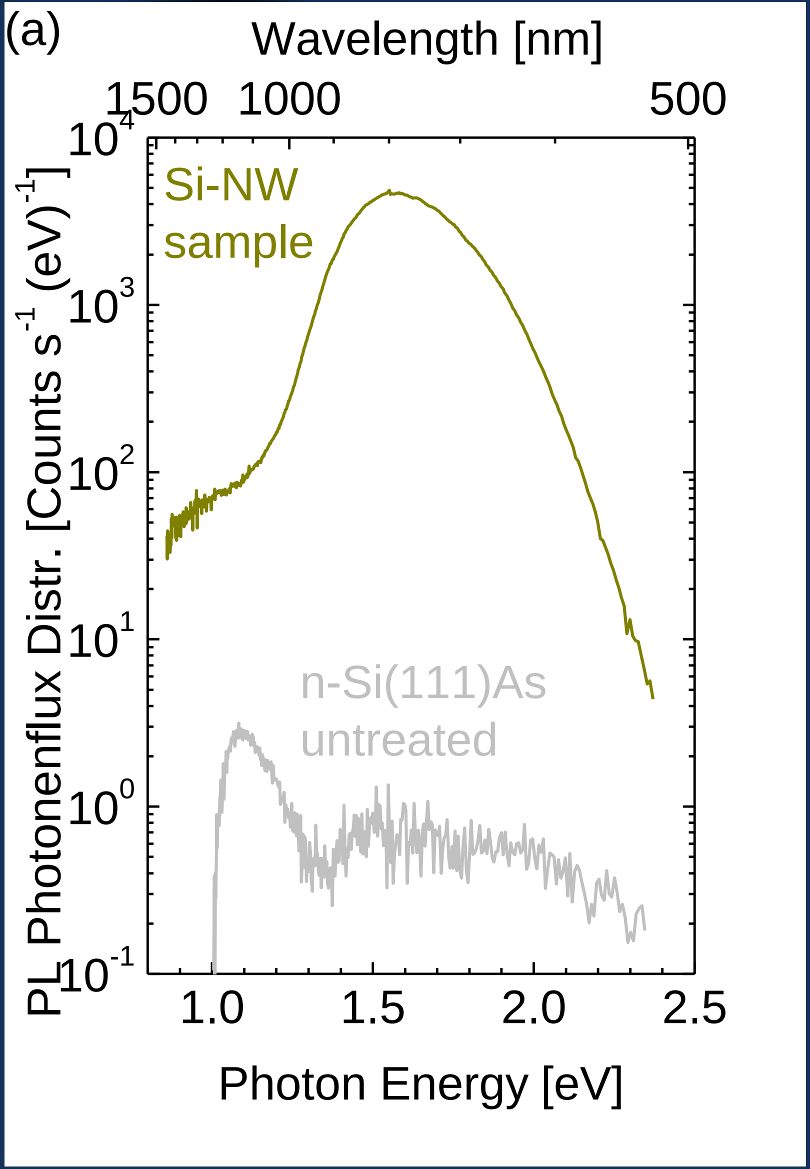
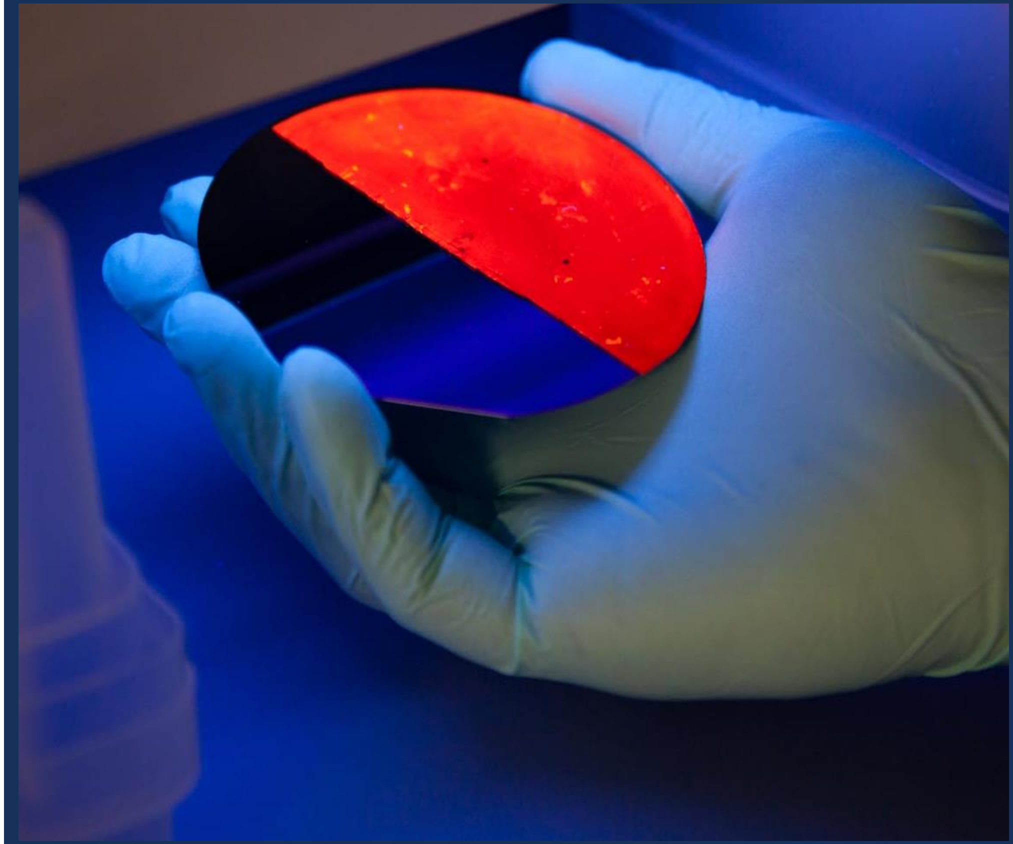


A=1-R-T

Top-down: Wet-Chemical Etching





V. A. Sivakov et al. Phys. Rev. B 82, 125446(2010)

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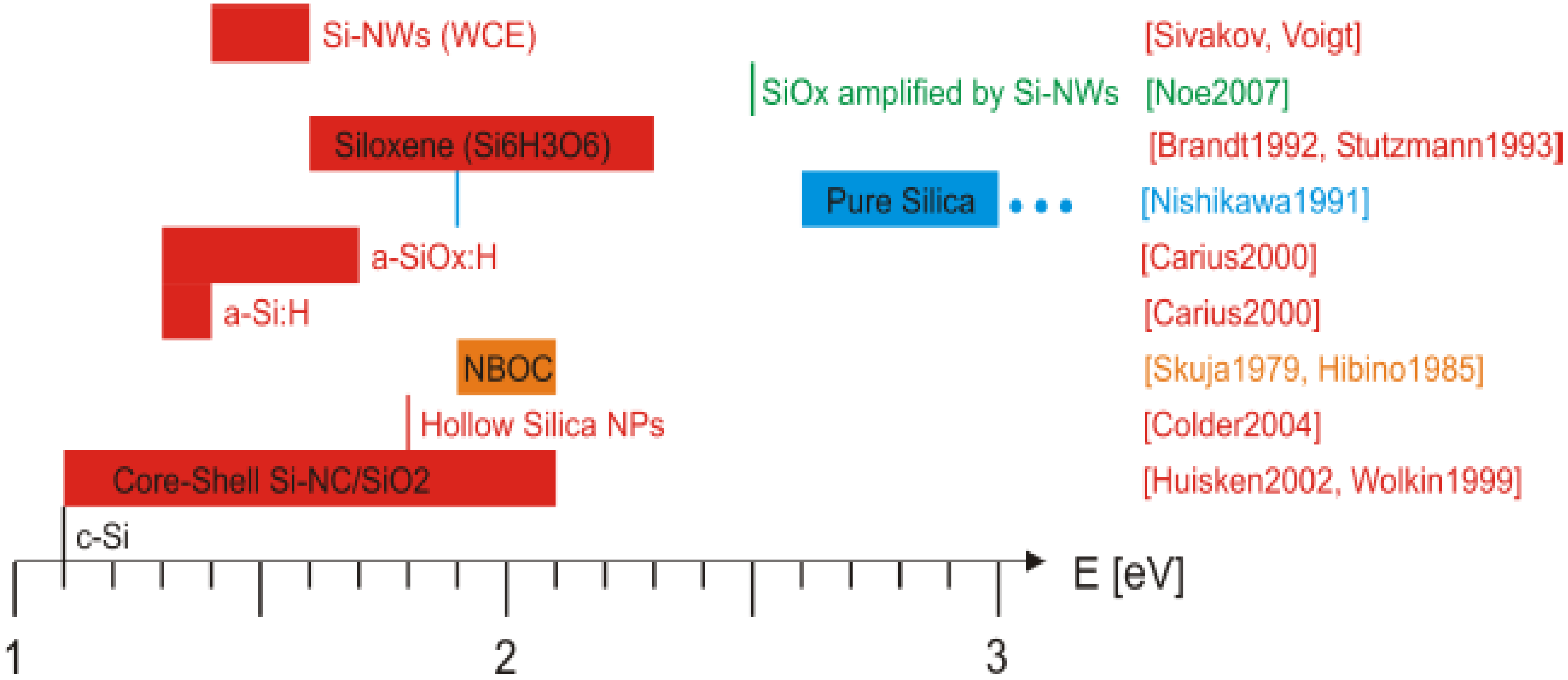
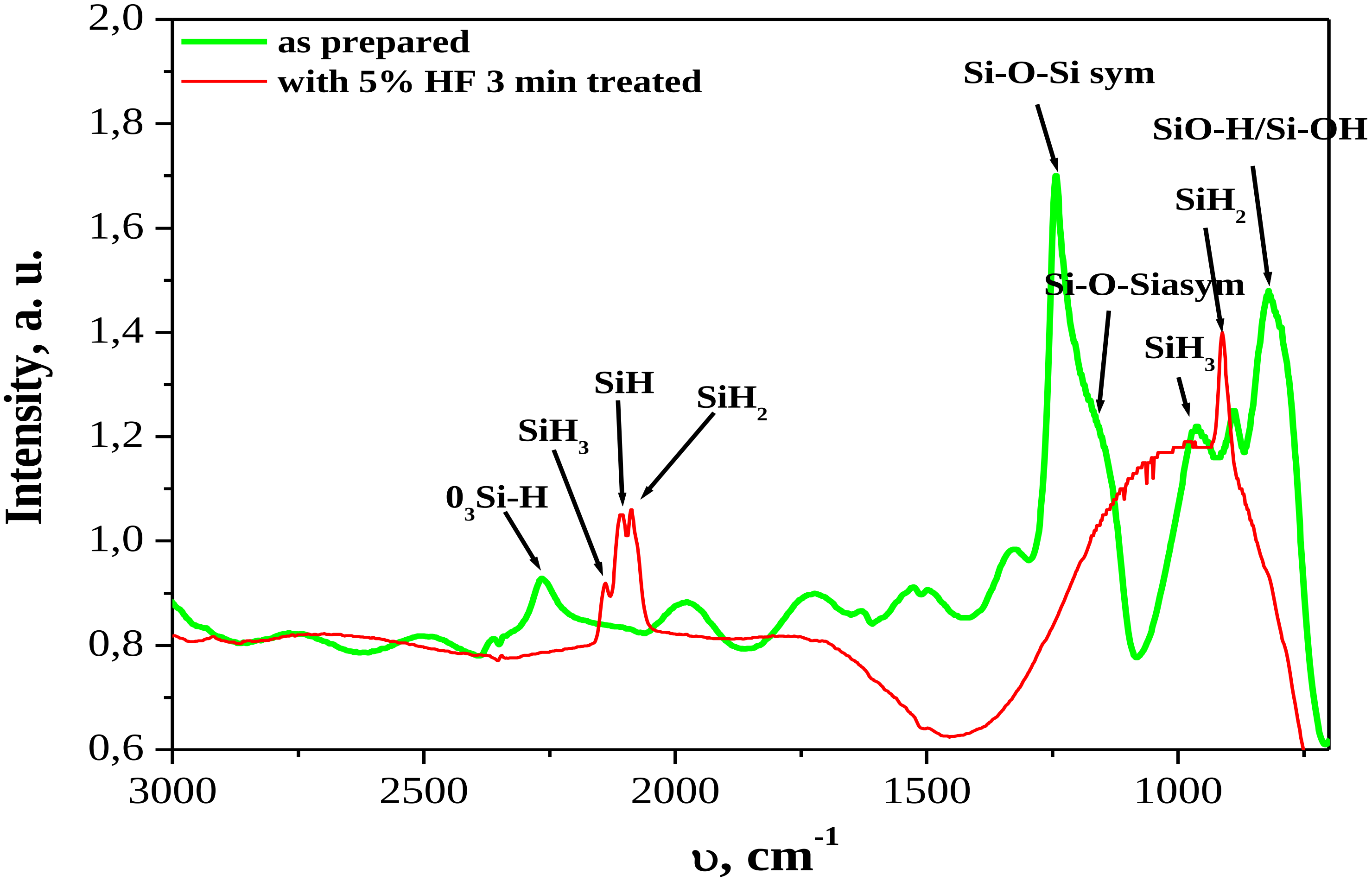


F. Voigt, V. A. Sivakov et al. Proceedings EMRS Spring Meeting 2010, Strasbourg, France, 7-11.06.2010.

Top-down: Wet-Chemical Etching



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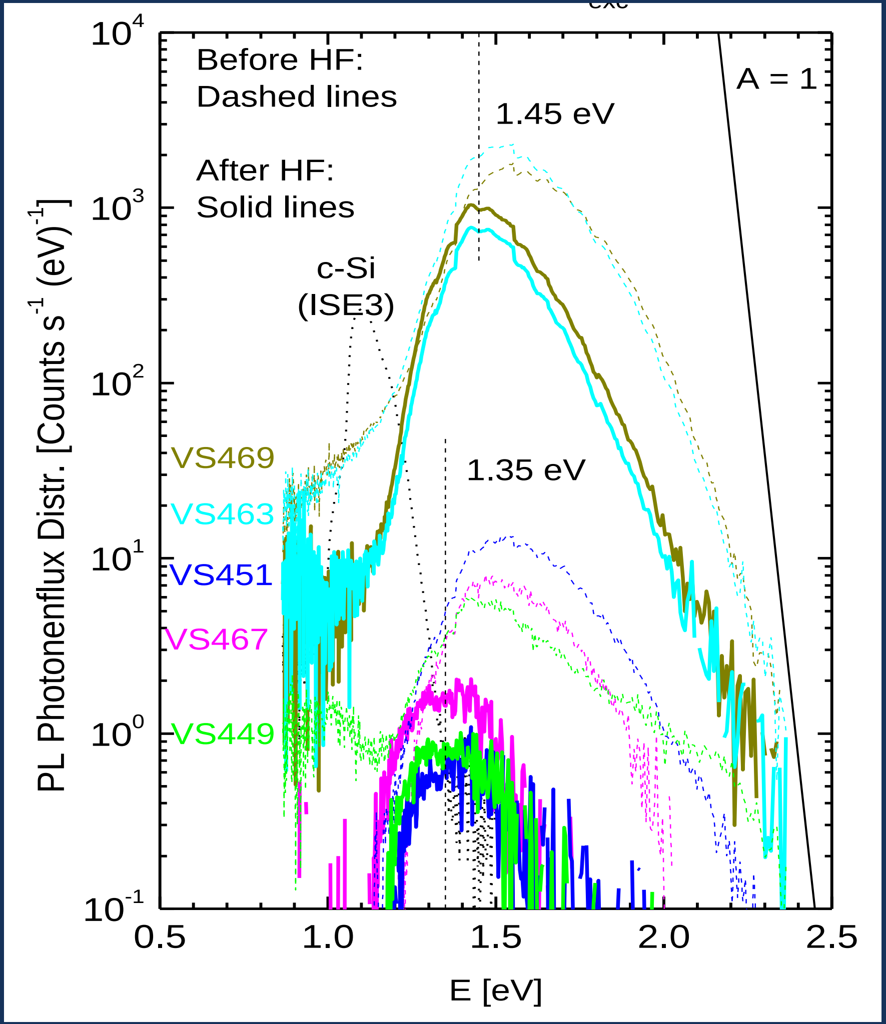

V. A. Sivakov et al. Phys. Rev. B 82, 125446 (2010);
F. Voigt , V. Sivakov et al., PSSa, 208(4), 893 (2011)

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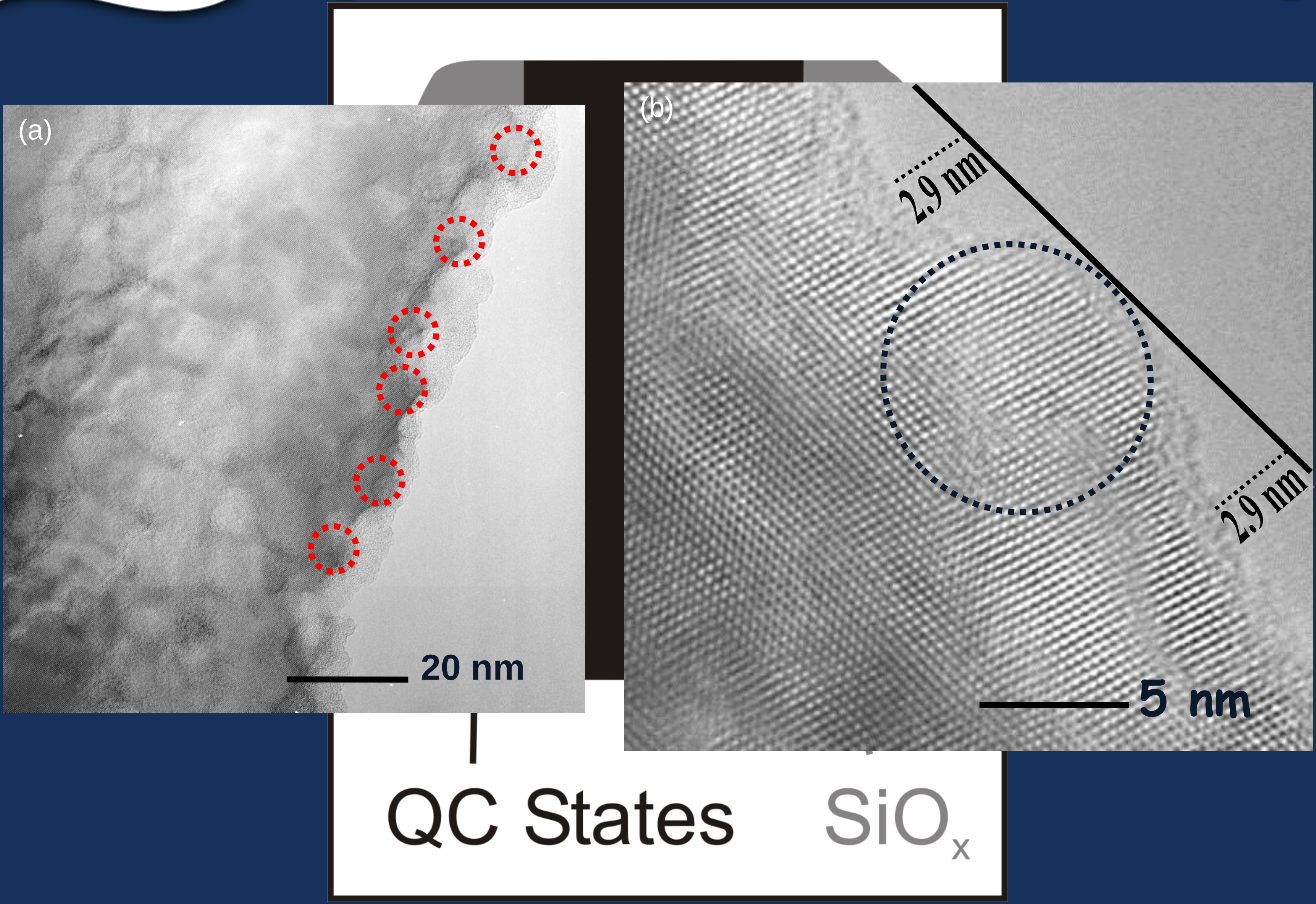

V. A. Sivakov et al. Phys. Rev. B 82, 125446(2010)

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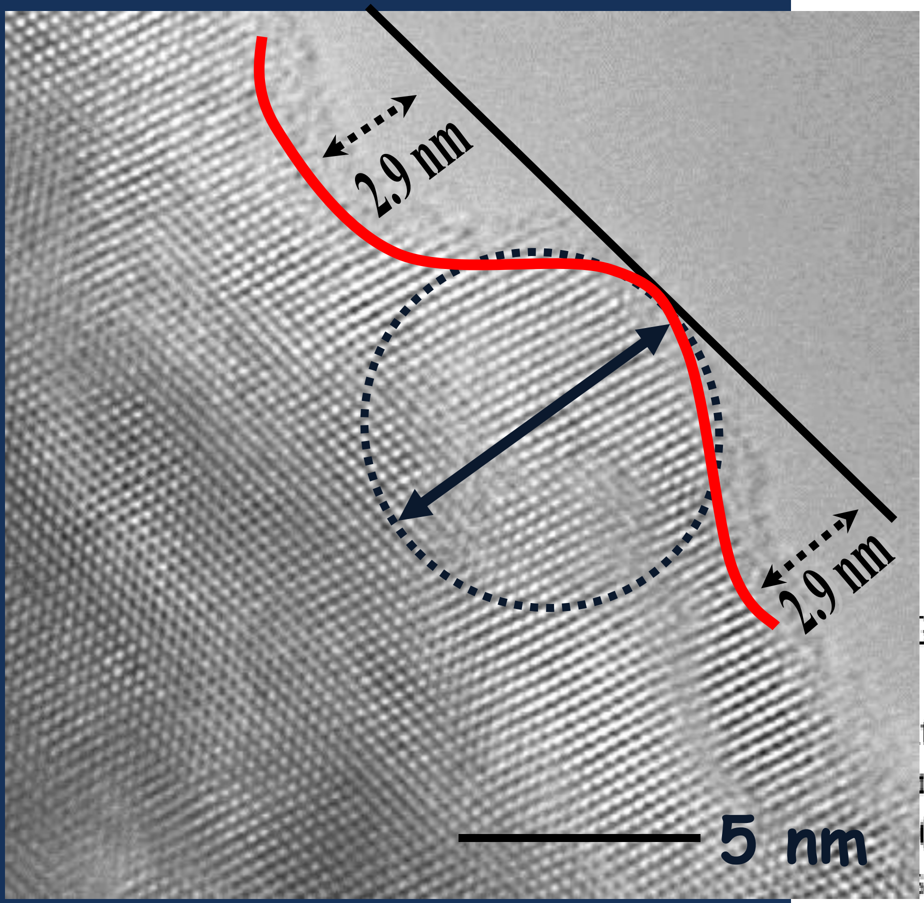
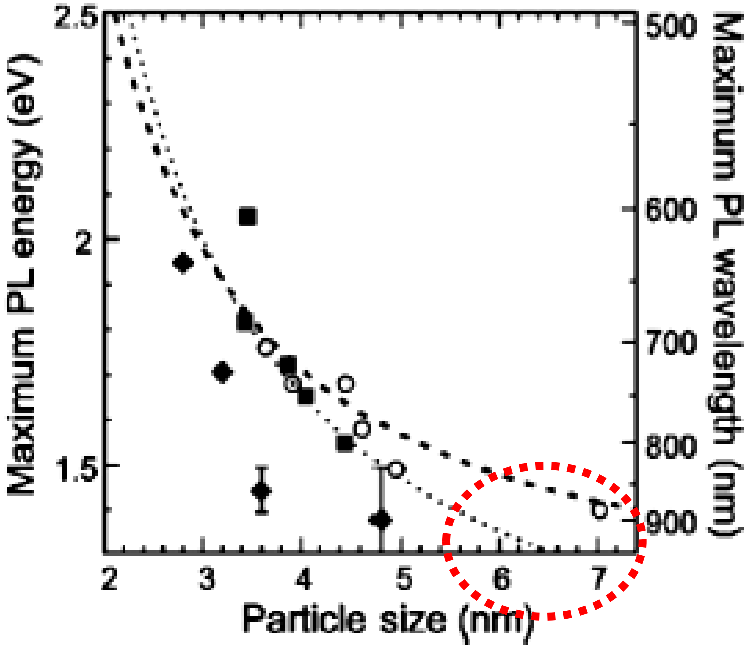
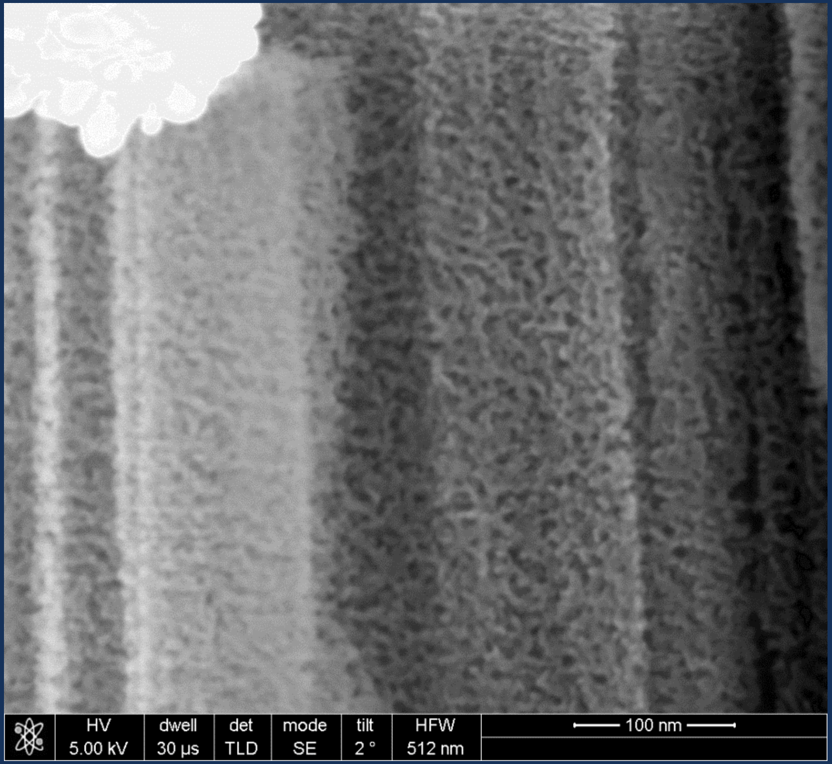


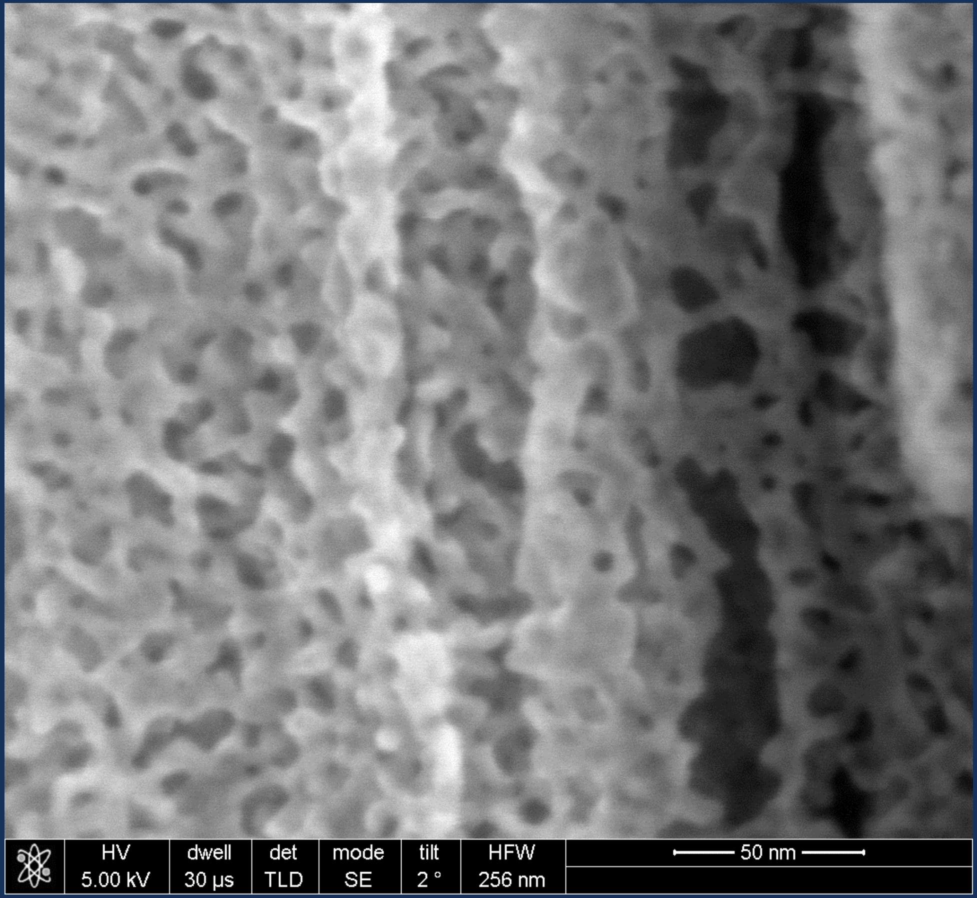


G. 7. Position of the PL maximum as a function of the size of
nanoclusters determined by TOFMS. For the data of the
t work we have used filled symbols (squares for the first and
nds for the second series) whereas the results of an earlier PL
(Ref. 17) are plotted as open circles. The dashed curve rep-
the theoretical results of Delerue, Allan, and Lannoo (Ref.
37), whereas the dotted curve includes the correction due to the
lattice variation according to Eq. (4).

Ledoux, G., et al., V. Phys. Rev. B 62, 15942 (2000)

Top-down: Wet-Chemical Etching





WCE vs VLS

- ☺ Cheap Formation
- ☺ Catalyst Free
- ☺ High Absorption
- ☺ Room PL (E_g=1.5 eV)
- ☺ Low Reflection

⬇

Photonic, Optoelectronic, PV, Sensoric

V. Sivakov et al. Intech . Nanowires / Book 1, p45-80 (2011)

SELF-CLEANING

Wetting of Silicon Nanograss: From Superhydrophilic to Superhydrophobic Surfaces

By *Christian Dorrer* und *Jürgen Rühe**

Self-Cleaning Properties

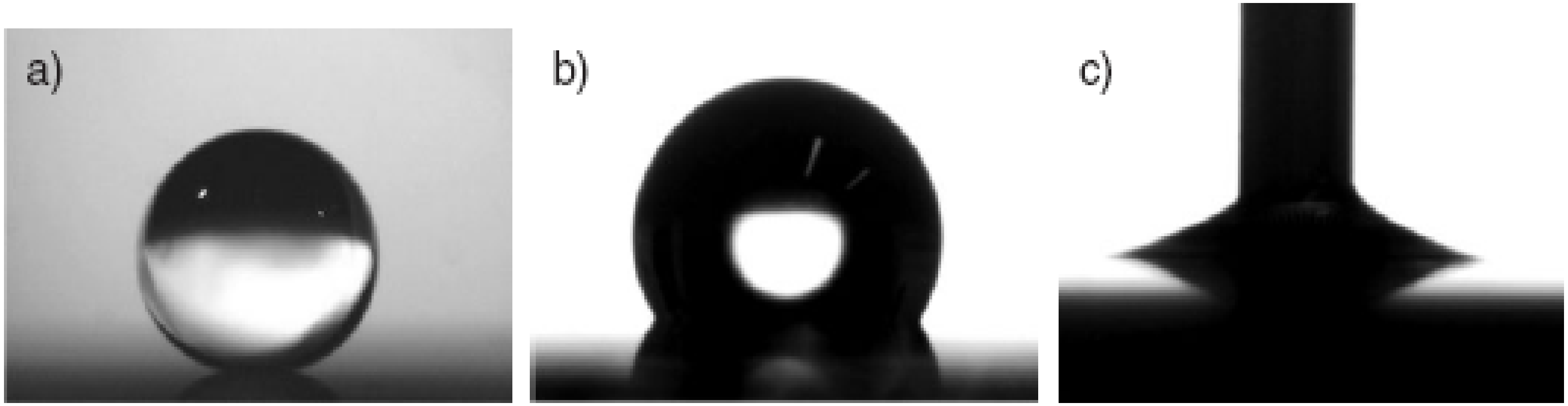


Figure 1. Drops on nanograss surfaces with different polymer coatings. a) Composite wetting on a poly(heptadecafluorodecylacrylate)-coated surface, b) Wenzel wetting on a polystyrene-coated surface, and c) superwetting on a poly(dimethylacrylamide)-coated surface.

Adv. Mater, 20, 159 (2008)

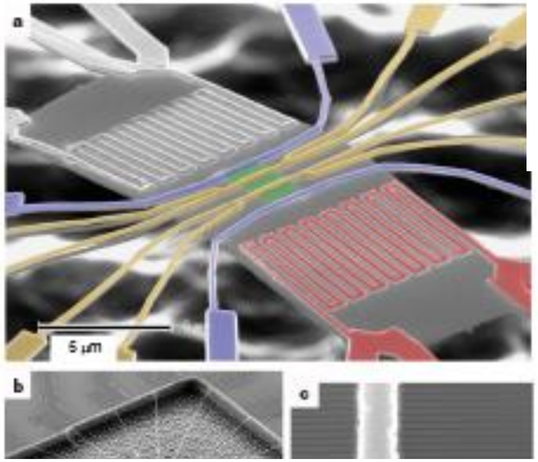
ENERGY

Silicon nanowires as efficient thermoelectric materials

Enhanced thermoelectric performance of rough silicon nanowires

Vol 451 | 10 January 2008 | doi:10.1038/nature06381

Allon I. Hochbaum[1]*, Renkun Chen[2]*, Raul Diaz Delgado[1], Wenjie Liang[1], Erik C. Garnett[1], Mark Najarian[3], Arun Majumdar[2,3,4] & Peidong Yang[1,3,4]



Approximately 90 per cent of the world's power is generated by heat engines that use fossil fuel combustion as a heat source and typically operate at 30–40 per cent efficiency, such that roughly 15 terawatts of heat is lost to the environment. Thermoelectric modules could potentially convert part of this low-grade waste heat to

figure
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thermo
materia

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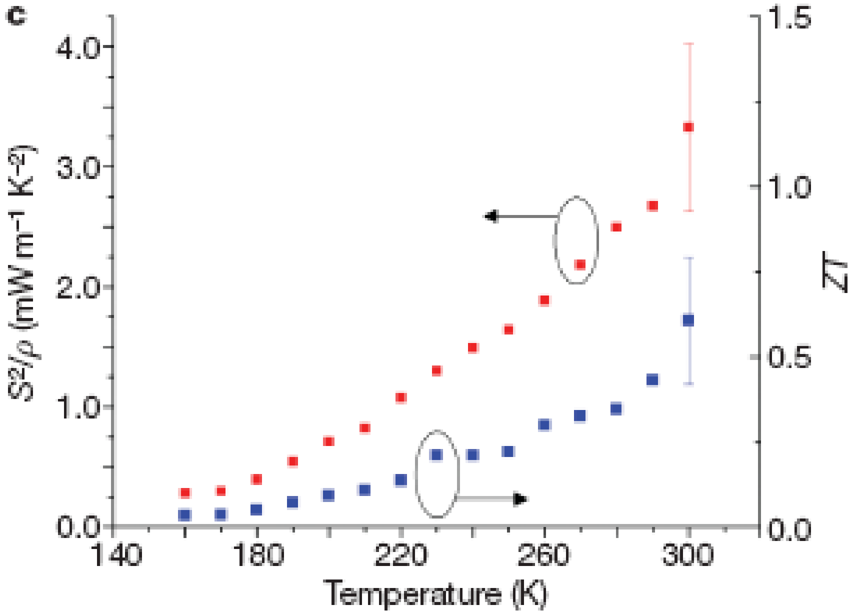
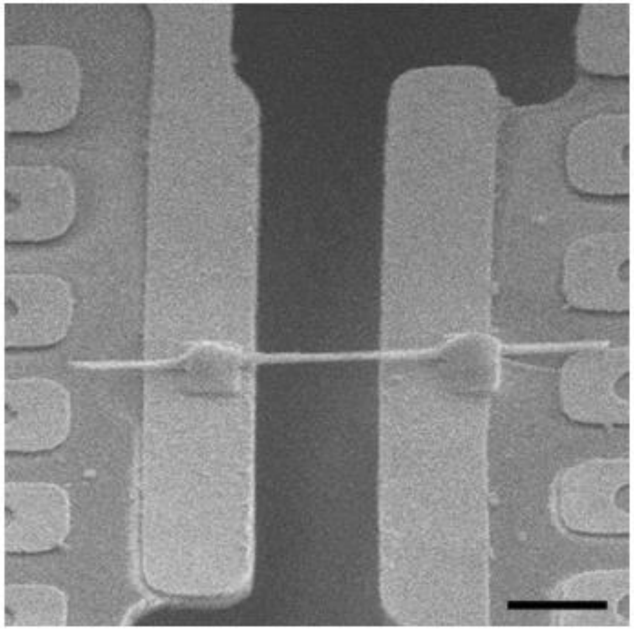
which have
coefficient,
emperature,
scale energy
this purpose
is the most
e industrial
ulk Si, how-
ure)^5, giving
of phonons



c, Single nanowire power factor (red squares) of the nanowire and calculated *ZT* (blue squares) using the measured *k* of the 52 nm nanowire in Fig. 2c. By



Newton's Law of Gravity

$$F_g = G\frac{m_1 m_2}{r^2}$$

The Proverbial Apple

The famous story that Newton came up with the idea for the law of gravity by having an apple fall on his head is not true, although he did begin thinking about the issue on his mother's farm when he saw an apple fall from a tree.

Friedrich August Kekulé said that he had discovered the ring shape of the benzene molecule after having a reverie or day-dream of a snake seizing its own tail (this is a common symbol in many ancient cultures known as the Ouroboros). This vision, he said, came to him after years of studying the nature of carbon-carbon bonds.

Observation of NATURE

Prof. Ulrich Gösele
Dr. Peter Werner
Prof. Jürgen Popp
Prof. Alois Lungstein
Dr. Thomas Stelzner
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Dr. Felix Voigt…..

Dipl. Ing. Alexander Schleusener
Dipl. Phys. Johannes Mühlenstädt
Dipl. Phys. Florian Talkenberg
Dipl. Phys. Arne Bochmann………

Династия

DFG Deutsche Forschungsgemeinschaft

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Thanks for your attention!

vladimir.sivakov@ipht-jena.de

Спасибо за внимание!