# Nanostructured Materials for Solar Fuel Production

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# Contents

- Background on Energy Challenges
  - Why Water splitting for Hydrogen Production?
  - Introduction to Water Splitting
- Research Plan
- Experimental Work
- Results

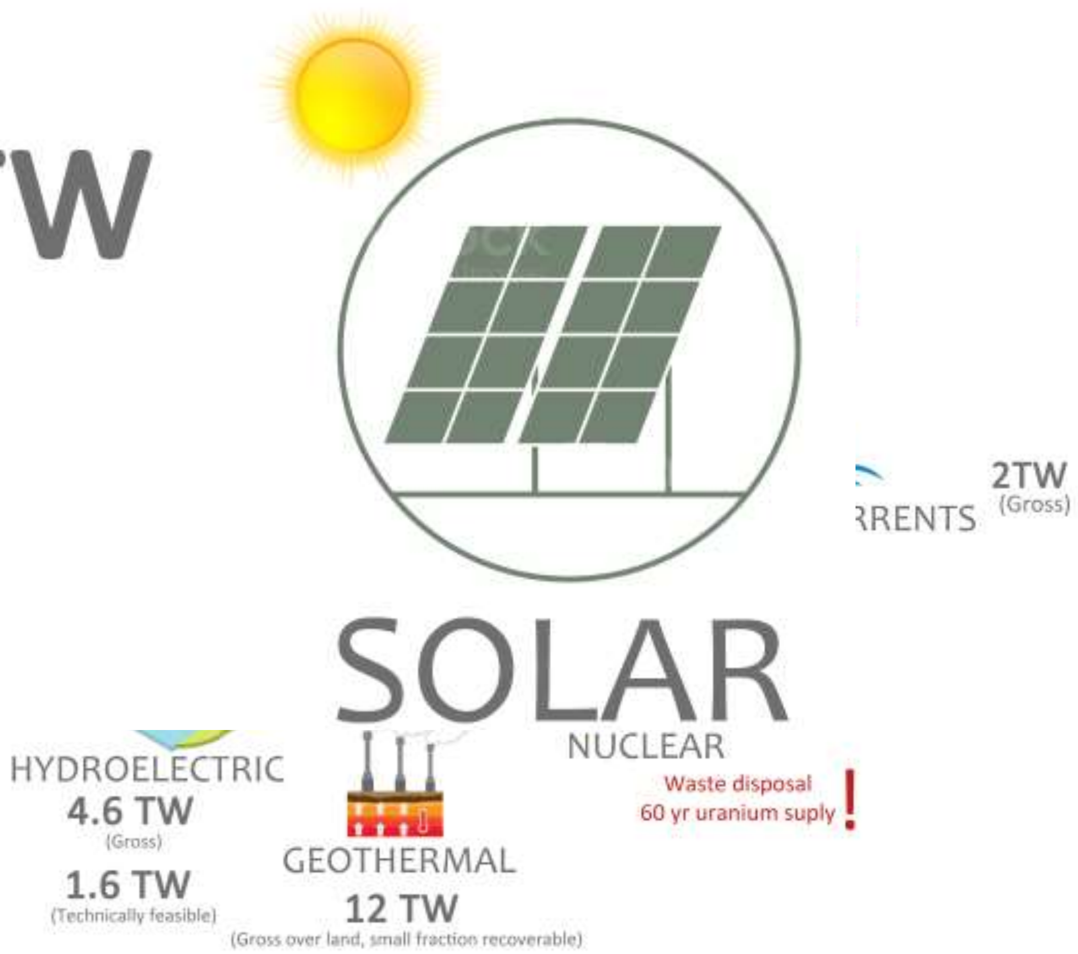
# Global Energy Challenge

$1.2 \times 10^5$ TW

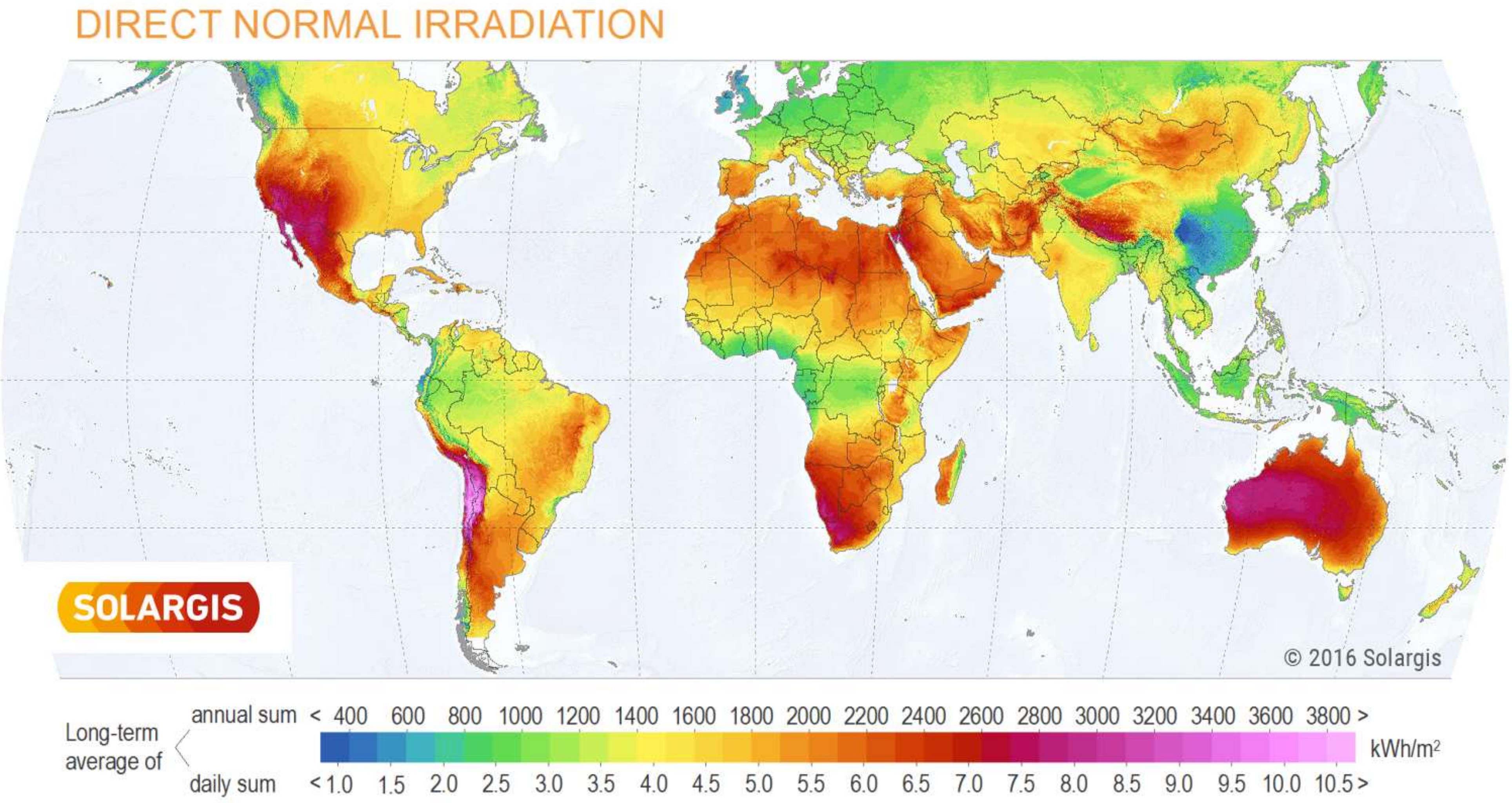
at Earth Surface

600 TW

(practical)



# Egypt!


DIRECT NORMAL IRRADIATION
SOLARGIS
© 2016 Solargis
Long-term average of
annual sum < 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000 3200 3400 3600 3800 >
daily sum < 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5 10.0 10.5 >
kWh/m2

# Solar Fuel

- Light is used as an energy source, with solar energy being transduced to *chemical energy* typically by
  - reducing protons to hydrogen

  or

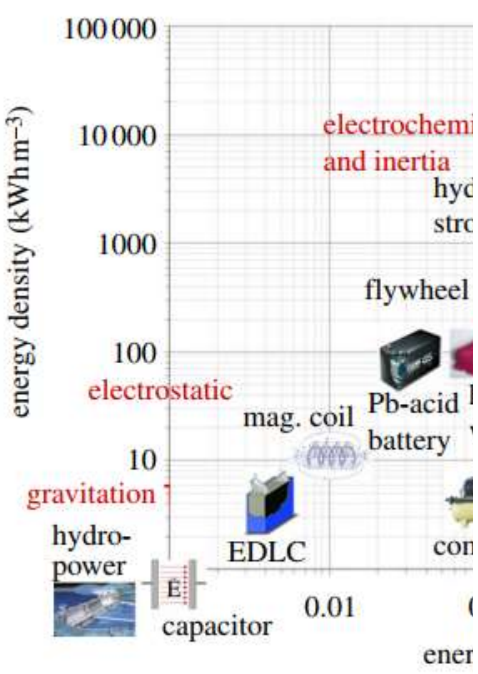
  - carbon dioxide to organic compounds.
- A solar fuel can be produced and stored for later usage, when sunlight is not available, making it an alternative to fossil fuels.

# Why Hydrogen?

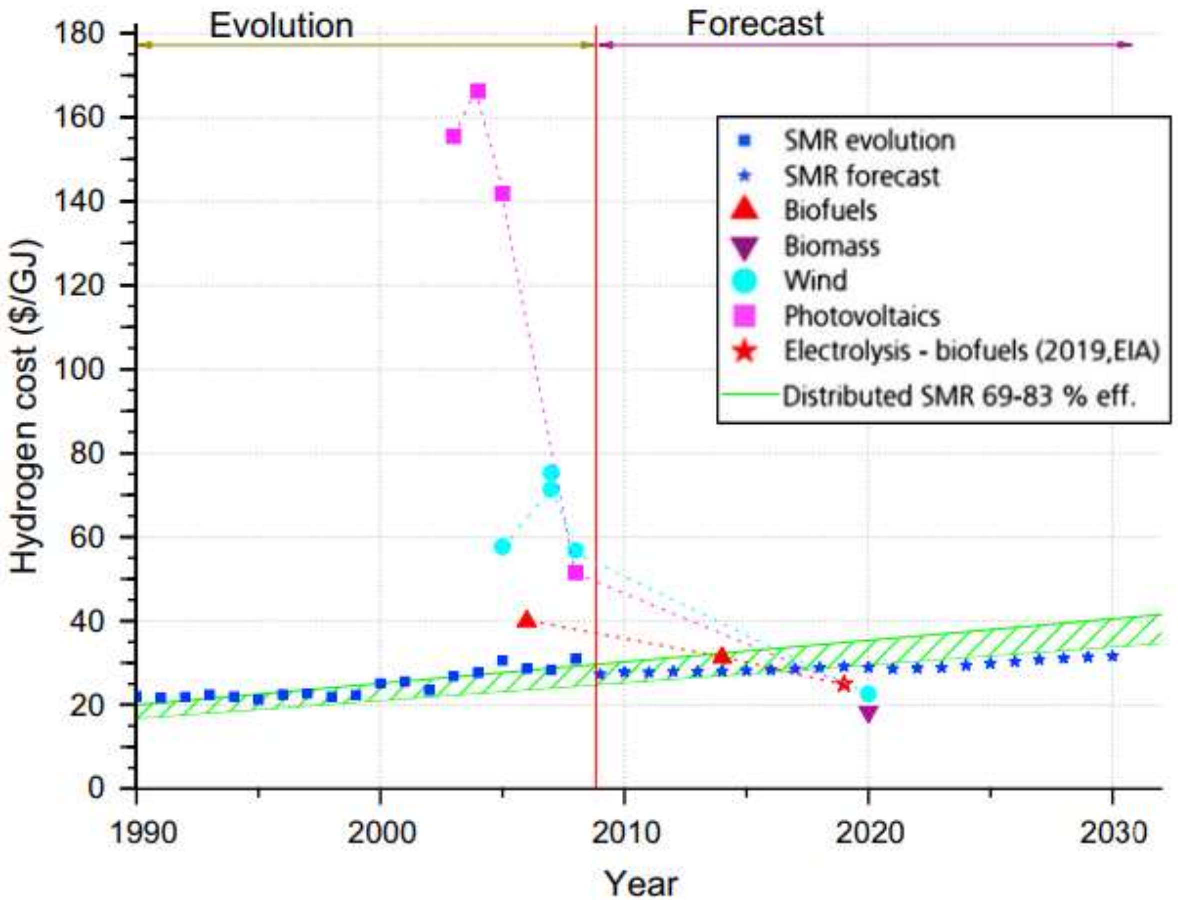
- Clean – no greenhouse gases
- Energy security – can be produced from abundant sources
- Economic growth demands for energy
- Efficient – fuel cells ~75% efficiency
- Portable: Car tanks, micro fuel cells…

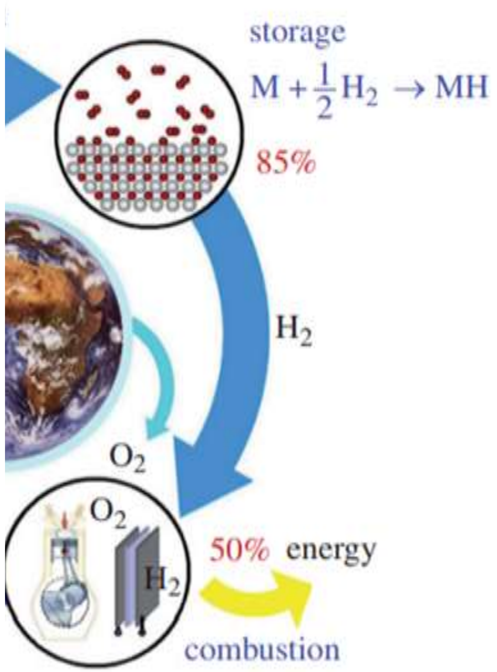
*New Materials for Photocatalytic Water Splitting, Fredrik Skullman, MATRL 286G, 05/26/2010

# Why Hydrogen?



Volumetric vs. gravim
of the major energy ca





n cycle in nature.*

Forecast of hydrogen production costs using different technologies.**

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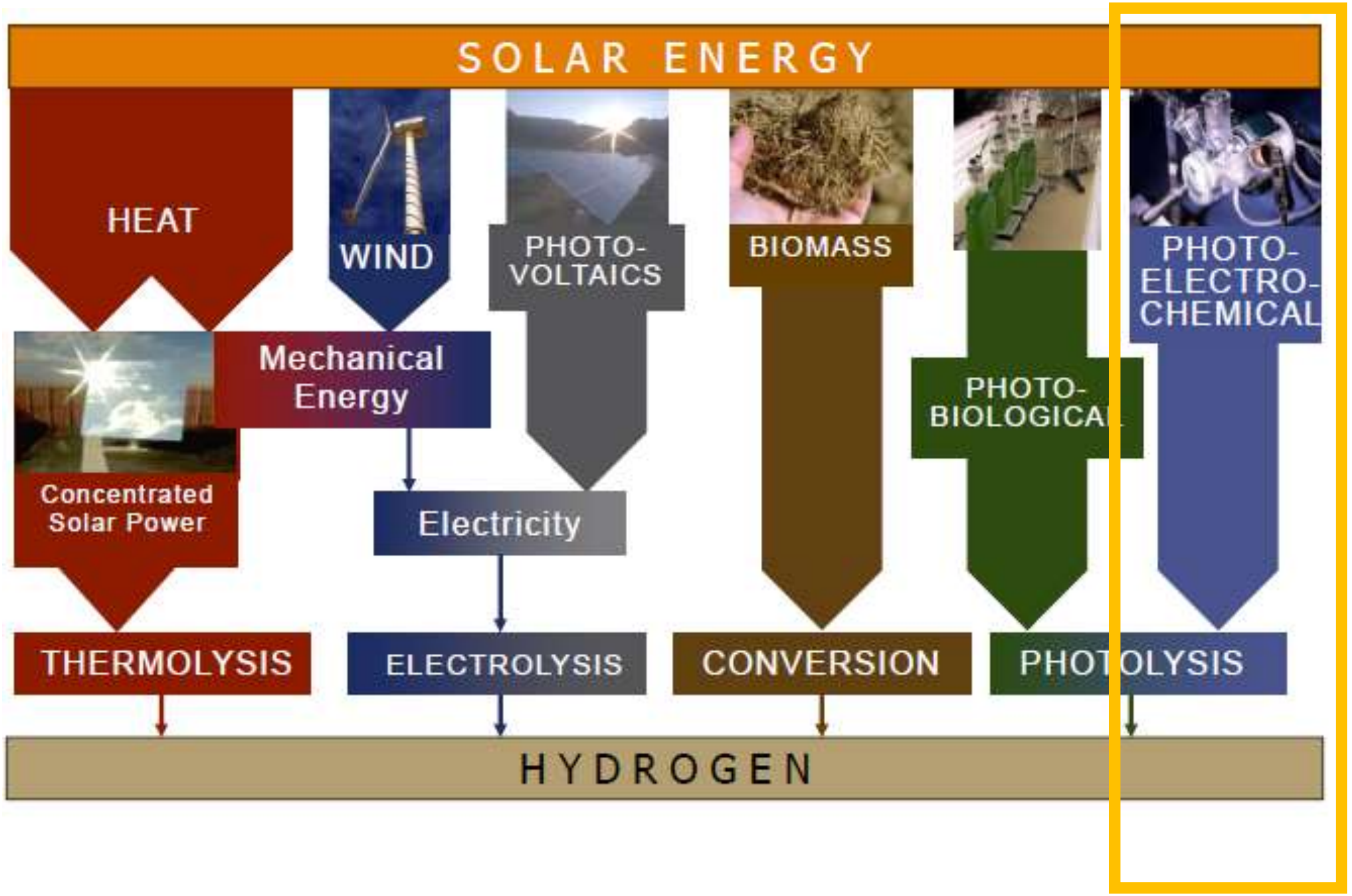
* Züttel, A.; Remhof, A.; Borgschulte, A.; Friedrichs, O. Hydrogen: The Future Energy Carrier. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2010**, *368* (1923), 3329–3342.

**Lemus, R. G.; Duart, J. M. M. Updated Hydrogen Production Costs and Parities for Conventional and Renewable Technologies. *Int. J. Hydrogen Energy* **2010**, *35* (9), 3929–3936.

# $H_2$ Production Routes



- Our Proposed Solution:
  - Split water with renewable energy sources

# Water Splitting Principle

Reduction reaction:

$$2H^{+} + 2e^{-} \rightarrow H_2 \quad (E^{0}_{red} = 0.00 \text{ V vs RHE})$$

Oxidation reaction:

$$2H_2O + 4h^{+} \rightarrow O_2 + 4H^{+} \quad (E^{0}_{ox} = -1.23 \text{ V vs RHE})$$

Overall reaction:

$$2H_2O \rightarrow 2H_2 + O_2 \quad (\Delta E = -1.23 \text{ V})$$

Schematic diagram of water electrolysis process.*

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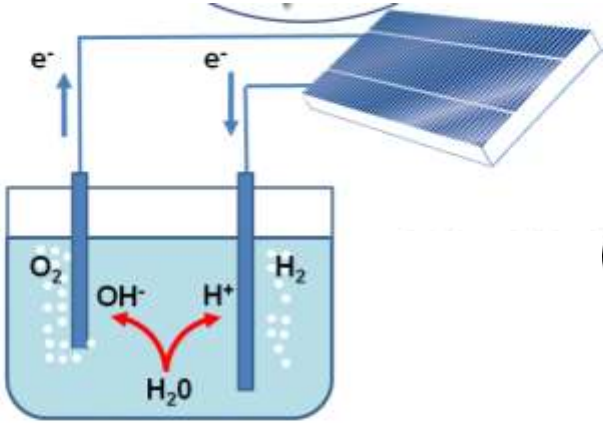
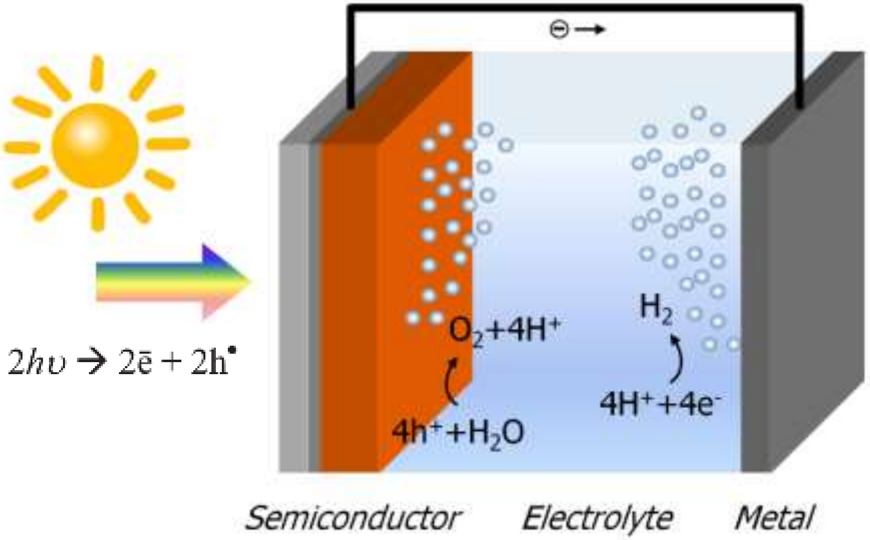
* Züttel, A.; Remhof, A.; Borgschulte, A.; Friedrichs, O. Hydrogen: The Future Energy Carrier. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci*. **2010**, *368* (1923), 3329–3342.

# Splitting Water *via* Renewable Resources

- Direct PV electrolysis
  - connecting a commercial electrolyser to a PV system.
  - Light harvesting > charge generation > electrolysis > hydrogen and oxygen

- PEC electrolysis
  - Photoelectrode(s) are immersed into the electrolyte and the photo-generated electron-holes are directly used to reduce and oxidize water.



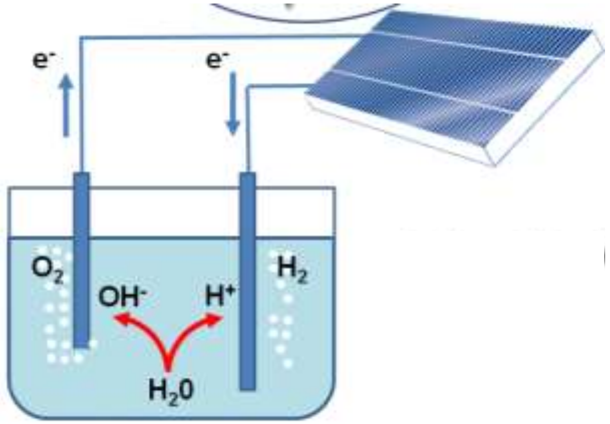


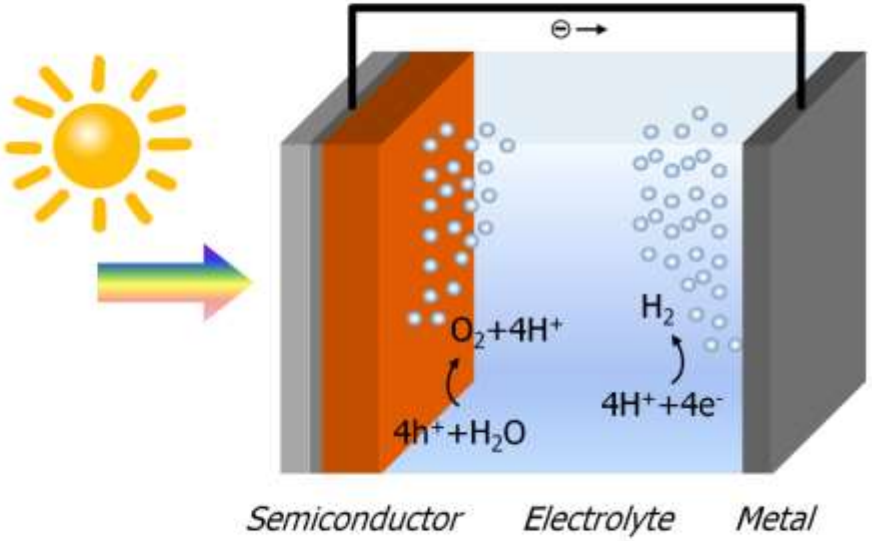
L. Minggu et al. An overview of photocells and photoreactors for photoelectrochemical water splitting, International Journal of Hydrogen Energy, Vol. 35, 11, 2010 5233-5244.

# Splitting Water *via* Renewable Resources

- Direct PV electrolysis
  - Expensive?
  - High current densities -> overpotential -> lower efficiency
  - Not compact?

- PEC electrolysis
  - Lower current densities -> higher electrolysis efficency
  - All in one package: cheap, compact.

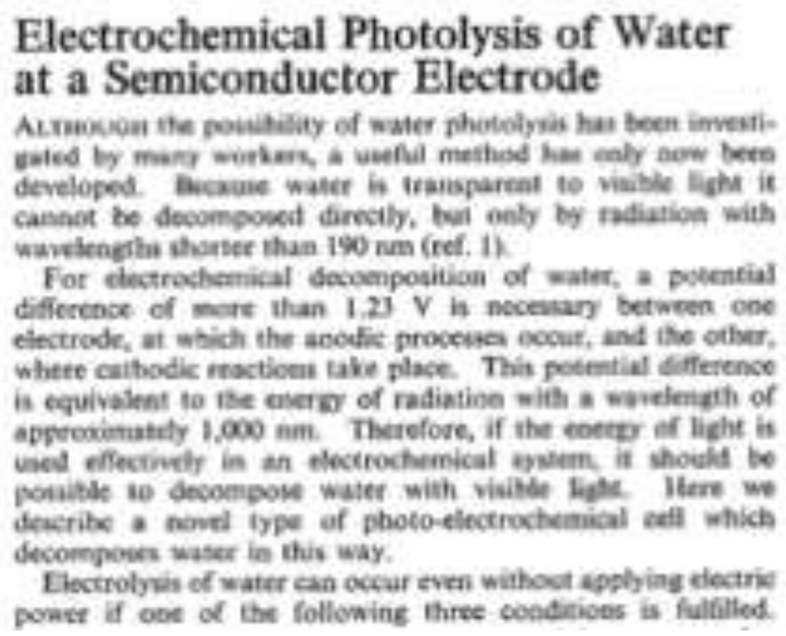




L. Minggu et al. An overview of photocells and photoreactors for photoelectrochemical water splitting, International Journal of Hydrogen Energy, Vol. 35, 11, 2010 5233-5244.

# PEC first demonstration

- First demonstration in 1972 by Fujishima and Honda,



## Electrochemical Photolysis of Water at a Semiconductor Electrode

ALTHOUGH the possibility of water photolysis has been investigated by many workers, a useful method has only now been developed. Because water is transparent to visible light it cannot be decomposed directly, but only by radiation with wavelengths shorter than 190 nm (ref. 1).

For electrochemical decomposition of water, a potential difference of more than 1.23 V is necessary between one electrode, at which the anodic processes occur, and the other, where cathodic reactions take place. This potential difference is equivalent to the energy of radiation with a wavelength of approximately 1,000 nm. Therefore, if the energy of light is used effectively in an electrochemical system, it should be possible to decompose water with visible light. Here we describe a novel type of photo-electrochemical cell which decomposes water in this way.

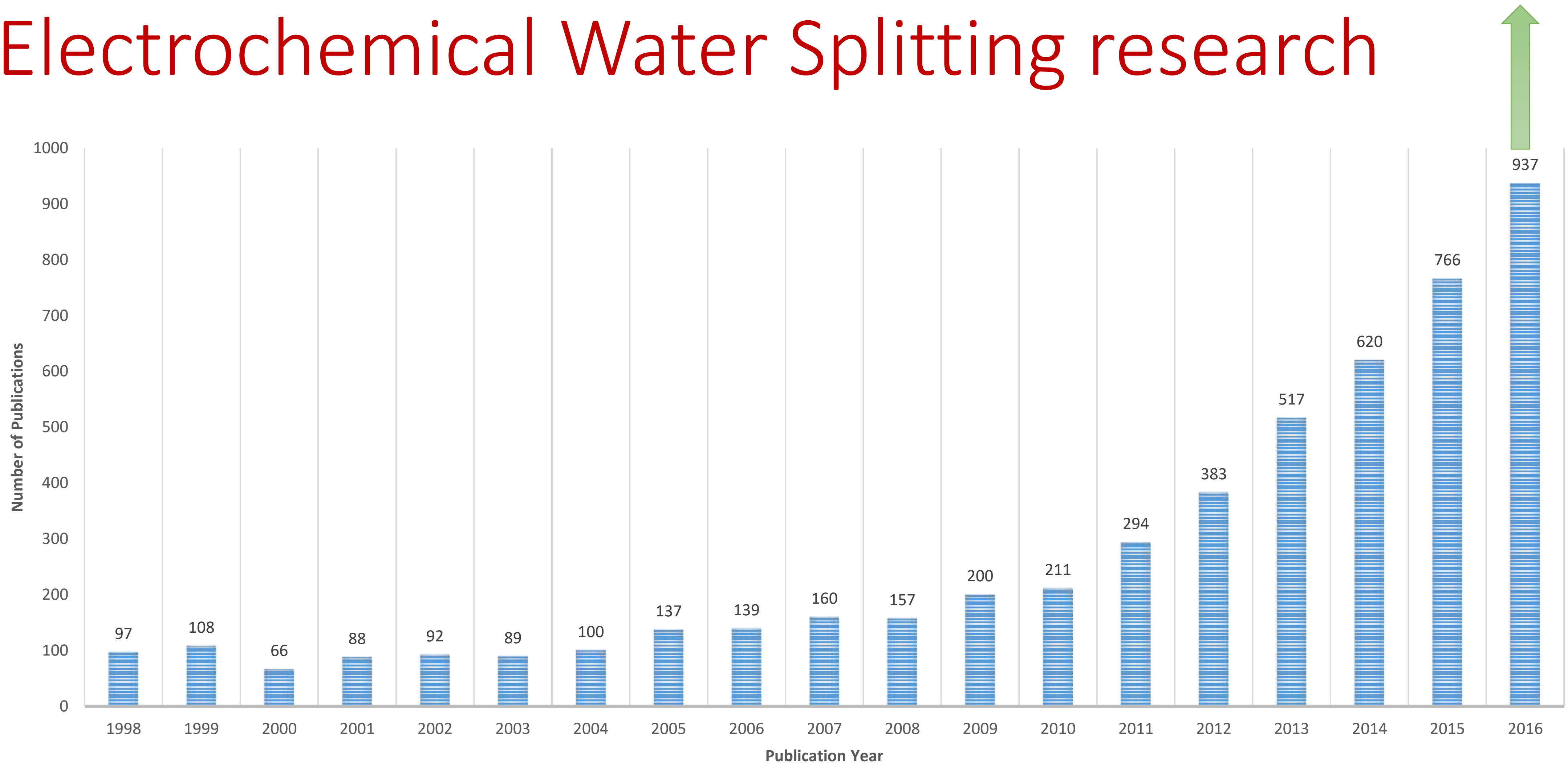
Electrolysis of water can occur even without applying electric power if one of the following three conditions is fulfilled.

Dr. Kenichi Honda (Japan)

Dr. Akira Fujishima (Japan)

Fujishima, A.; Honda, K. Electrochemical Photolysis of Water at a Semiconductor Electrode. *Nature* **1972**, *238* (5358), 37–38.

# Development of the scientific field for Photo-Electrochemical Water Splitting research



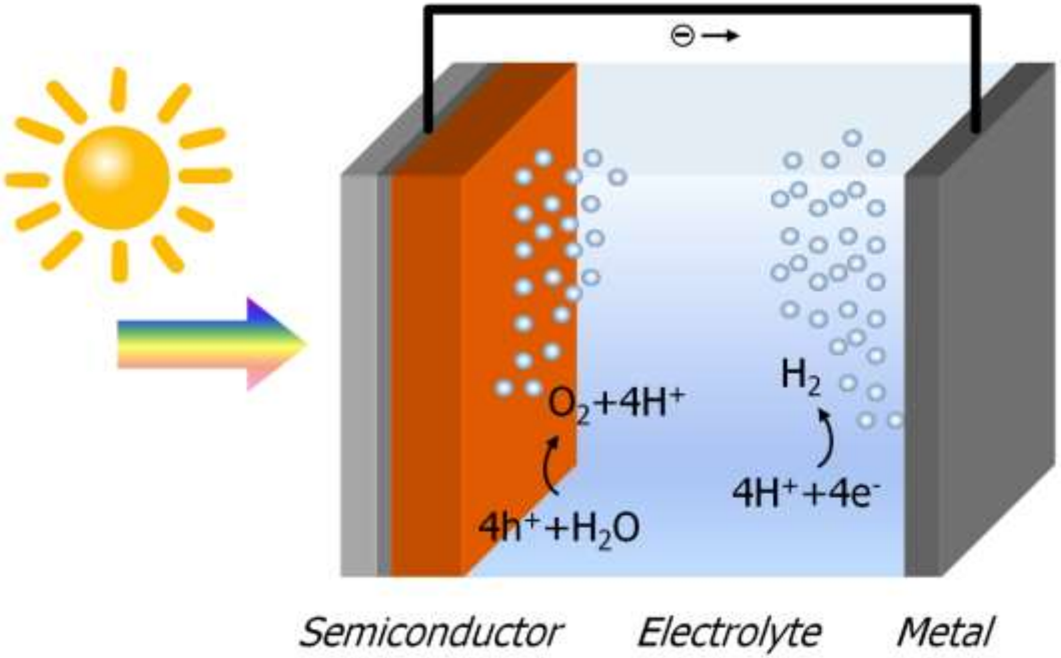
*Based on "Photo-Electrochemical Water Splitting" Keyword on Sciencedirect.com on 27/8/2016

# PEC WS Principle

- It combines the harvesting of solar energy and the electrolysis of water into a single device.
- PEC: Photoelectrochemical
  1. Photo
  2. Electro
  3. Chemical

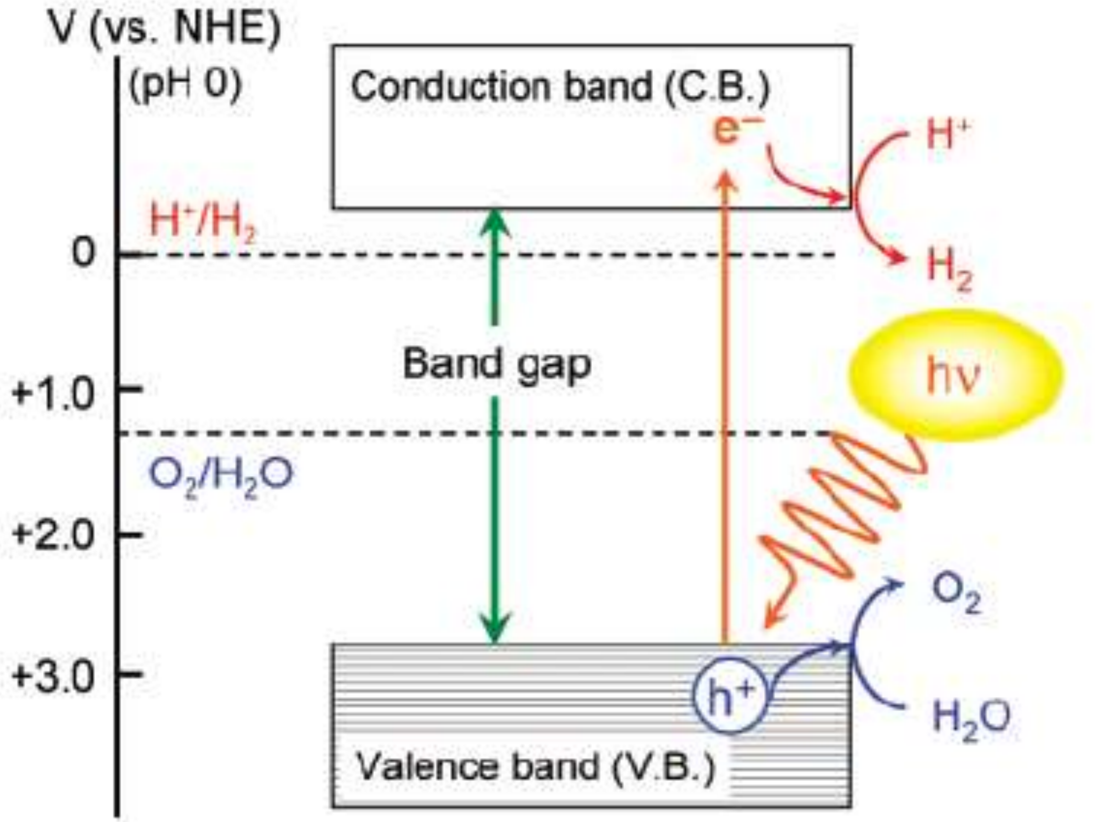
# PEC Water Splitting Processes

- Incoming photons (hv) generate electrons ($e^-$) and holes ($h^+$)
  - with an efficiency labeled $\eta_{e^-/h+}$
- The photogenerated electrons and holes then separate and travel through the semiconductor in opposite directions;
  - the efficiency associated with the charge transport process is labeled $\eta_{transport}$
- The holes drive the Oxygen Evolution Reaction at the surface of the semiconductor working electrode.



# Material criteria to be met

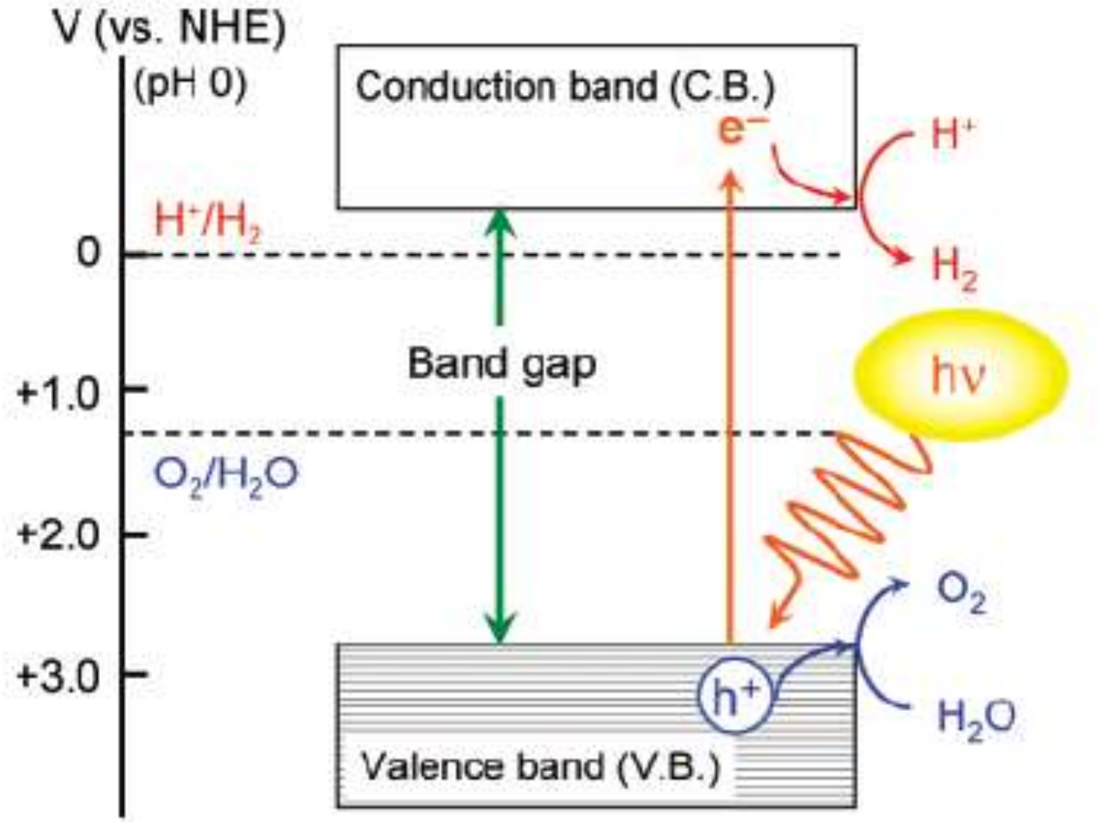
- The semiconductor system must *generate sufficient voltage* upon irradiation to split water
  - Or an external bias needs to be applied.
- The bulk band gap must be small enough to *absorb a significant portion of the solar spectrum*
- The *band edge potentials at the surfaces must straddle* the hydrogen and oxygen redox potentials



Domen et al. New Non-Oxide Photocatalysts Designed for Overall Water Splitting under Visible Light. *J. Phys. Chem. 2007*

# Material criteria to be met

- The system must exhibit *long-term stability* against corrosion in aqueous electrolytes
  - Metal oxides: Charge transfer kinetics > anodic decomposition rate
  - Non-oxides: thin oxide layer formation, dissolving.
- The *charge transfer* from the surface of the semiconductor to the solution must be facile to minimize energy losses due to kinetic overpotential



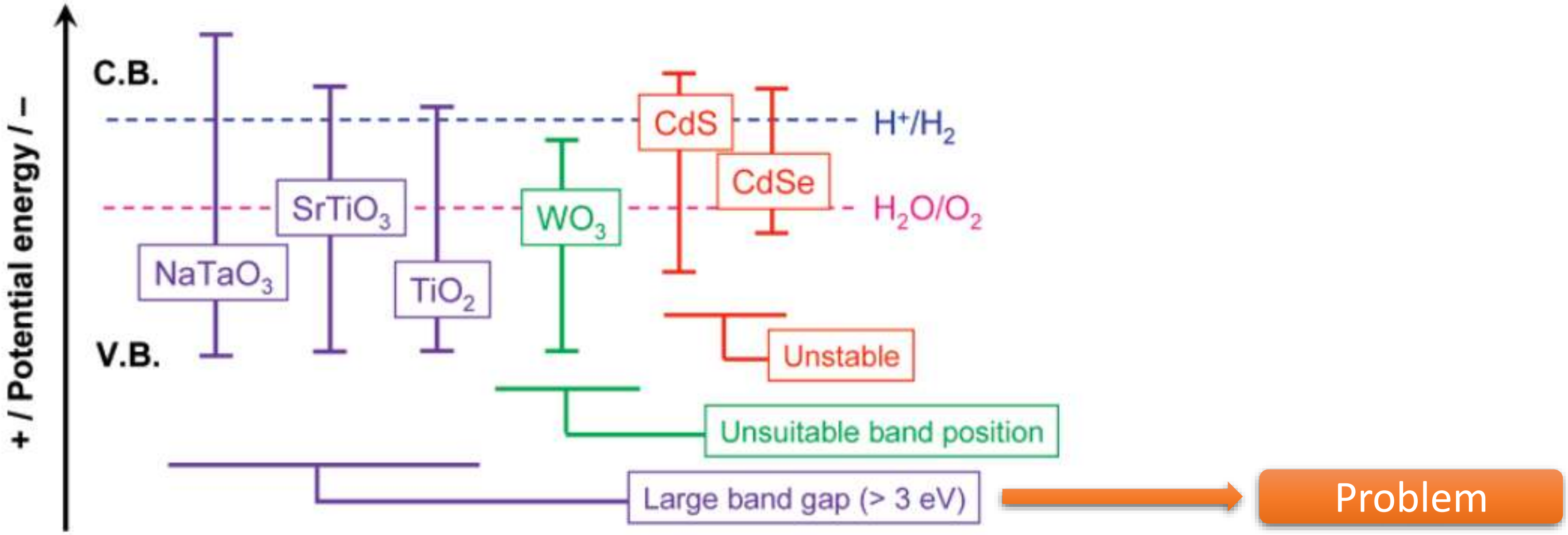
Domen et al. New Non-Oxide Photocatalysts Designed for Overall Water Splitting under Visible Light. *J. Phys. Chem. 2007*

# Target

- Band gap greater than 1.23 eV* but low enough to absorb visible light
- Band edge straddling
- High stability
- Fast charge transfer
- Low cost

# Current Challenge

- As far as we know, no cost-effective materials system satisfies all of the technical requirements listed above for practical hydrogen production.
- Schematic illustration of band structures of several semiconductor



Domen et al. New Non-Oxide Photocatalysts Designed for Overall Water Splitting under Visible Light. *J. Phys. Chem. 2007*

*Chen, Z.; Dinh, H.; Miller, E. *Photoelectrochemical water splitting*.

# Possible Solutions

- Materials Engineering
  - Introducing elements to reduce BG (Doping/Alloying)
    - e.g.: $N_2$
      - Since N replaces O in certain positions, providing a smaller band gap.
- Nanostructuring
  - Increasing surface area
  - Tuning electronic properties
- Different annealing conditions

# Why NTs?

- In 1991, Iijima reported on the formation of carbon nanotubes
  - Milestone in MSE
  - Then transition to MOs
- quantum size and dimensionality may fully be effective on physical and chemical properties, such as electron mobility, optical band gap, and surface reactivity.
- NTs attracts tremendous interest due to specific advantages:
  - Geometric Factors:
    - High surface area
    - Size exclusion effects
    - Diffusion behavior
  - Biological Interactions
  - Directional Charge and Ion transport

*Lee, Kiyoung, Anca Mazare, and Patrik Schmuki. "One-dimensional titanium dioxide nanomaterials: nanotubes." *Chemical reviews* 114.19 (2014): 9385-9454.

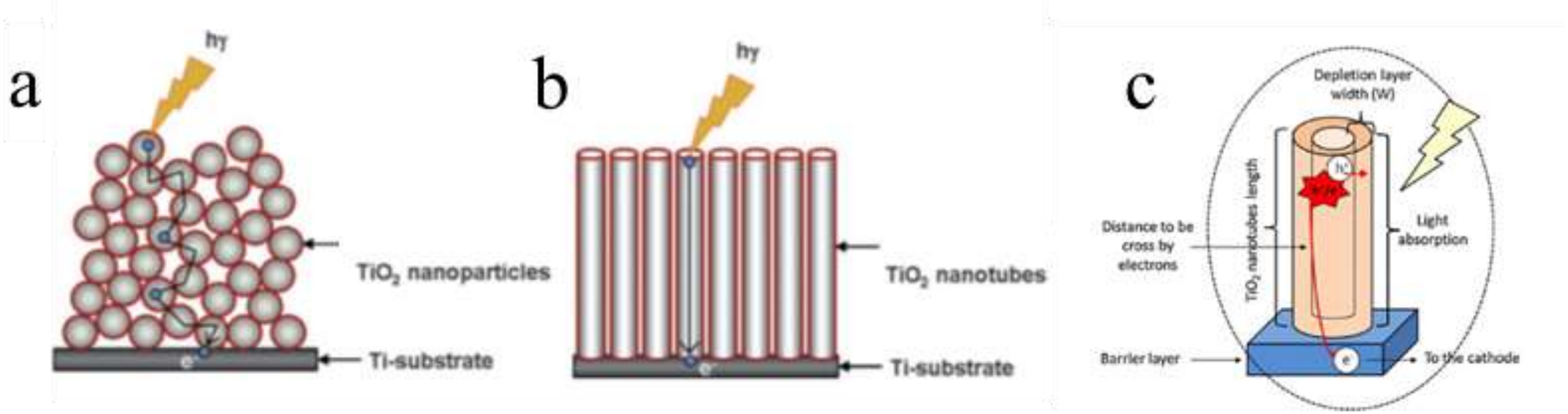
# Why NTs?

- Classical 1D quantum size effects:
  - Reduced e- scattering (ballistic transport)
  - Extreme surface curvature (Modified physical and chemical properties)
  - Diffusion length of holes lies within the range of tube wall thickness
  - Orthogonal carrier separation:
    - Hole to the wall
    - E- to the back contact
  - Core shell Structures (Carrier Separation)
  - Decoration of wall ability
  - Nano test-tubes (high observation length)
- IPCE in NT >> NP layers
  - Since high current collection efficiency
    - Since (Taw NT) (transport time constant) > NPs
  - Since surface recombination NT < NPs

*Lee, Kiyoung, Anca Mazare, and Patrik Schmuki. "One-dimensional titanium dioxide nanomaterials: nanotubes." *Chemical reviews* 114.19 (2014): 9385-9454.

# Why NTs?

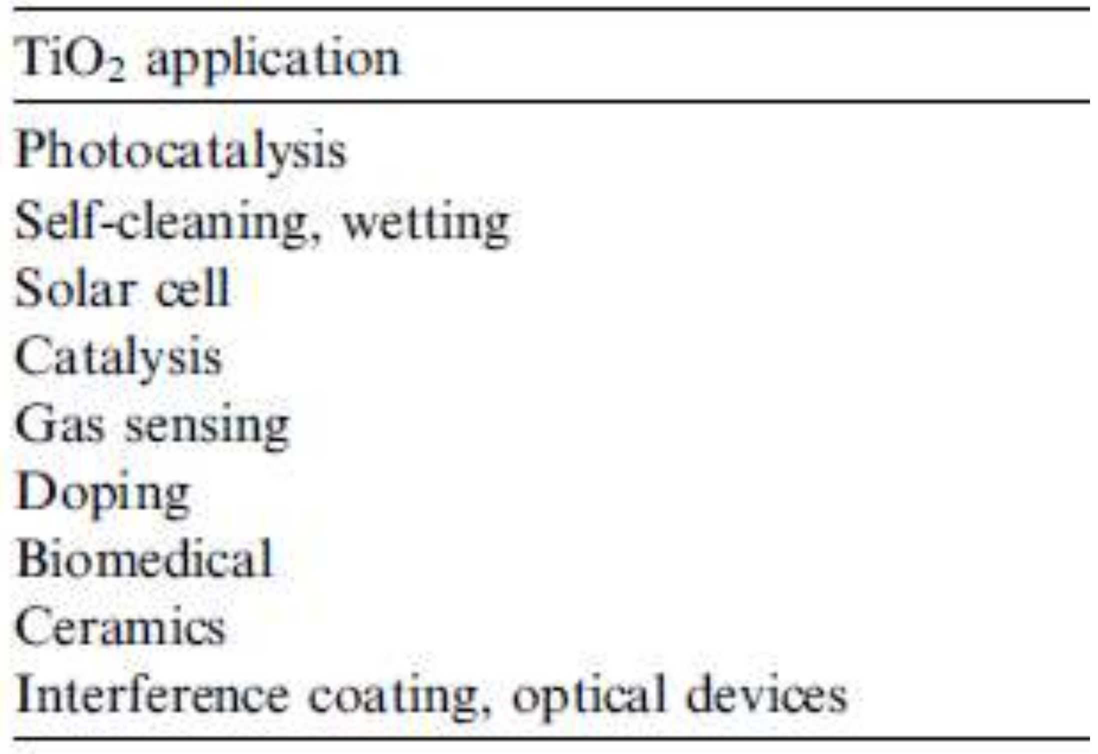
- High surface area allows for increased photon absorption
  - Twice the surface area/unit volume compared to NPs and NRs with the same outer diameter
- NTs perpendicular to the substrate surface, reduce $e^-$ diffusion path to the external circuit



*Haring, Andrew, Amanda Morris, and Michael Hu. "Controlling morphological parameters of anodized titania nanotubes for optimized solar energy applications." Materials 5.10 (2012): 1890-1909.

# Why Ti?

- This is due to a broad set of outstanding properties that this class of materials has to offer.



| $TiO_2$ application |
|---|
| Photocatalysis |
| Self-cleaning, wetting |
| Solar cell |
| Catalysis |
| Gas sensing |
| Doping |
| Biomedical |
| Ceramics |
| Interference coating, optical devices |

Macak, J. M., et al. "TiO 2 nanotubes: self-organized electrochemical formation, properties and applications." *Current Opinion in Solid State and Materials Science* 11.1 (2007

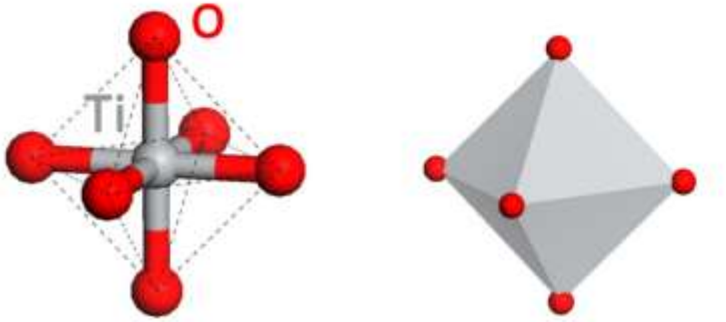
Ghicov, Andrei, and Patrik Schmuki. "Self-ordering electrochemistry: a review on growth and functionality of TiO 2 nanotubes and other self-aligned MO x structures." Chemical Communications 20

# Why $TiO_2$?

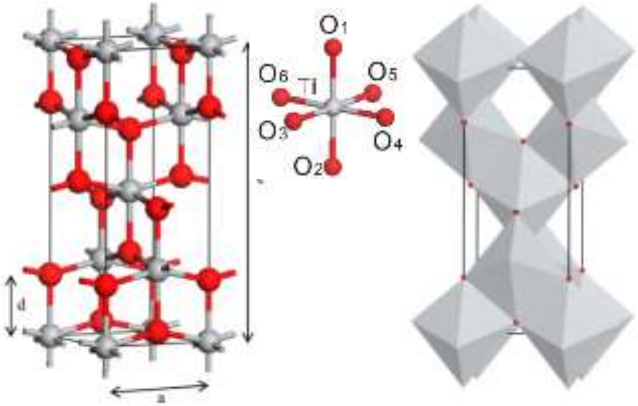
- $TiO_2$ has shown to be an excellent photocatalyst
  - long-term stability, low-cost preparation and a strong enough oxidizing power to be useful for the decomposition of unwanted organic compounds
- The *anatase form* of $TiO_2$ shows the highest solar energy conversion efficiency

Macak, J. M., et al. "TiO 2 nanotubes: self-organized electrochemical formation, properties and applications." *Current Opinion in Solid State and Materials Science* 11.1 (2007): 3-18.

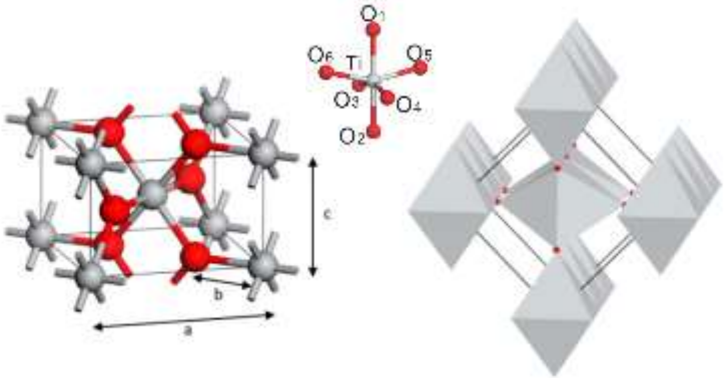
# Main $TiO_2$ Crystal Structures



Anatase



Rutile



# Why TNTs?

- Enhanced properties
- Cost-effective construction,
- higher surface-to-volume ratio
- Due to its photocatalytic property

Indira, K., et al. "A Review on TiO2 Nanotubes: Influence of Anodization Parameters, Formation Mechanism, Properties, Corrosion Behavior, and Biomedical Applications." *Journal of Bio-and Tribo-Corrosion* 1.4 (2015): 1-22.

# Proposed Material

- Ti 3510
  - (Ti-35Zr-10Nb)
- Why?
  - The fabricated Ti-Nb-Zr-O nanotubes showed a *17.5%* increase in the photoelectrochemical water oxidation efficiency as compared to that measured for pure $TiO_2$ nanotubes under UV illumination.
  - Nb, Zr alloying
    - shifts absorption band edges towards visible region
    - Enhances charge transfer

# Objective

- Fabrication of a complex metal oxide NTs and tuning its morphology for an efficient water splitting performance.
- Investigating the formation and growth of the NTs.
- Assessing the PEC performance of the fabricated NTs.

# Research Plan

- Literature Review on Water Splitting and different requirement for materials used.
- Selection of Material/Alloy.
- Material Preparation and Synthesis.
- Material Processing by Annealing at different temperatures and in different atmospheres.
- Studying the effect of different annealing conditions on the structure and properties of the material.
- Material characterization and assessment of the required properties for Water splitting.

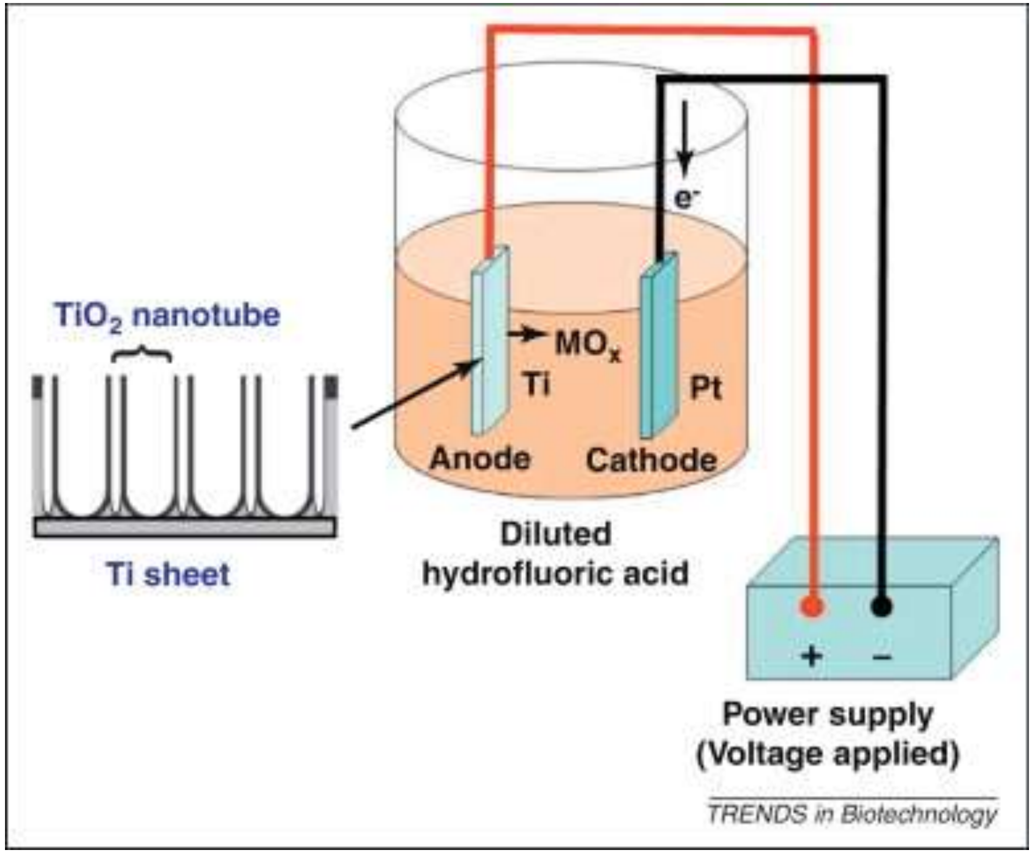
# Experimental Methods

# Main Phases

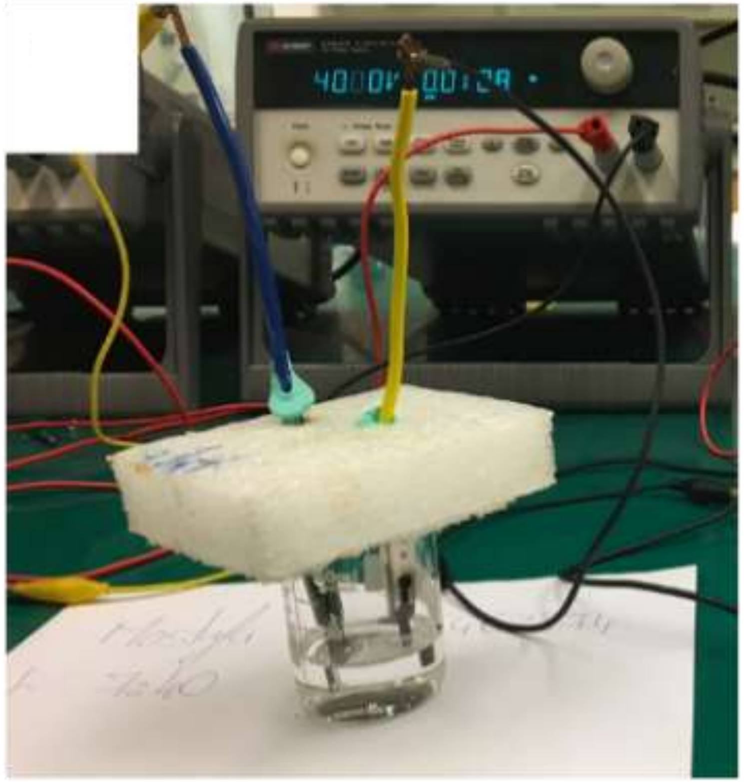
1. NTs Synthesis
    - *Via* Anodization
        - Optimization of anodization parameters
2. Morphology Investigation
    1. Studying effect of time
    2. Studying effect of Anodization Potential
    3. Selection of the most promising condition
3. Characterization

# I. NTs Synthesis

- Via Anodization



*TRENDS in Biotechnology*



# Experimental Work

- Anodization

Electrolyte Preparation

1.5 ml Distilled Water + 0.389 gm $NH_4F$

+

1 ml $H_3PO_4$ + 50 ml Formamide

Sample Preparation

Grinding and Polishing

+

Sonication (10 mins acetone > 10 mins ethanol > 10 mins distilled water

Anodization @ 40 V

Time

- 4 hrs
- 10 hrs
- 12 hrs
- 16 hrs
- 18 hrs
- 20 hrs

Optimize Tube Length, Diameter, and thickness

Allam, Nageh K., Faisal Alamgir, and Mostafa A. El-Sayed. "Enhanced photoassisted water electrolysis using vertically oriented anodically fabricated Ti– Nb– Zr– O mixed oxide nanotube arrays." *ACS nano* 4.10 (2010): 5819-5826.

# Anodization Conditions

| Sample Preparation | Time | Voltage |
|---|---|---|
| Grinded | 0.5 h | 40 V |
| Polished | 1 h | |
| | 2 h | |
| | 4 h | |
| | 6 h | |
| | 8 h | |
| | 10 h | |
| | 12 h | |
| | 14 h | |
| | 16 h | |
| | 18 h | |
| | 20 h | |

# Anodization Conditions

| Sample Preparation |
|---|
| Grinded |
| Polished |

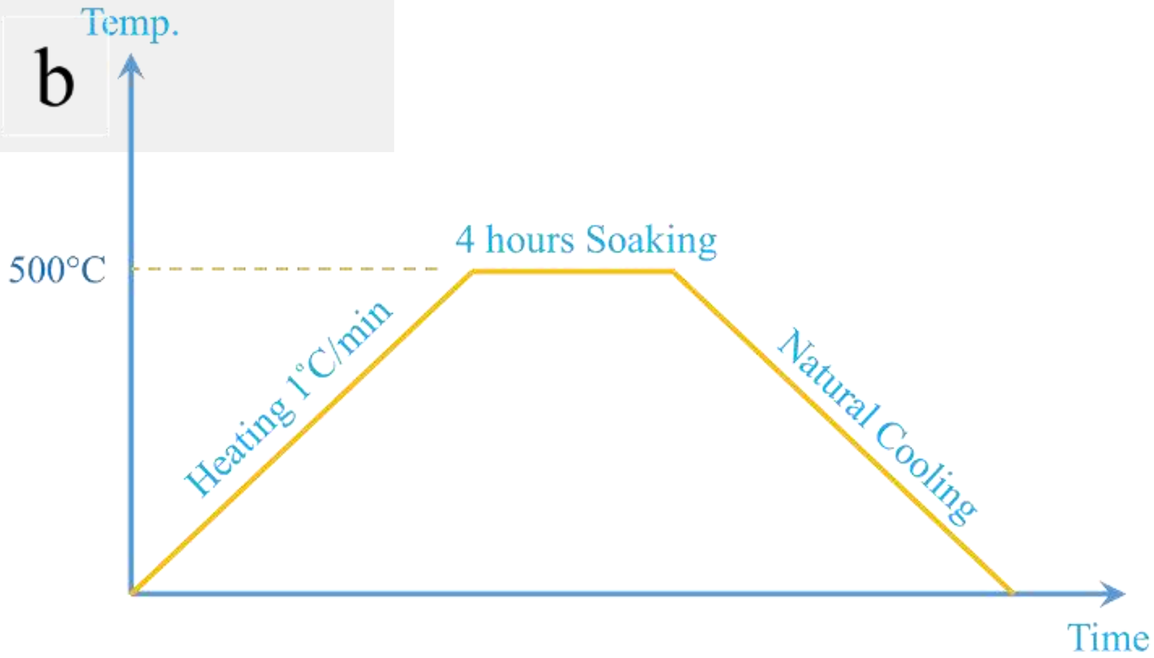
| Time |
|---|
| 2 hrs |
| 4 hrs |
| 8 hrs |
| 14 hrs |

| Voltage |
|---|
| 10 V |
| 20 V |
| 30 V |
| 40 V |
| 50 V |
| 60 V |
| 80 V |
| 100 V |

| | | **Anodization Time** | | | |
|---|---|---|---|---|---|
| | | 2 hrs | 4 hrs | 8 hrs | 14 hrs |
| **Anodization Potential** | 10 V | | | | |
| | 20 V | | | | |
| | 30 V | | | | |
| | 40 V | | | | |
| | 50 V | | | | |
| | 60 V | | | | |
| | 80 V | | | | |
| | 100 V | | | | |

# Annealing Conditions

| Atmospheres | Temp. | Ramp rate |
|---|---|---|
| $H_2$ | 500 ˚C | 1 ˚C/min |
| Air | | |



# 3. Different Characterization Techniques Used

- Surface/Morphology:
  - SEM
- Structural:
  - X-ray Diffraction - XRD
- Elemental:
  - Energy-dispersive X-ray spectroscopy - EDX
  - X-ray photoelectron spectroscopy - XPS
- Optical:
  - UV-Vis Spectroscopy
  - Raman Spectroscopy
- Electrochemical:
  - LSV
  - I-t

# Results

# I. NTs Fabrication

# 1. NTs Layer Adhesion

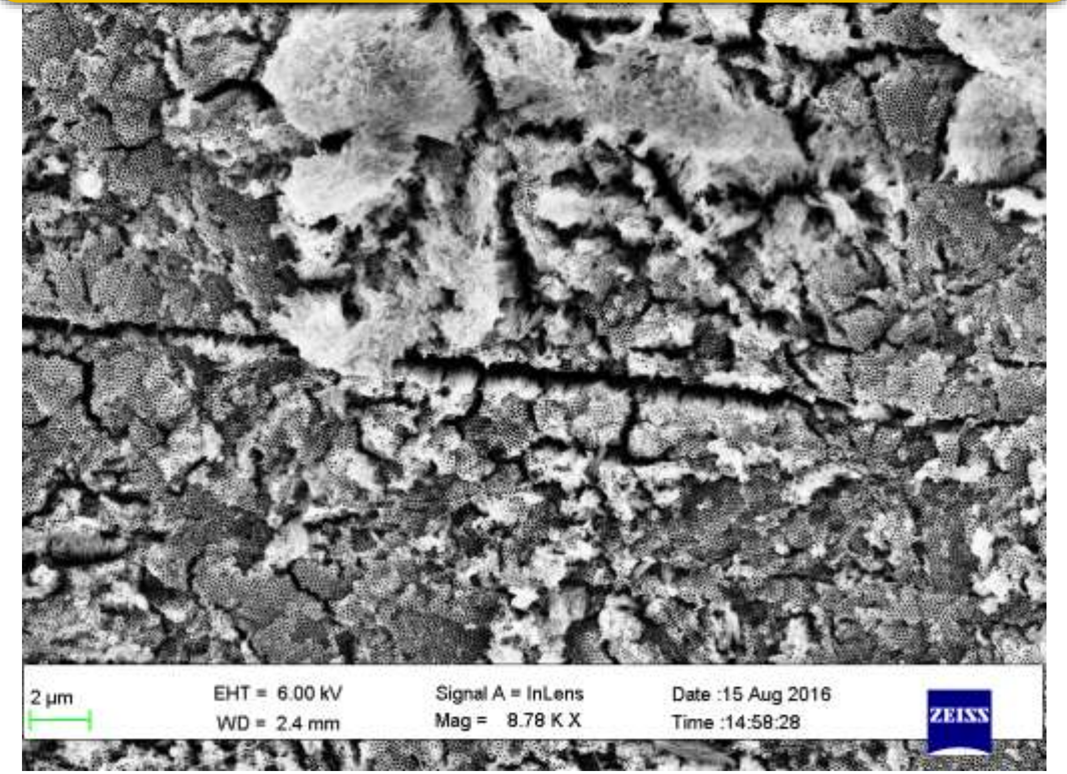
Good Adhesion

Poor Adhesion

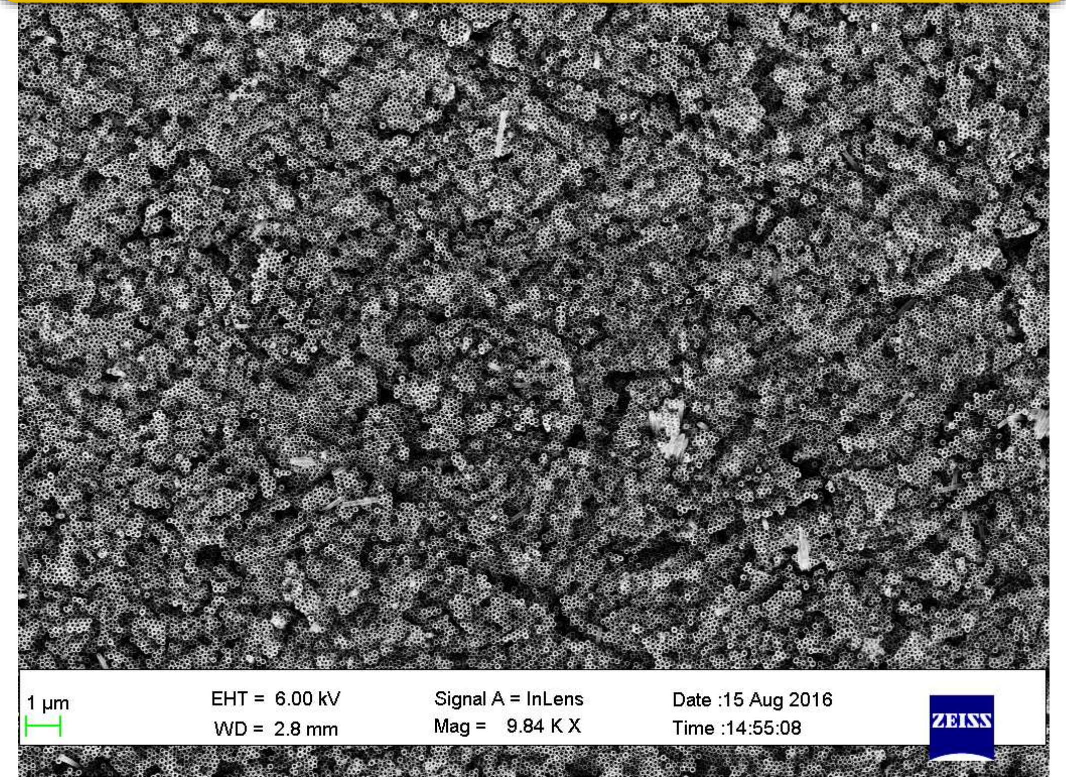
~ No Adhesion

# 2. Effect of Surface roughness

**18 hrs grinded**

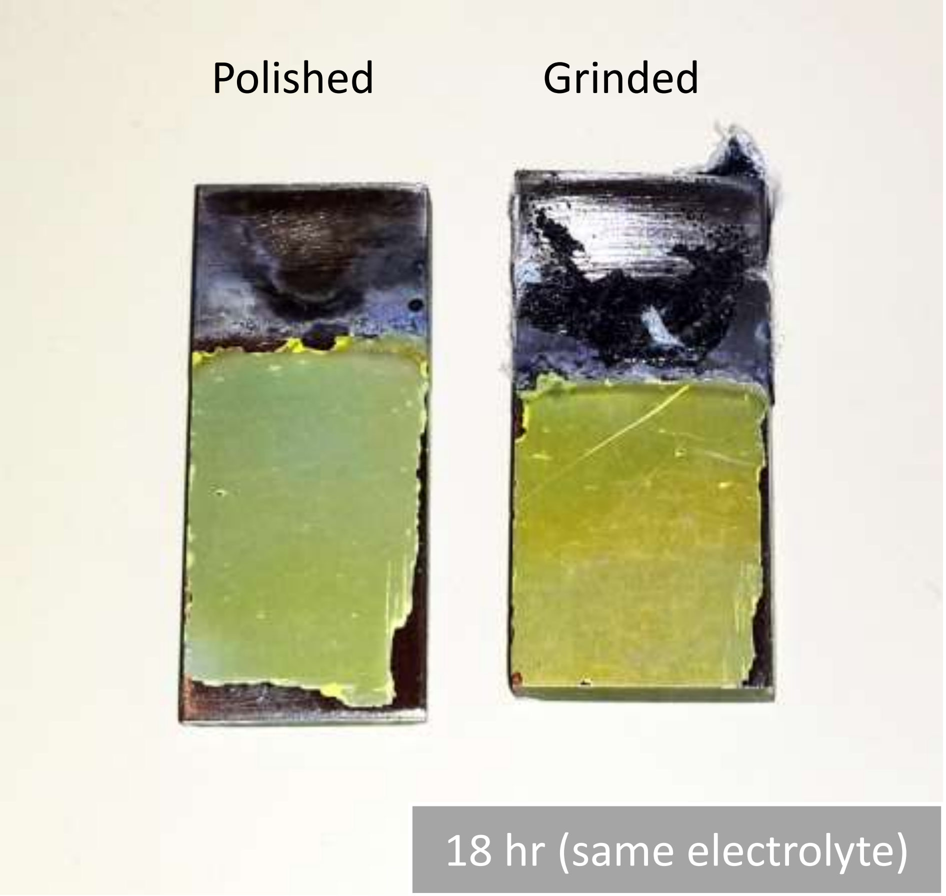


**18 hrs Polished**



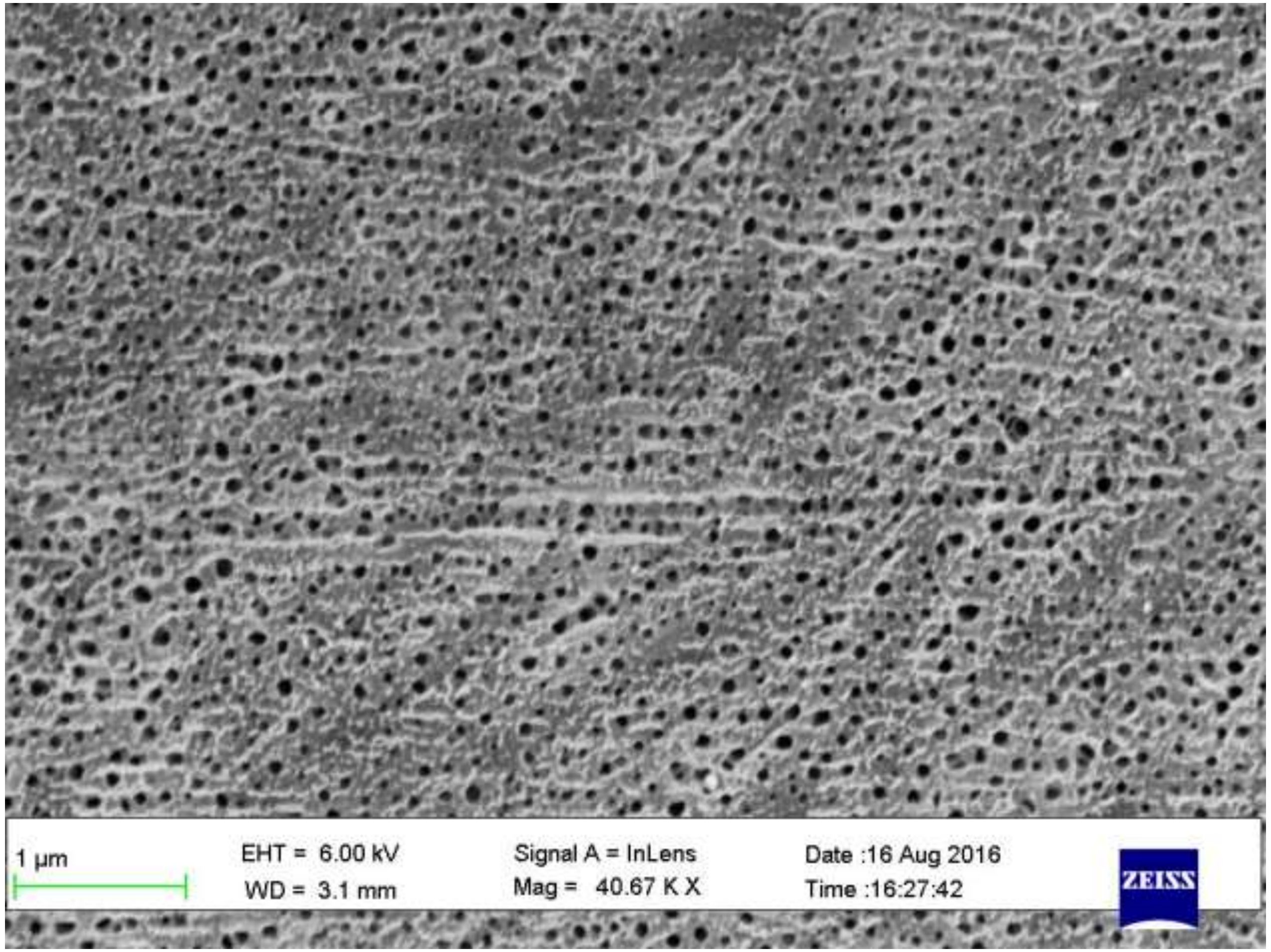
# Potential causes

- ~~Electrolyte~~
  - Using same electrolyte
- ~~Grinding / Polishing~~
  - Almost same conditions
- Sonication?
  - Pealed off even when drying under air stream!
- Fluorine rich layer?
  - Existed on both long and short times



18 hr (same electrolyte)

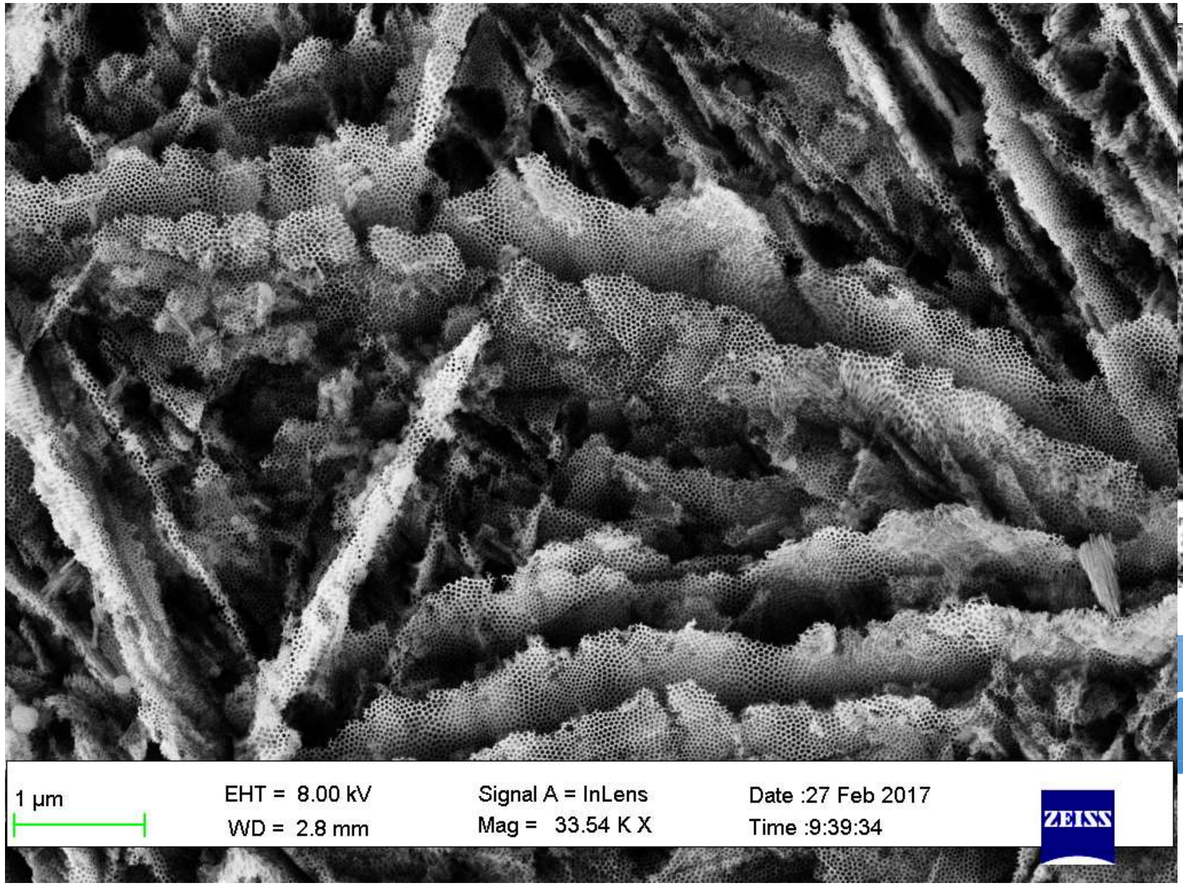
# Porous Layer instead of NTs!

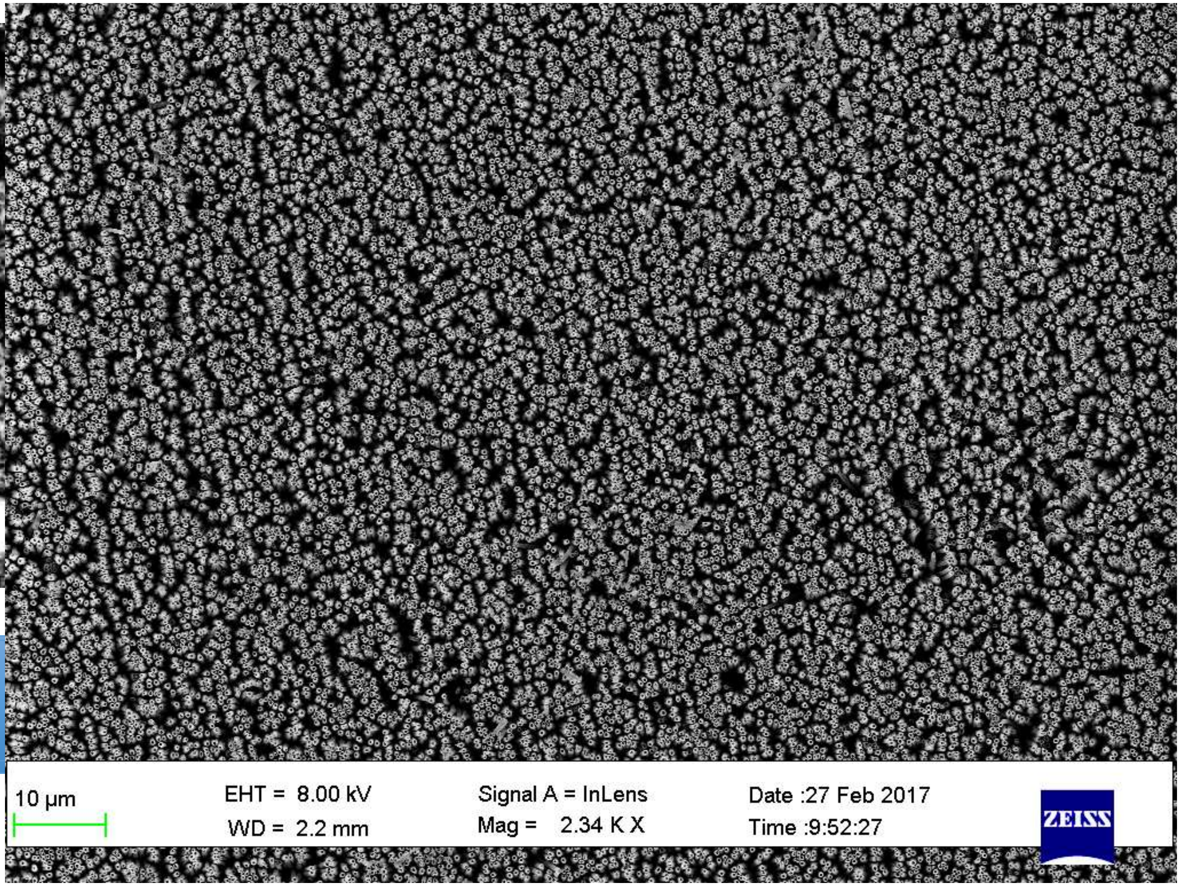


# Effect of time and Anodization Potential

# Effect of Anodization Potential on the Morphology

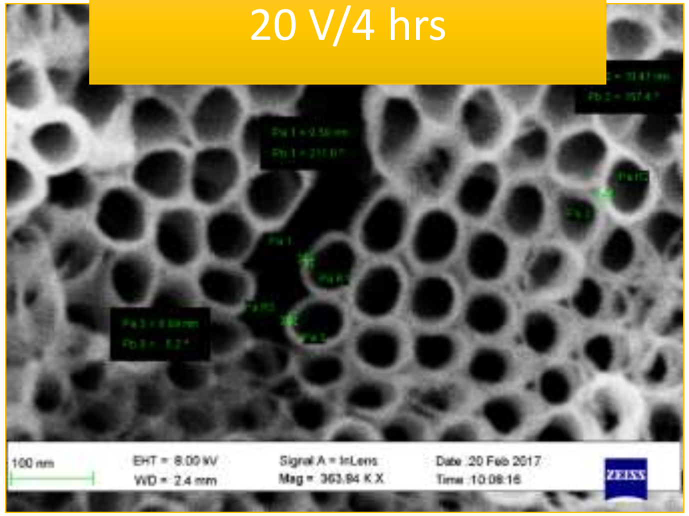
10 V → 30 V → 50 V → 60 V → 80 V → 100V



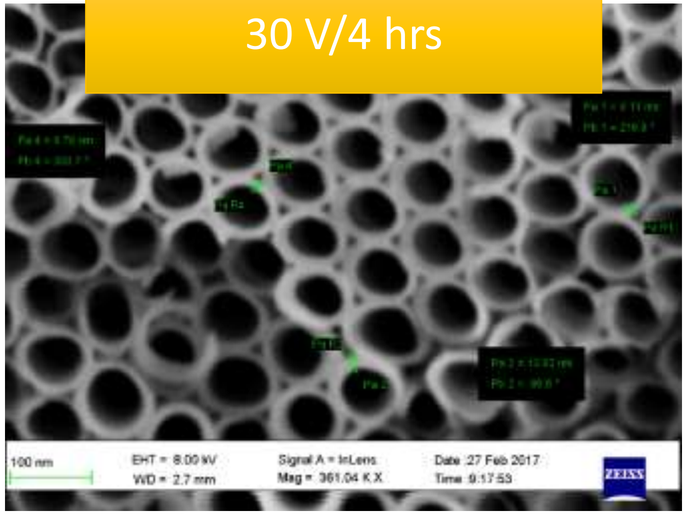


# Effect of Anodization Potential on the NTs Top pore

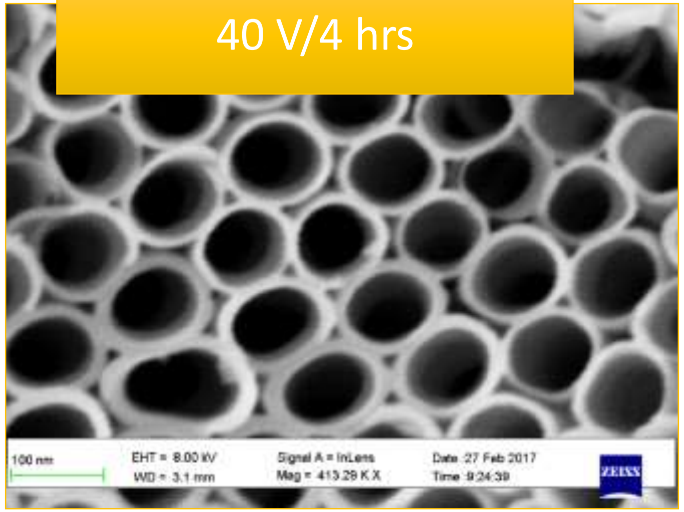
20 V/4 hrs



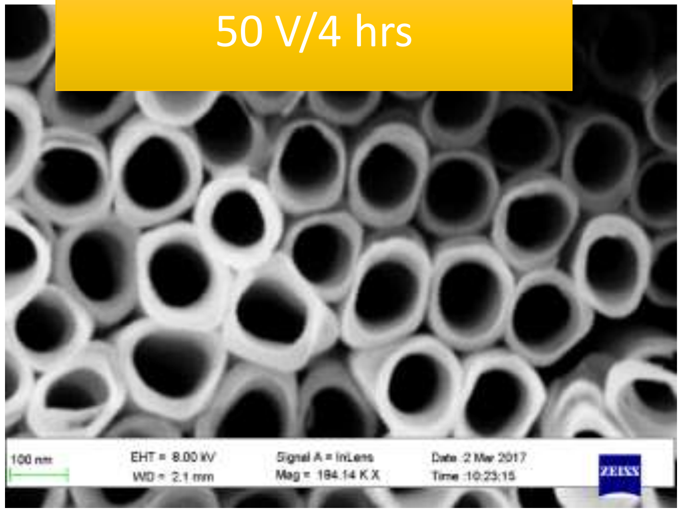
30 V/4 hrs



40 V/4 hrs

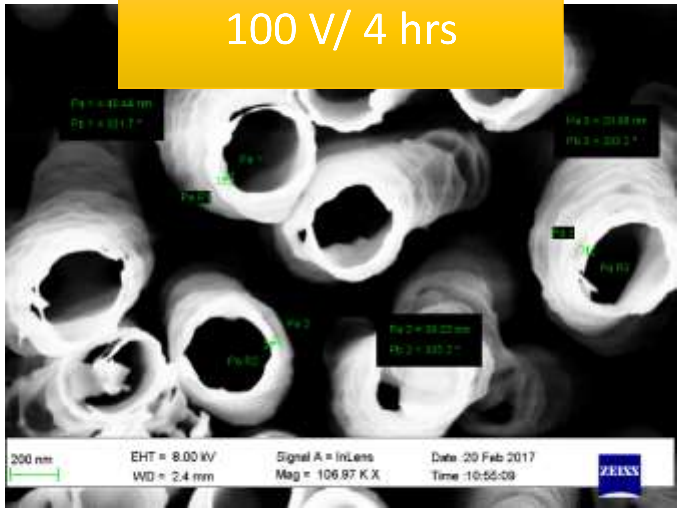


50 V/4 hrs



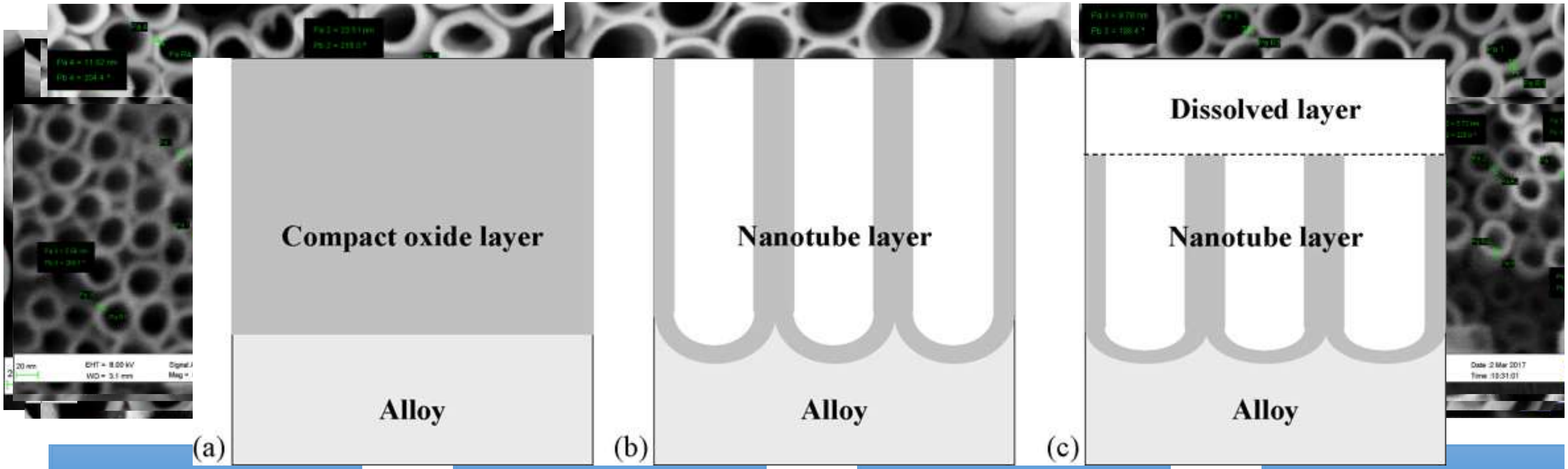
80 V/4 hrs

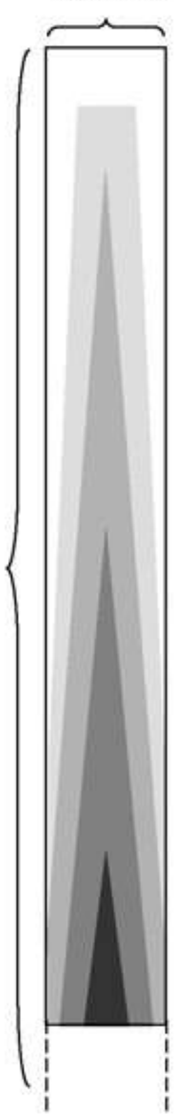
100 V/ 4 hrs



# Effect of Anodization Time on the Morphology

10 V ← 20 V ← 30 V ← 40 V ← 50 V ← 60 V ← 80 V ← 100 V





2 hrs

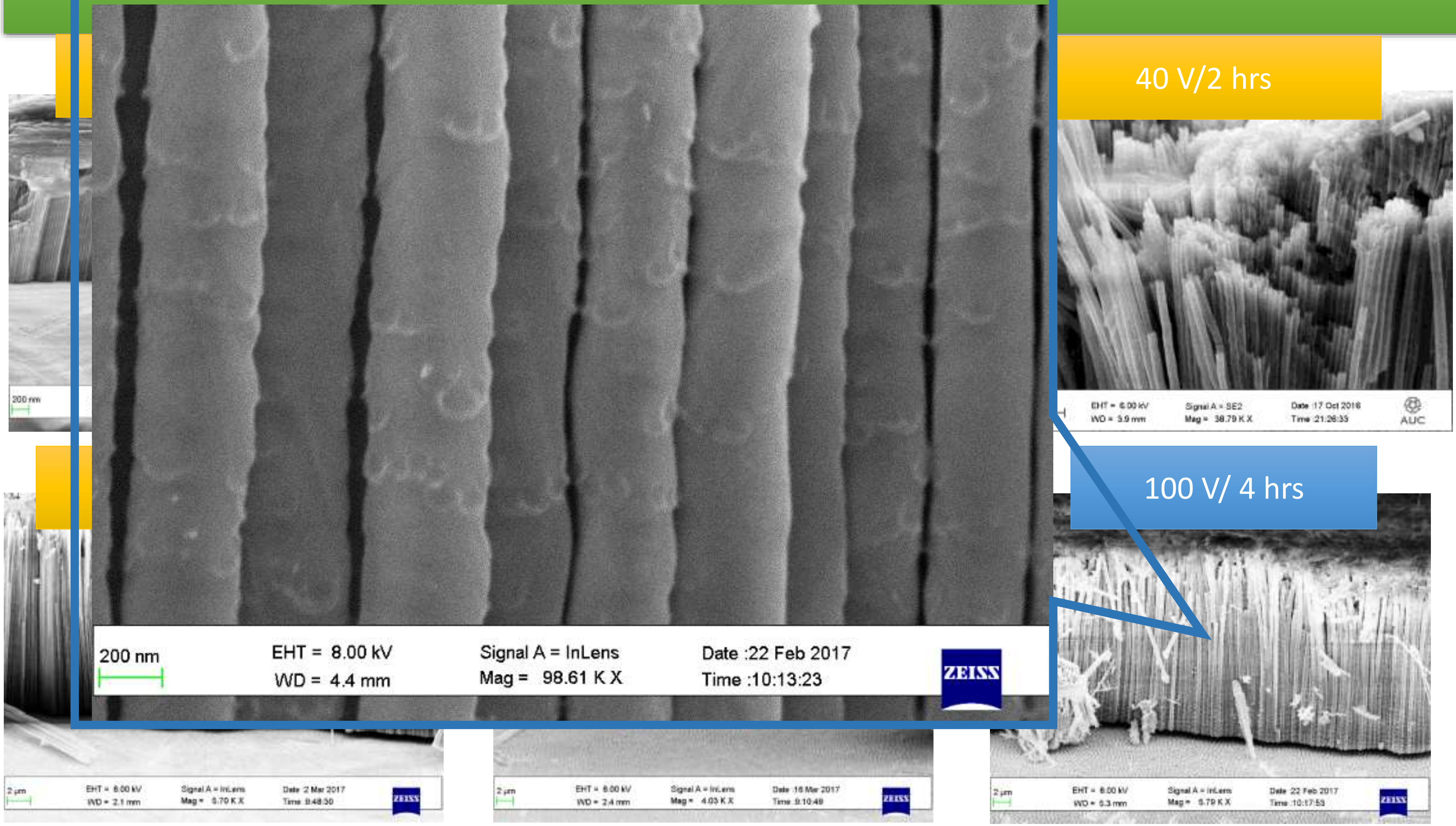
4 hrs

8 hrs

14 hrs

4 hrs

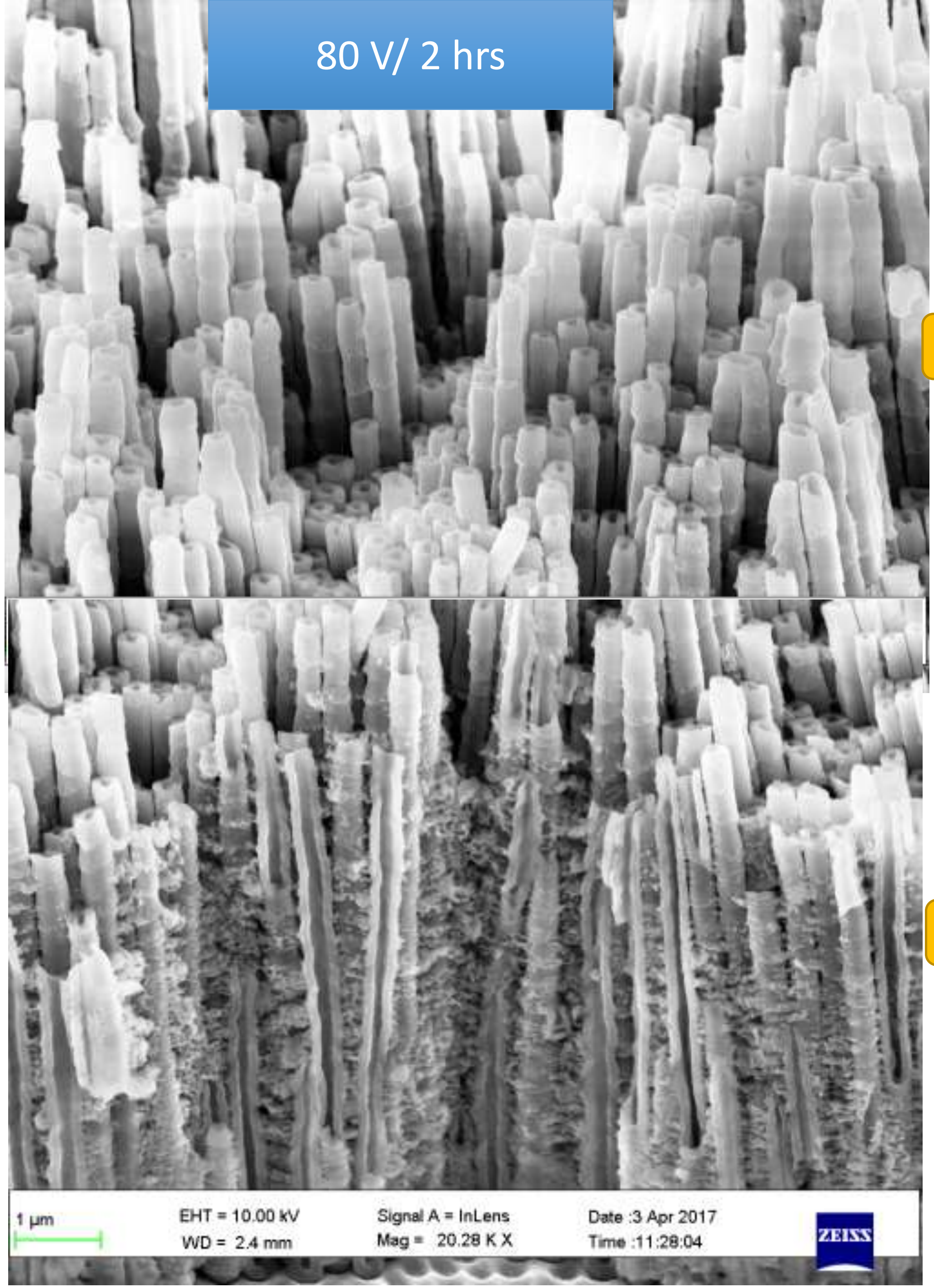
# Effect of Time on the Tube Walls



40 V/2 hrs

100 V/ 4 hrs

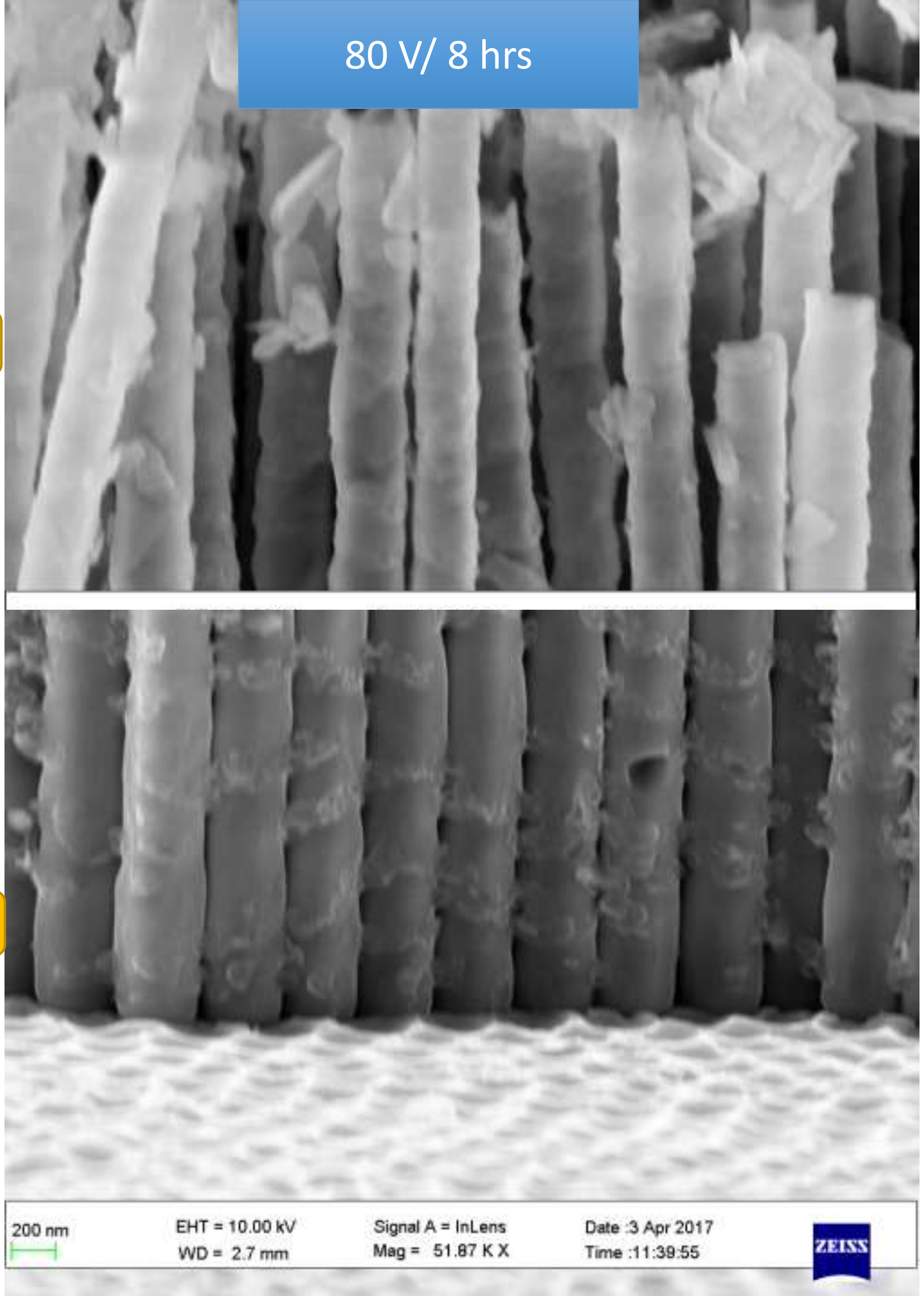
80 V/ 2 hrs

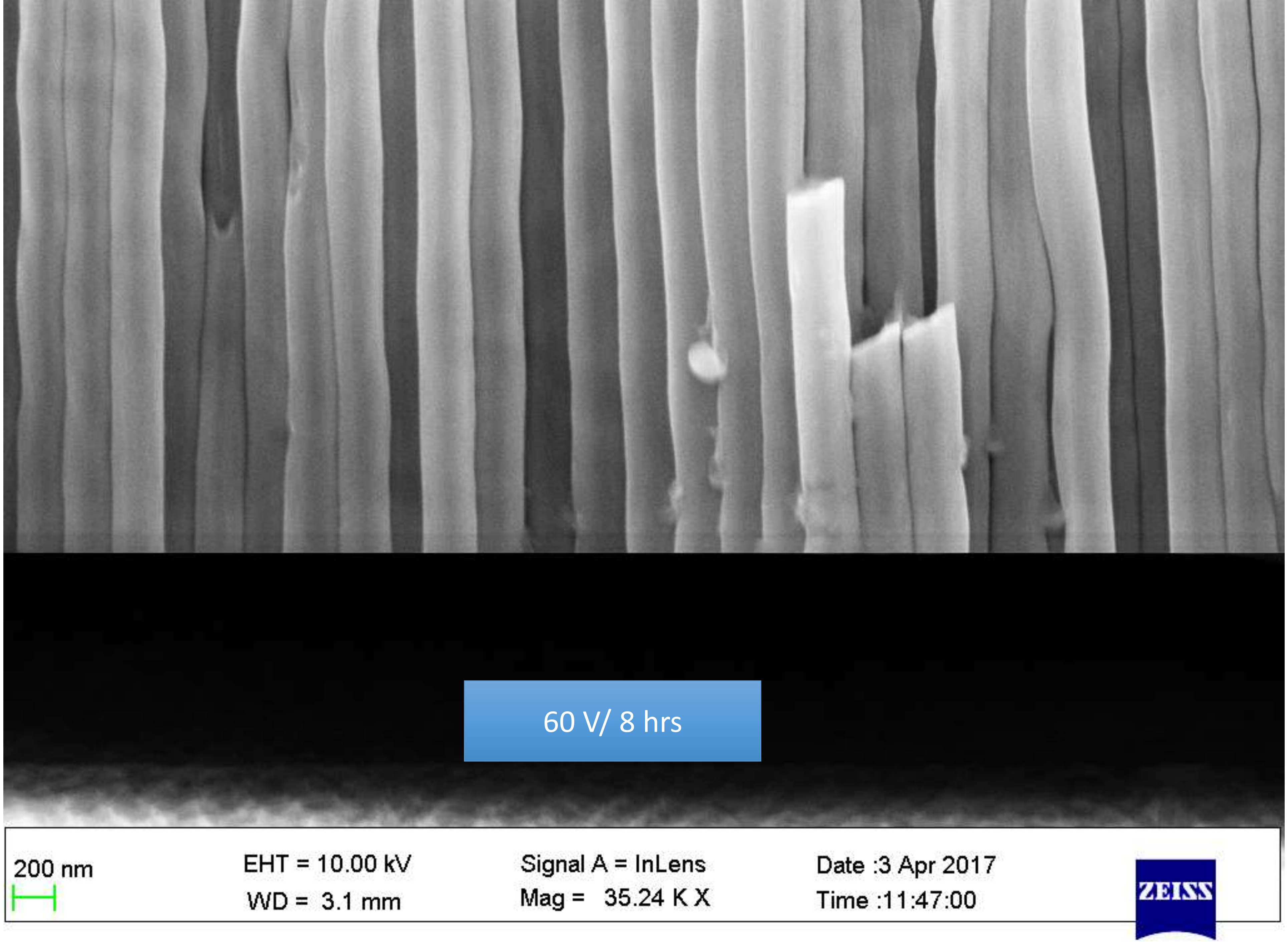


Top

Base

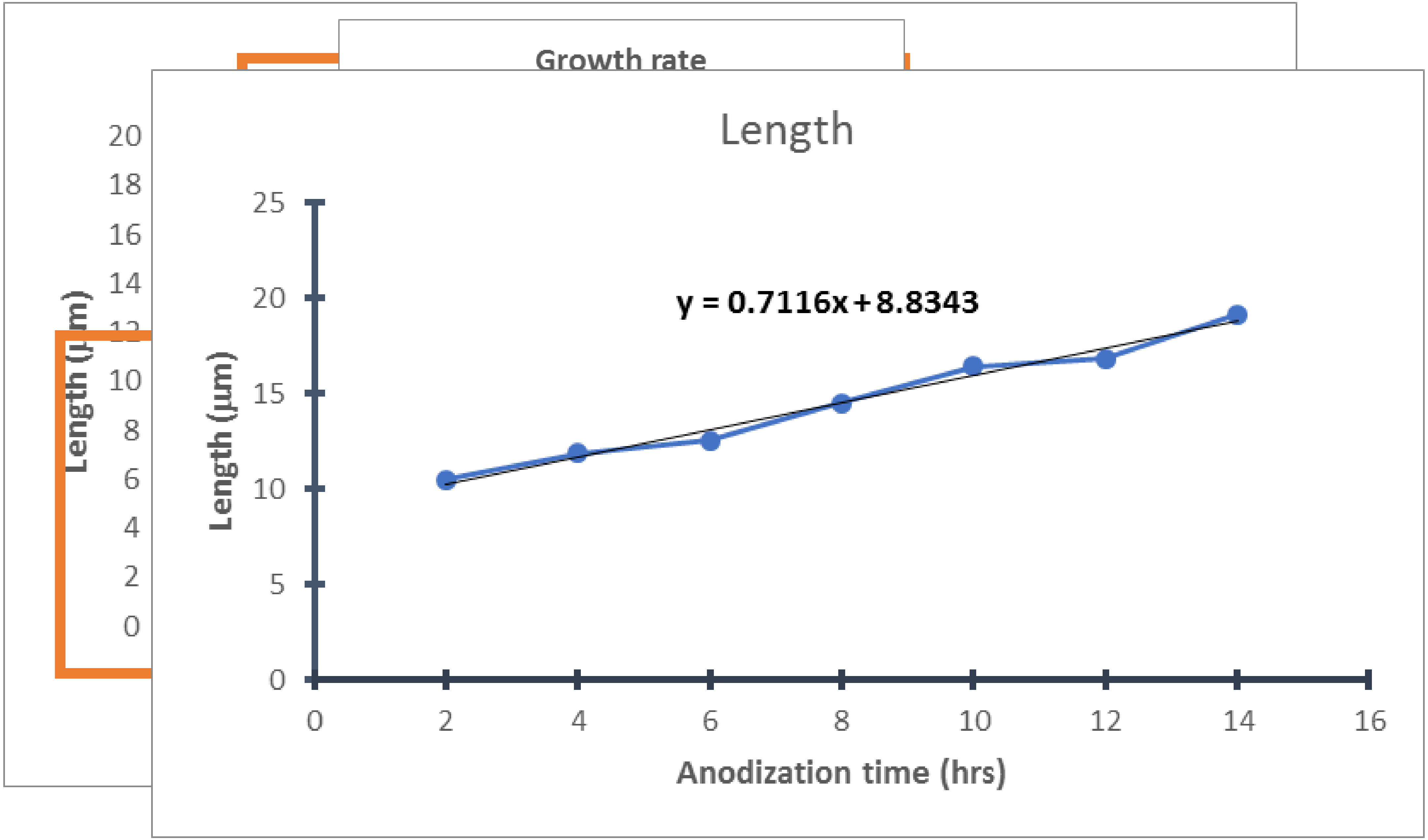
80 V/ 8 hrs




200 nm
EHT = 10.00 kV
WD = 3.1 mm
Signal A = InLens
Mag = 35.24 K X
Date :3 Apr 2017
Time :11:47:00
ZEISS

60 V/ 8 hrs

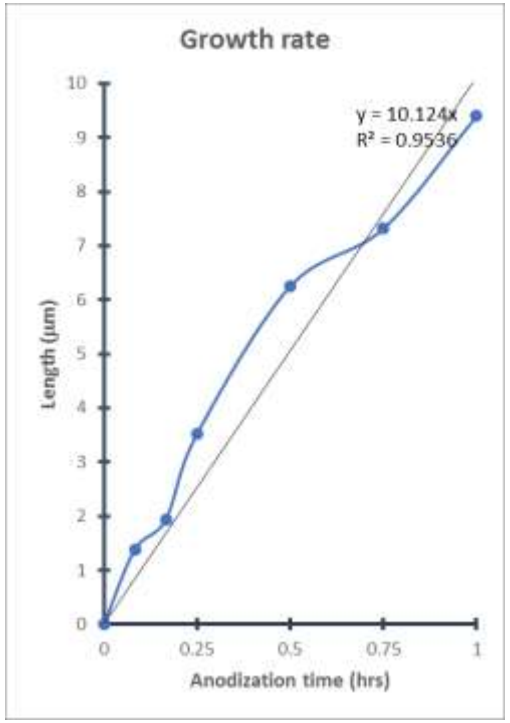
# Ti3510 @ 40 V


Growth rate
20
18
16
14
12
10
8
6
4
2
0
Length (µm)
Length
y = 0.7116x + 8.8343
25
20
15
10
5
0
Length (µm)
0
2
4
6
8
10
12
14
16
Anodization time (hrs)

# Growth rates

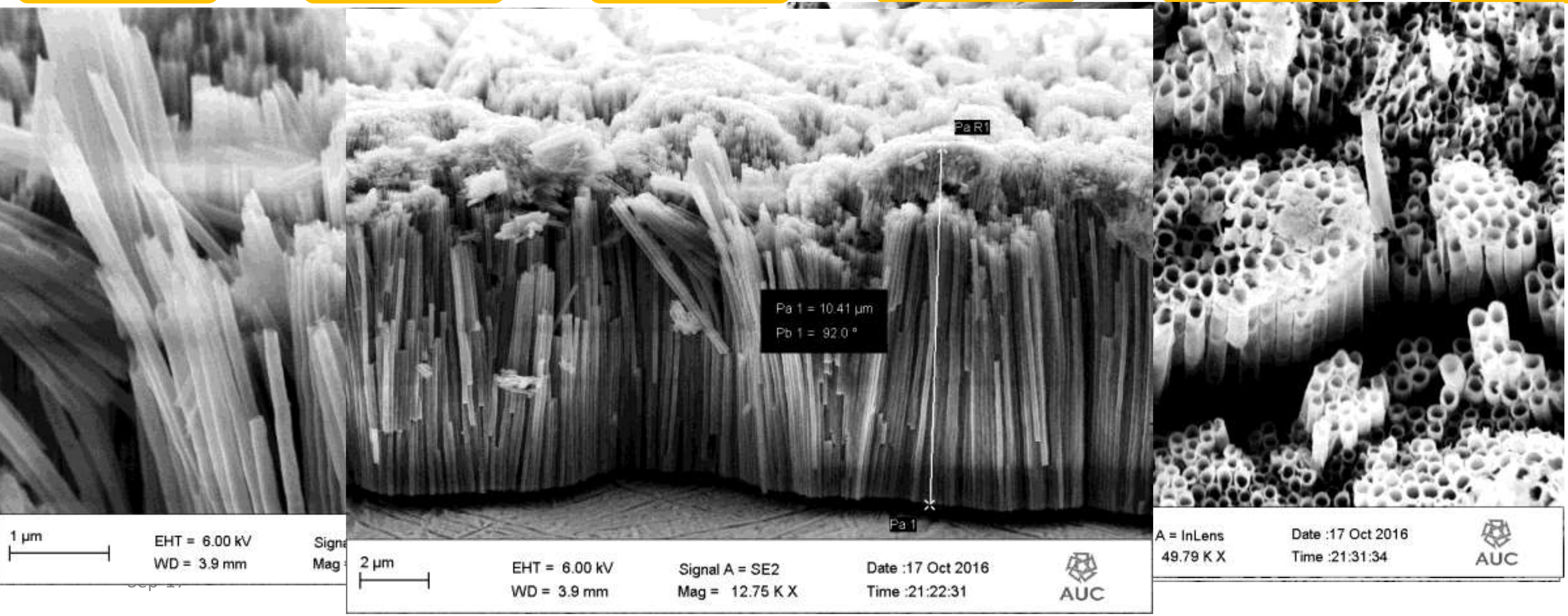
- Initial Growth Rate$)_{40\,\mathrm{V}}$= $\frac{9.4 \times 103\ (nm)}{1 \times 60 \times 60\ (s)} = 2.61\ nm/sec$

- Steady State Growth rate$)_{40\mathrm{V}}$= 0.198 nm/s

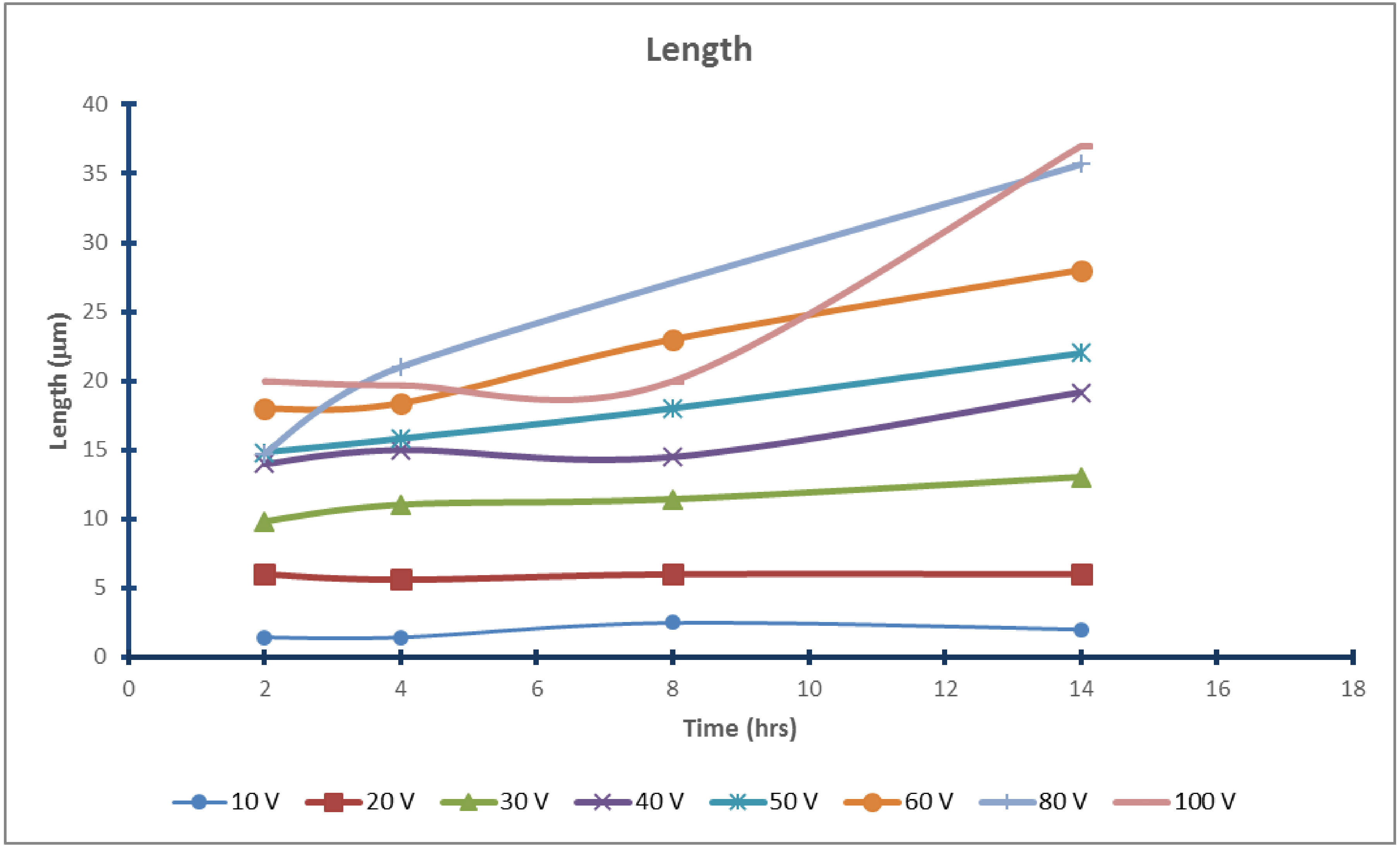


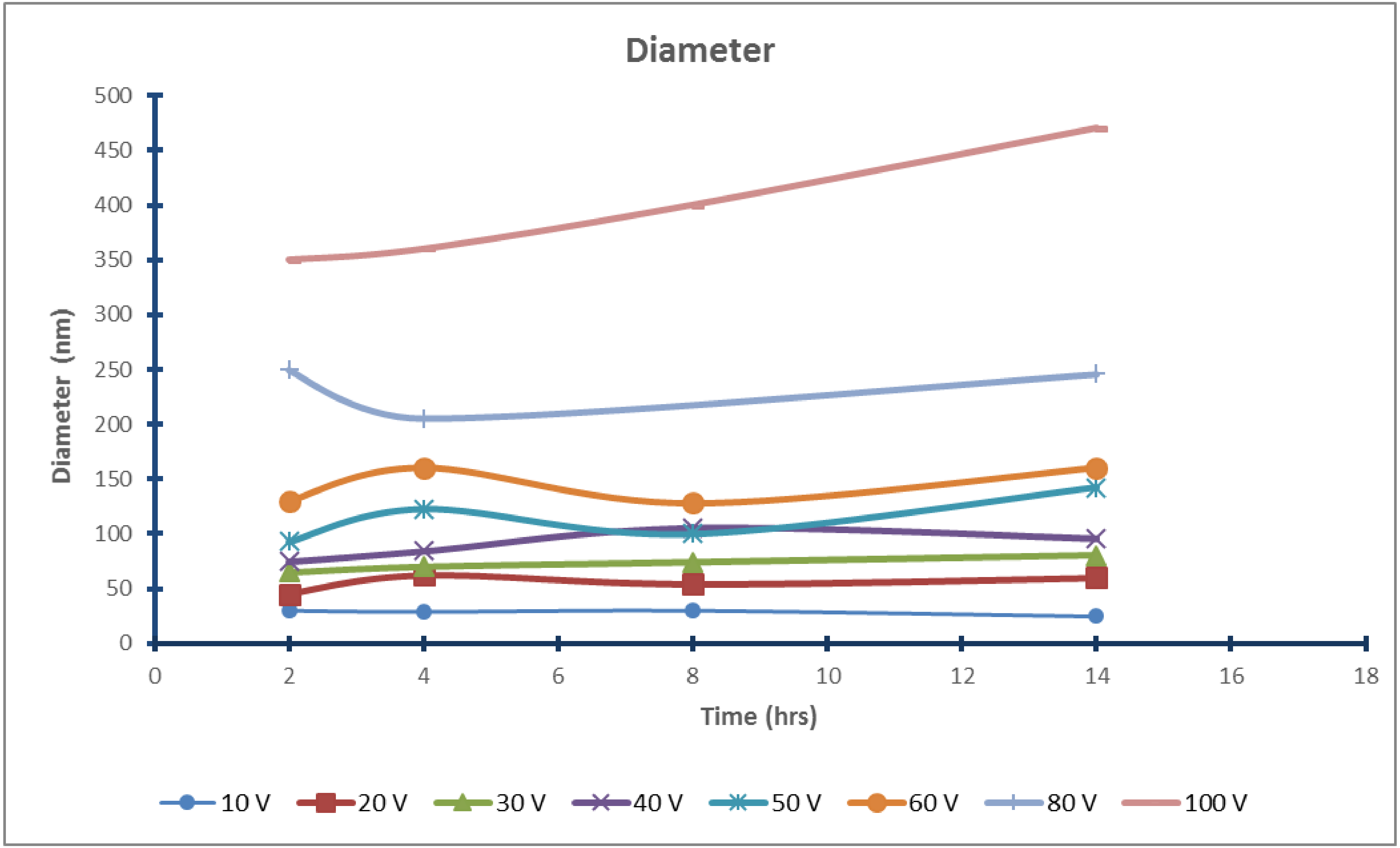
# Initial Growth Stage

5 min → 10 min → 15 min → 30 min → 1 hrs. → 2 hrs.



# NTs Geometry Analysis

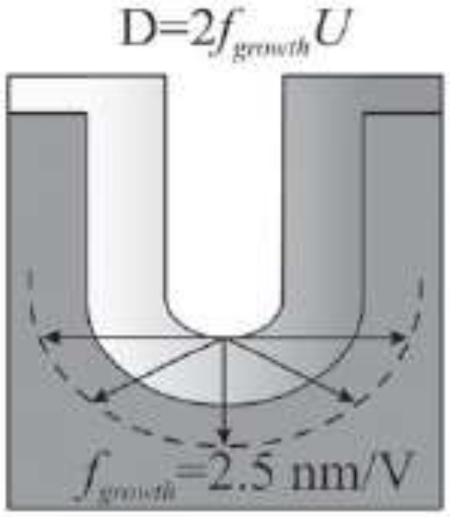

Length
40
35
30
25
20
15
10
5
0
Length (µm)
0
2
4
6
8
10
12
14
16
18
Time (hrs)
10 V
20 V
30 V
40 V
50 V
60 V
80 V
100 V

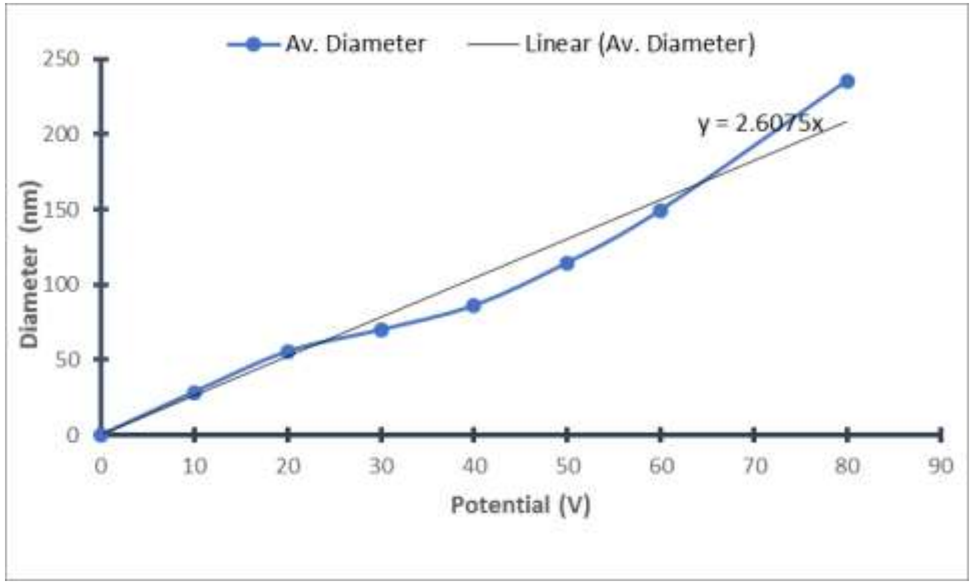


Diameter
Diameter (nm)
500
450
400
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
16
18
Time (hrs)
10 V
20 V
30 V
40 V
50 V
60 V
80 V
100 V

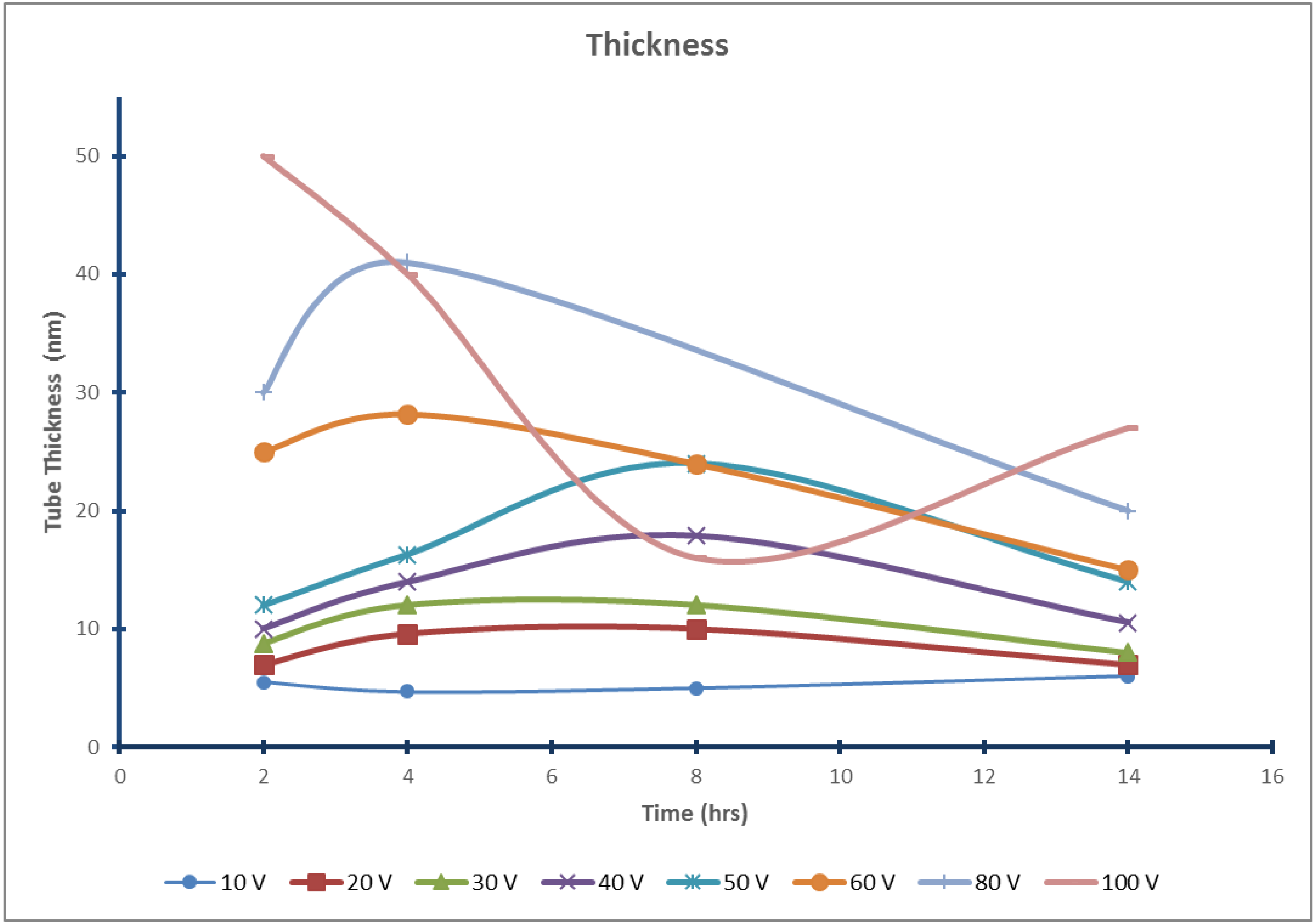
# Anodic Growth Factor ($f_g$)

- Migration of ions expressed as the max. radius of the oxide per applied potential
- $D=2f_gV$
- .:.$f_g)_{\text{Ti310}}= 2.6$ nm/V
  - Compared to 2.5 nm/V for $TiO_2$

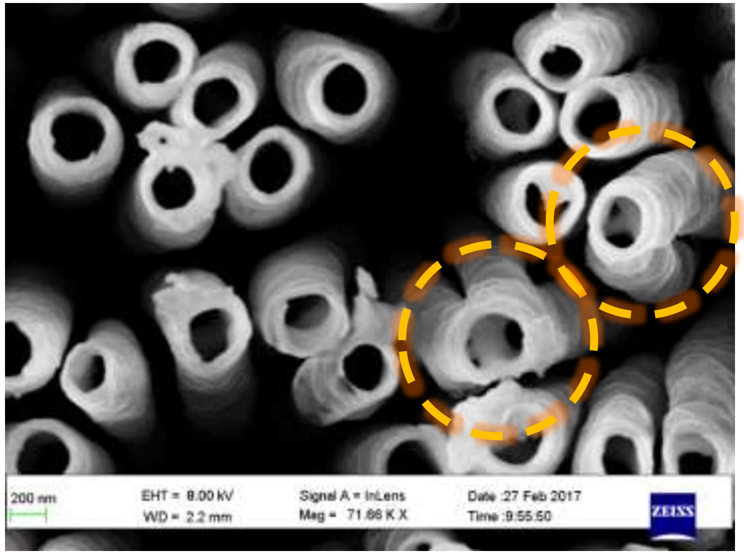


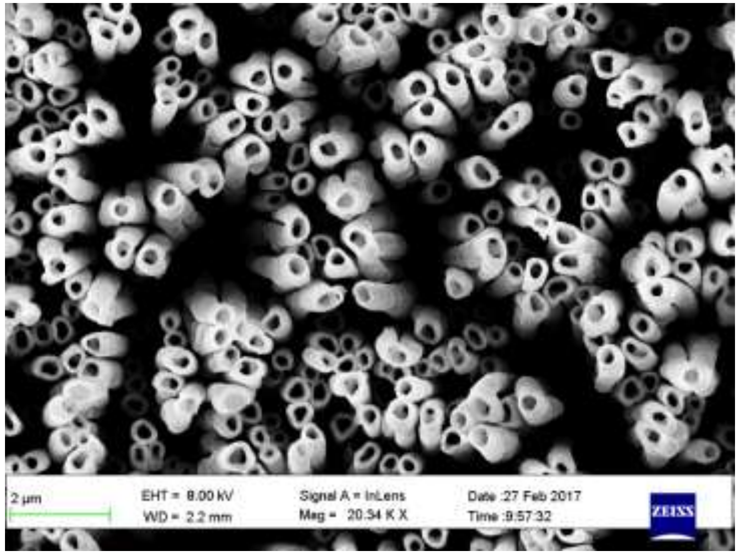


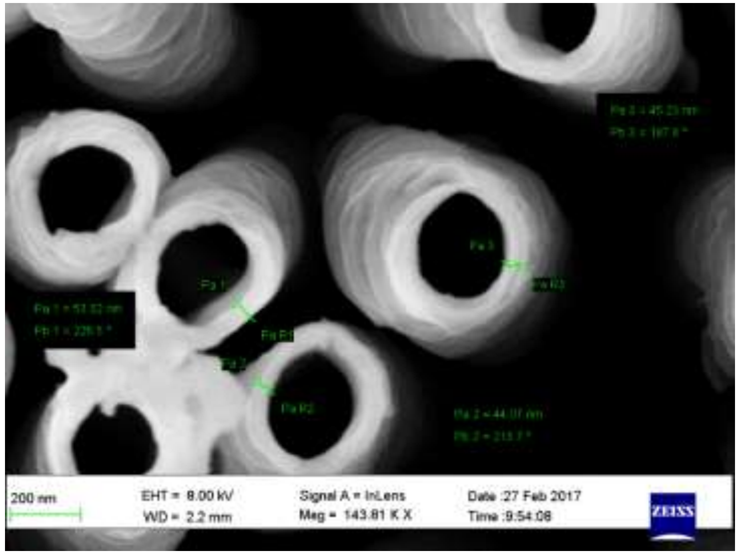
Macak, J. M., et al. "TiO 2 nanotubes: self-organized electrochemical formation, properties and applications." *Current Opinion in Solid State and Materials Science* 11.1 (2007): 3-18.


Thickness
Tube Thickness (nm)
0
10
20
30
40
50
Time (hrs)
0
2
4
6
8
10
12
14
16
10 V
20 V
30 V
40 V
50 V
60 V
80 V
100 V

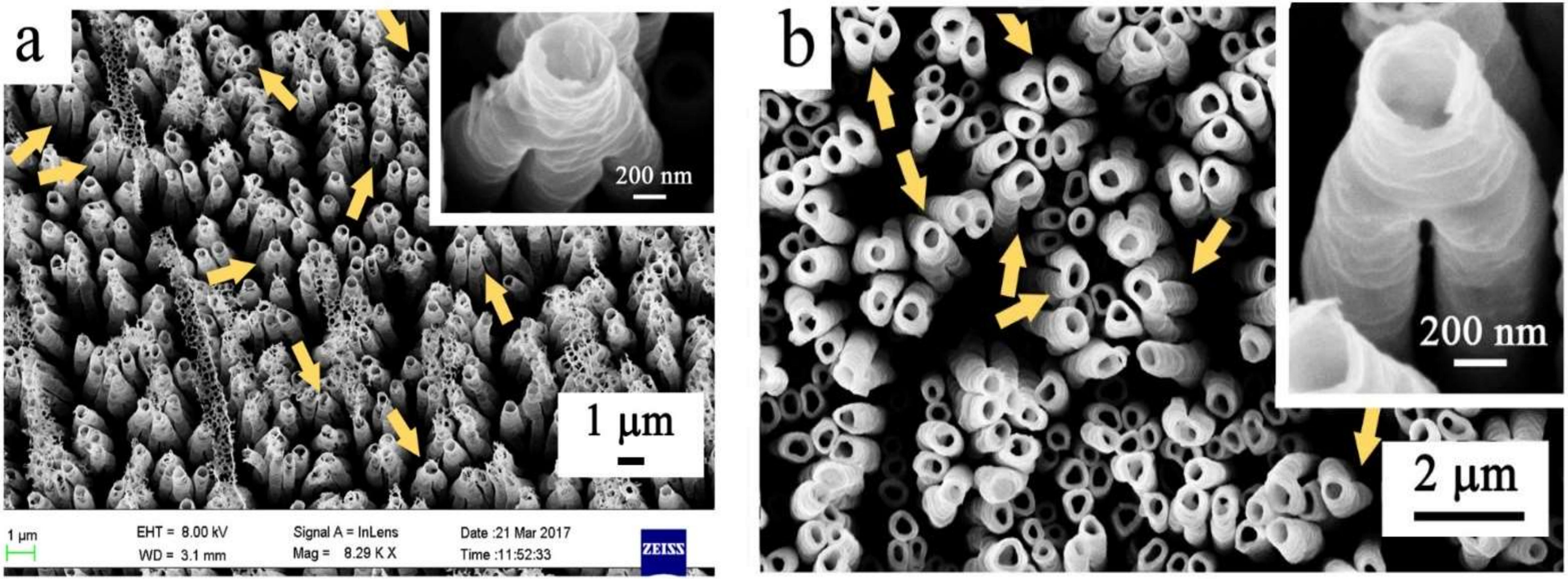
# 4. 2,3 tubes -1 pore!



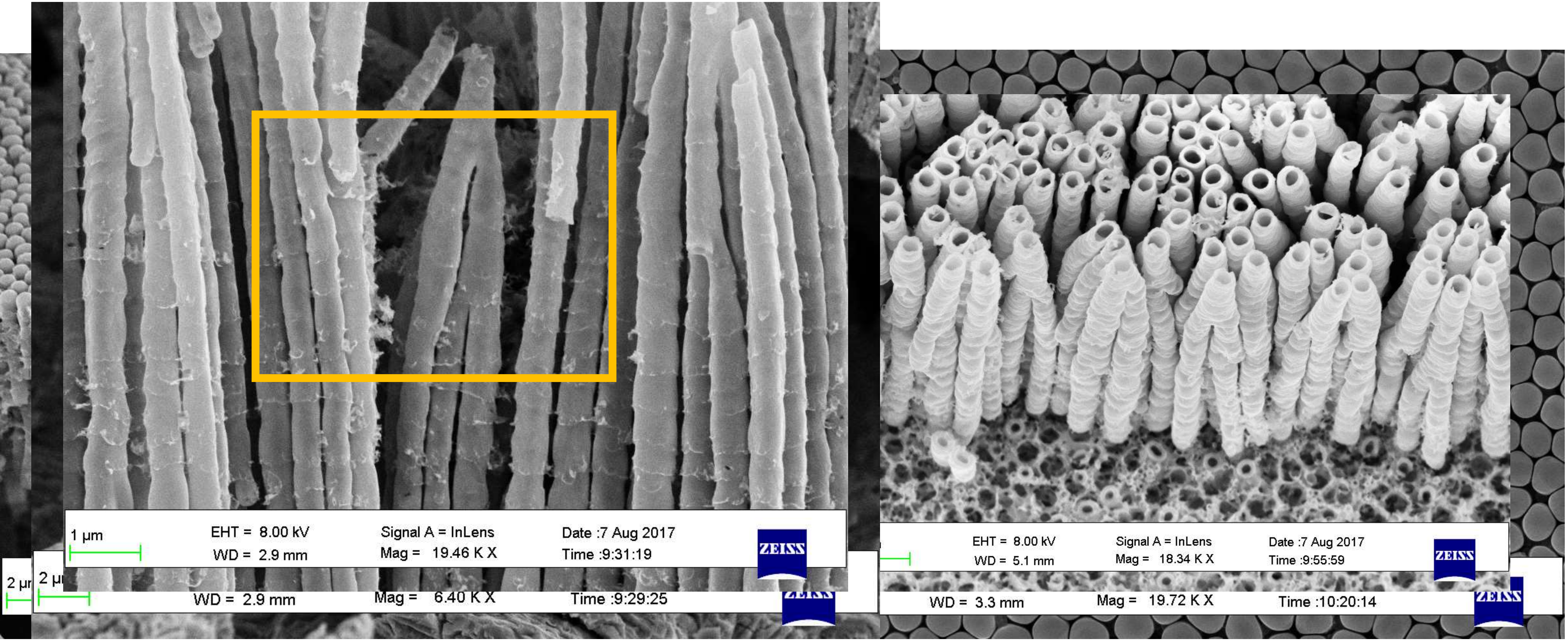


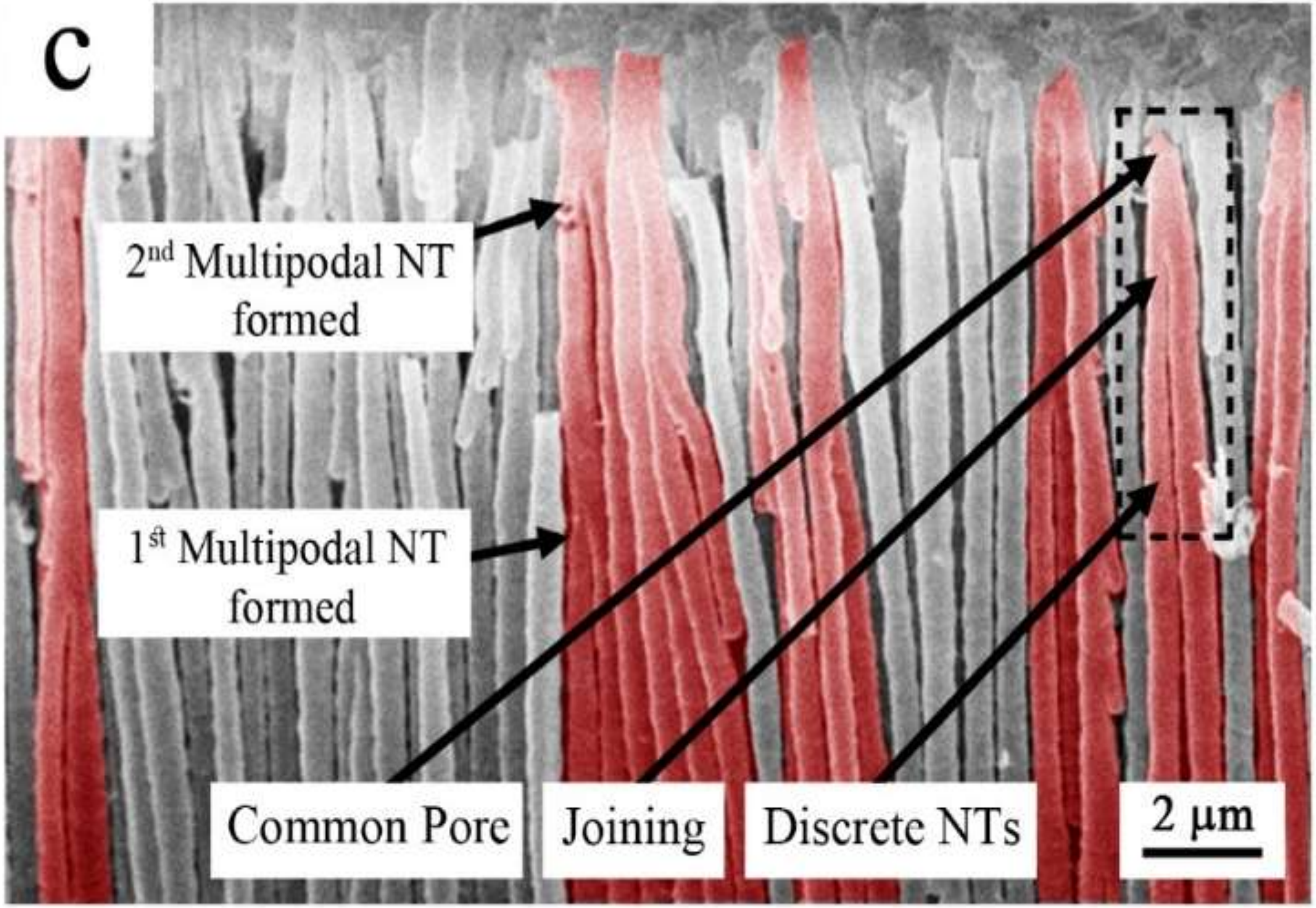


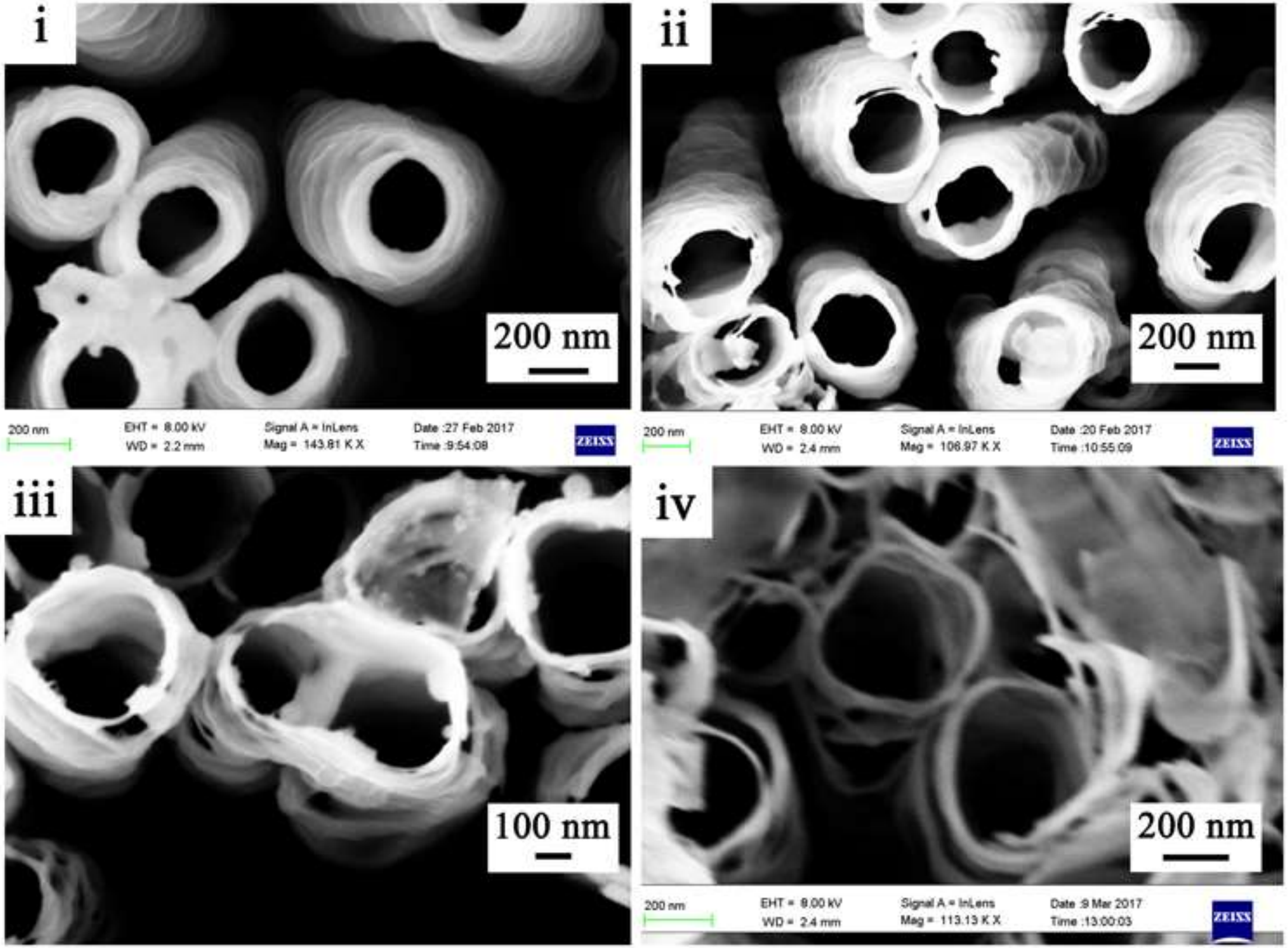
# Multipodal NTs Formation Mechanism



a
200 nm
1 µm
1 µm
EHT = 8.00 kV
WD = 3.1 mm
Signal A = InLens
Mag = 8.29 K X
Date :21 Mar 2017
Time :11:52:33
ZEISS
b
200 nm
2 µm


1 µm
EHT = 8.00 kV
WD = 2.9 mm
Signal A = InLens
Mag = 19.46 K X
Date :7 Aug 2017
Time :9:31:19
2 µ
2 µ
WD = 2.9 mm
Mag = 6.40 K X
Time :9:29:25
EHT = 8.00 kV
WD = 5.1 mm
Signal A = InLens
Mag = 18.34 K X
Date :7 Aug 2017
Time :9:55:59
WD = 3.3 mm
Mag = 19.72 K X
Time :10:20:14


c
2nd Multipodal NT formed
1st Multipodal NT formed
Common Pore
Joining
Discrete NTs
2 μm

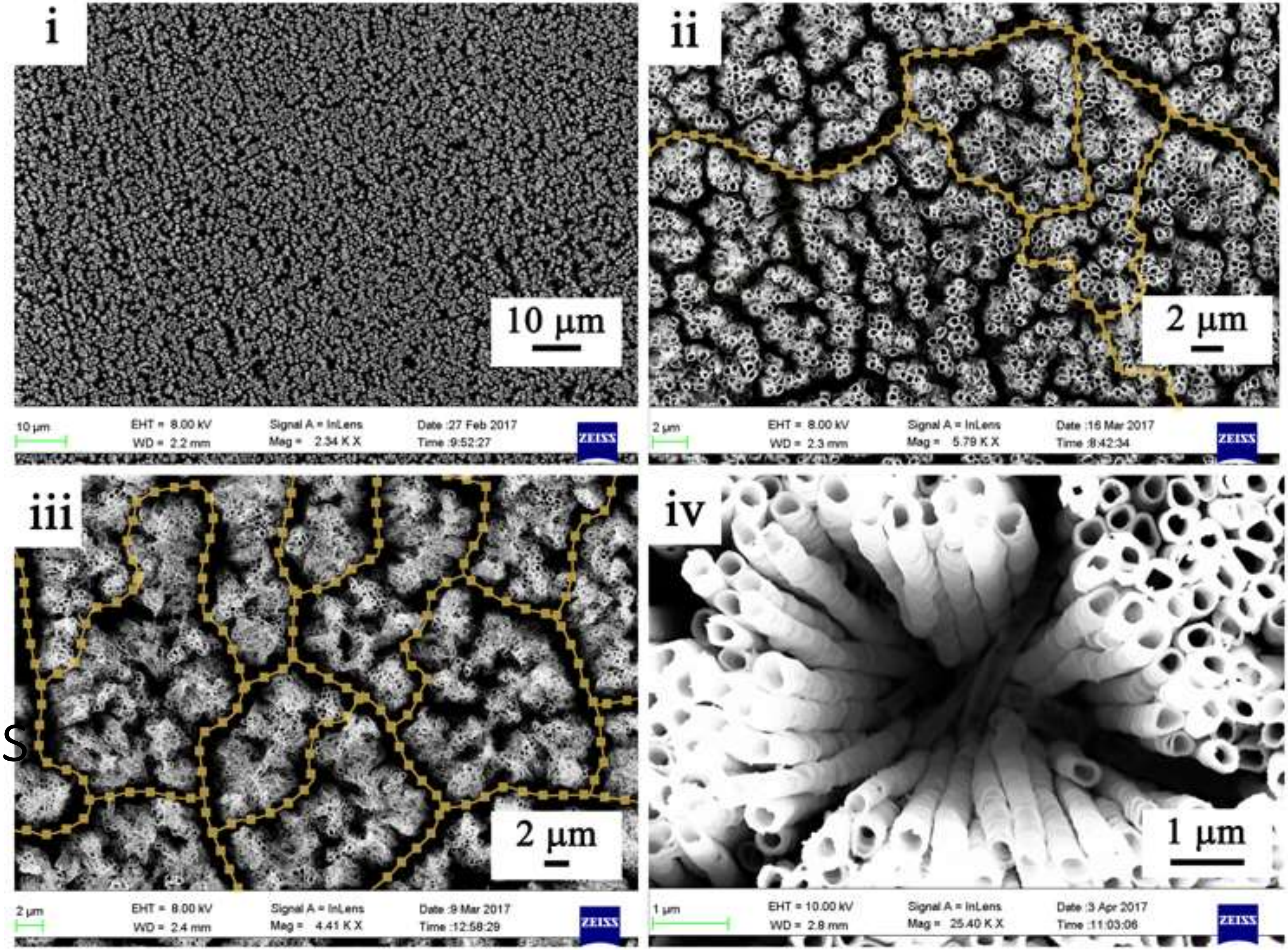


2 hrs

4 hrs

8 hrs

14 hrs



2 hrs

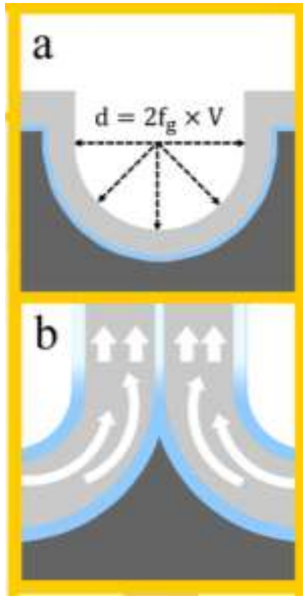
4 hrs

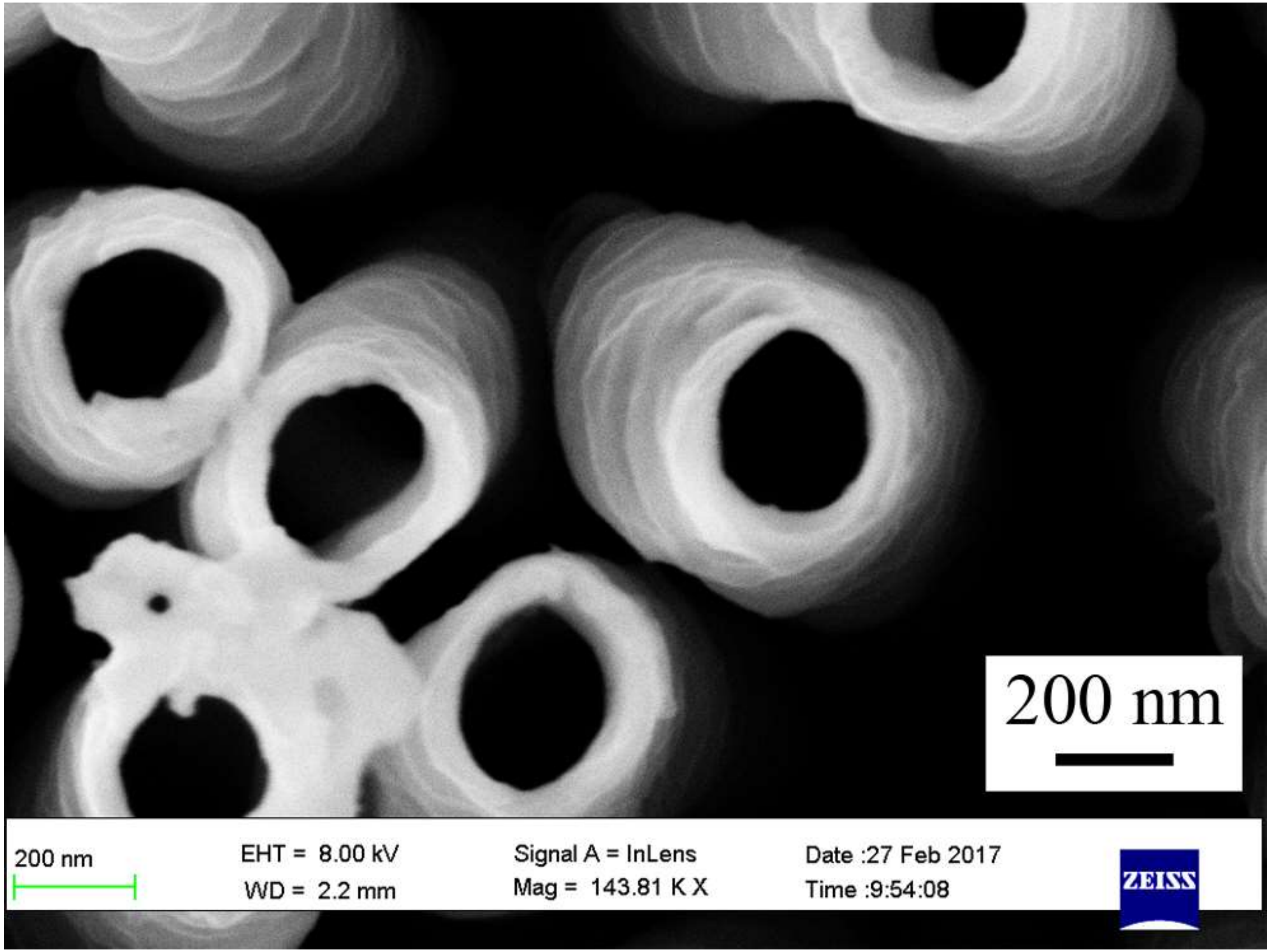
8 hrs

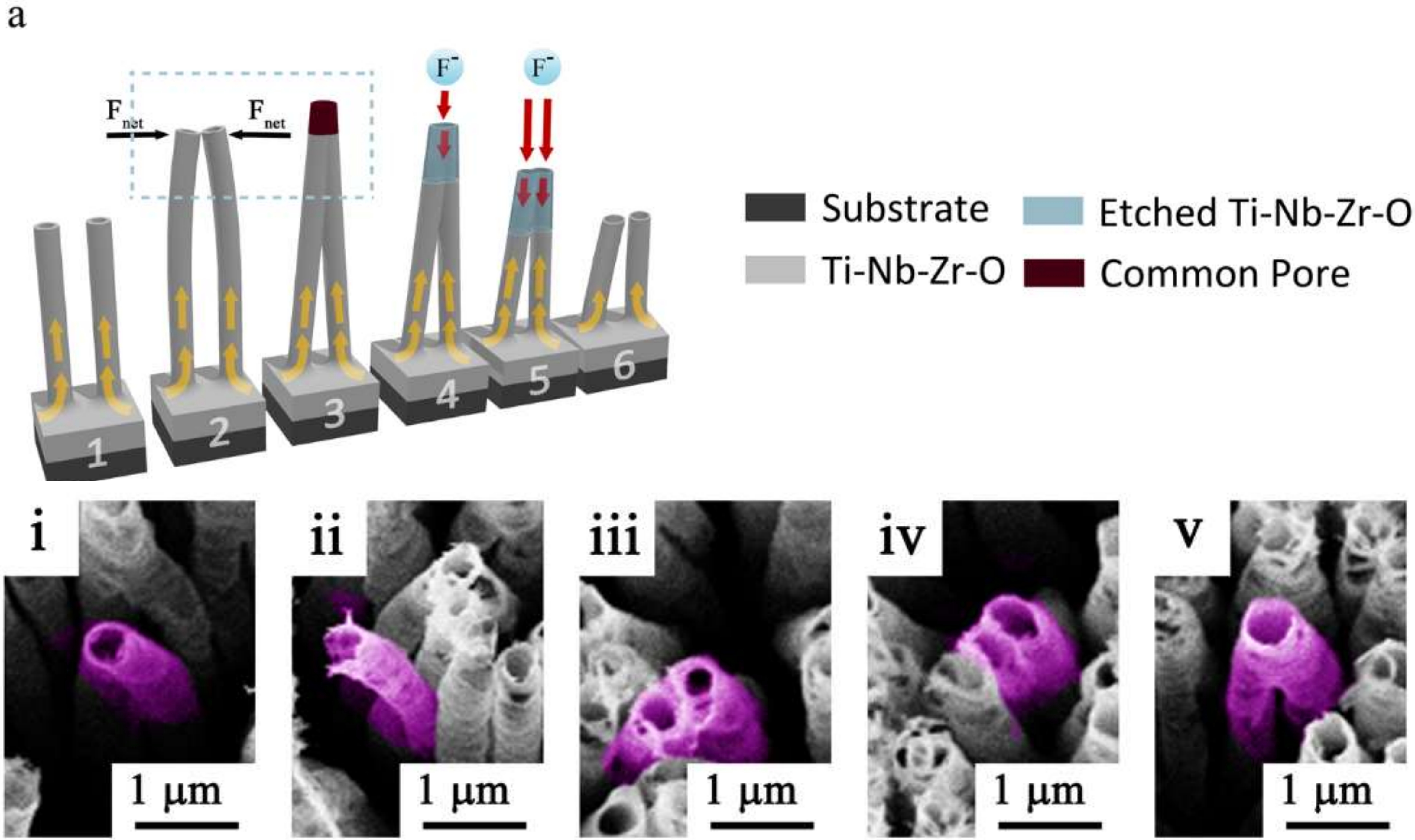
# *Taper Shape*

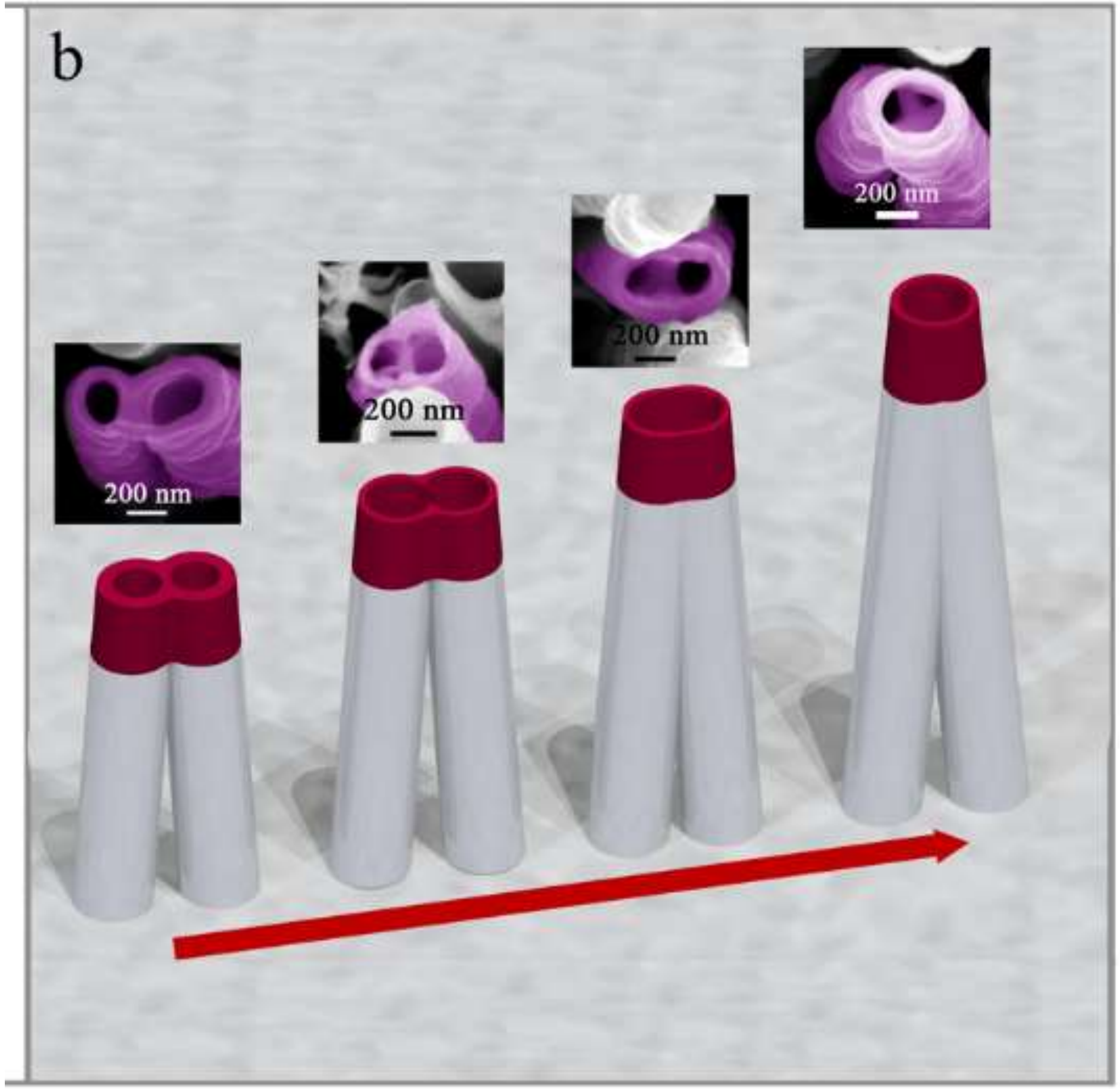
$$d = 2f_g \times V$$

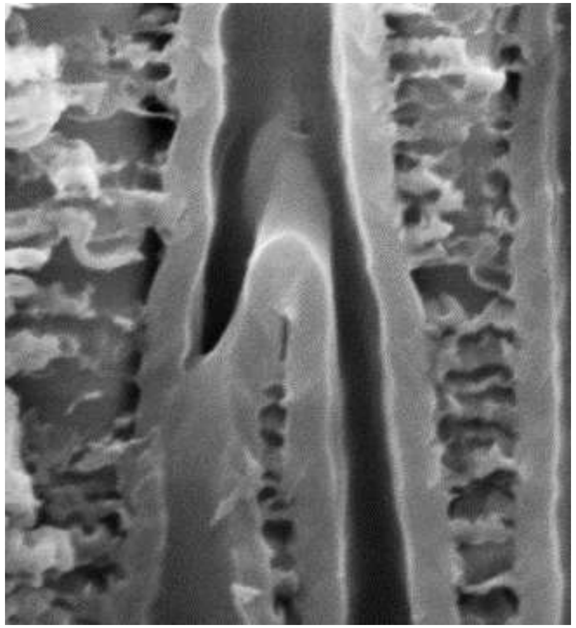
$$E = \frac{(V_{\text{applied}} - IR_{\Omega})}{d}$$

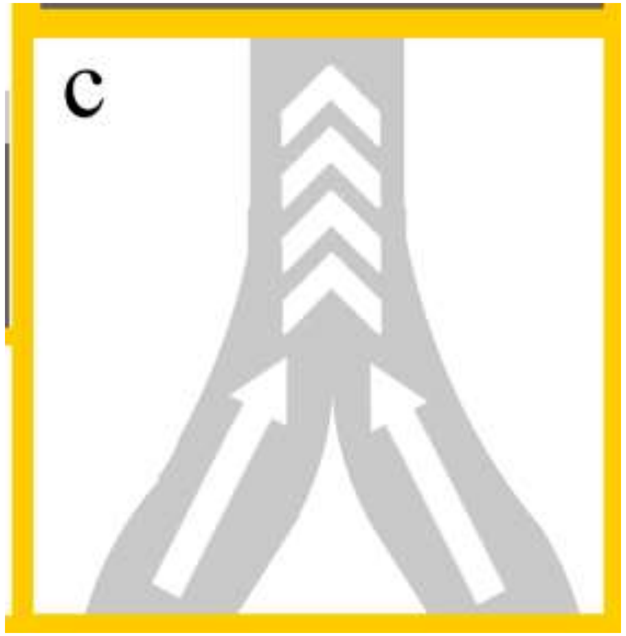


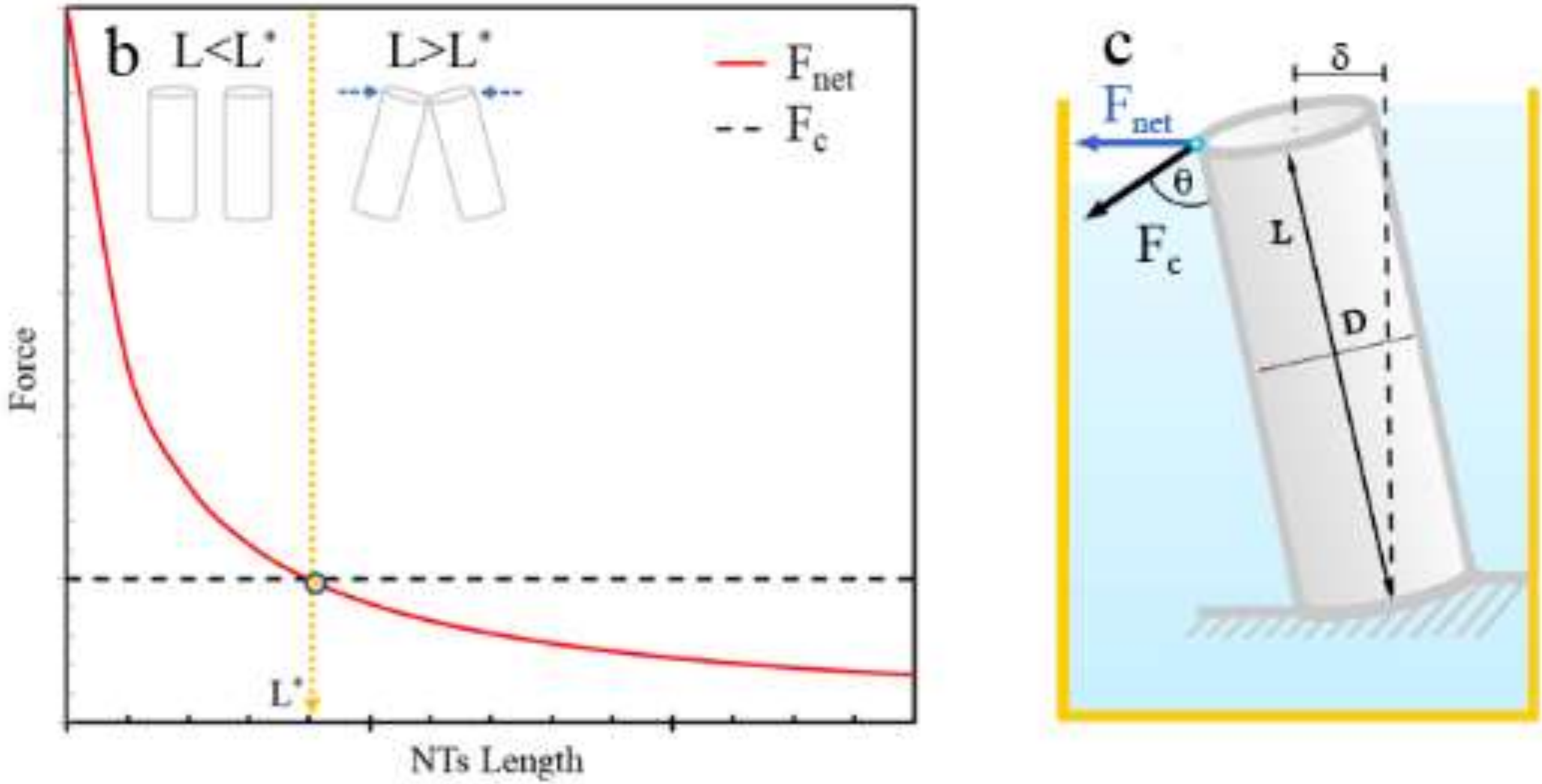



a
F net
F net
F-
F-
1
2
3
4
5
6
Substrate
Ti-Nb-Zr-O
Etched Ti-Nb-Zr-O
Common Pore
i
ii
iii
iv
v
1 µm
1 µm
1 µm
1 µm
1 µm


b
200 nm
200 nm
200 nm
200 nm




c

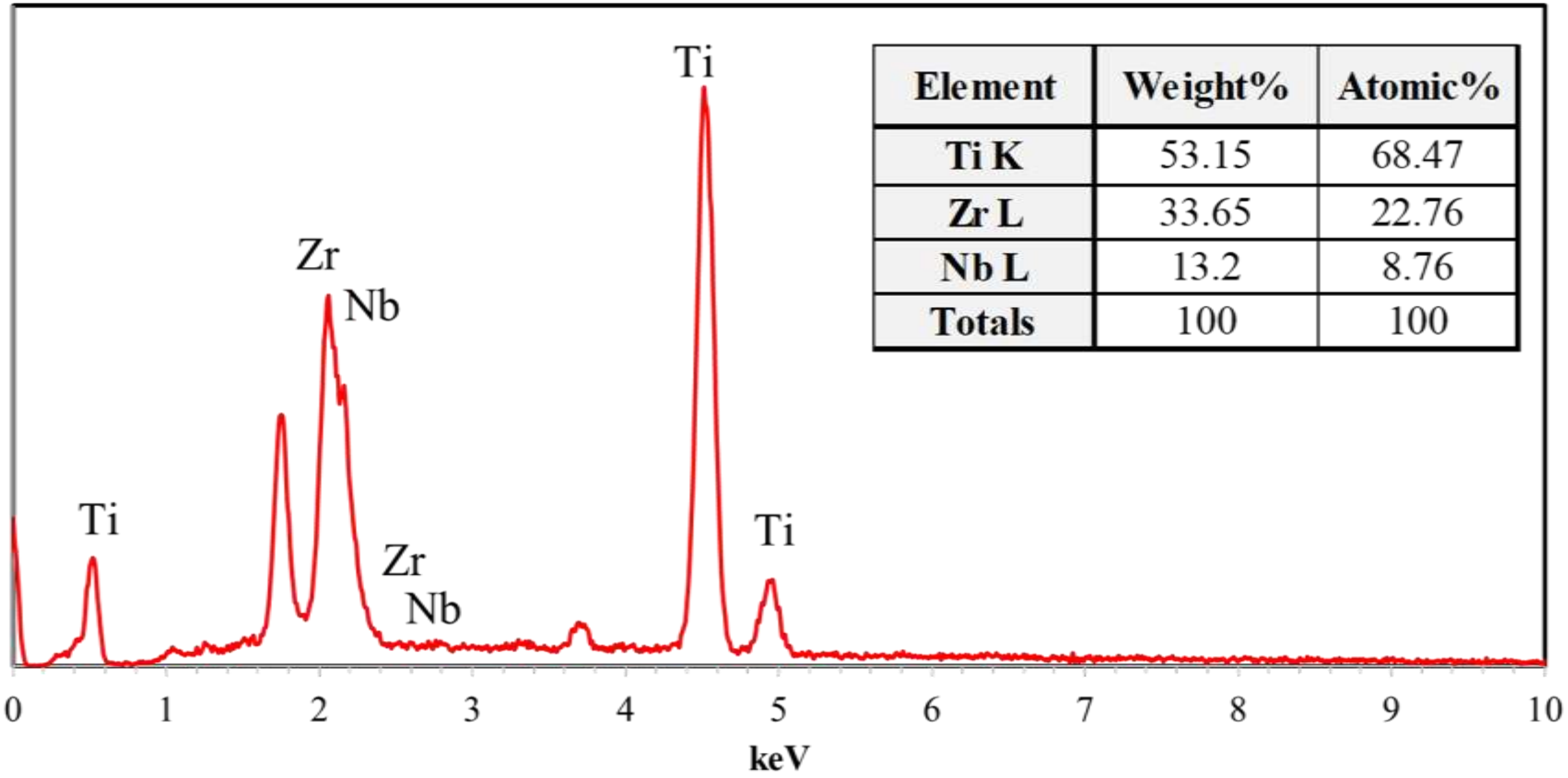

b
L<L*
L>L*
Fnet
Fc
Force
NTs Length
L*
c
δ
Fnet
θ
Fc
L
D

# III. Characterization

# Material Characterization

- Structural
- Optical
- PEC

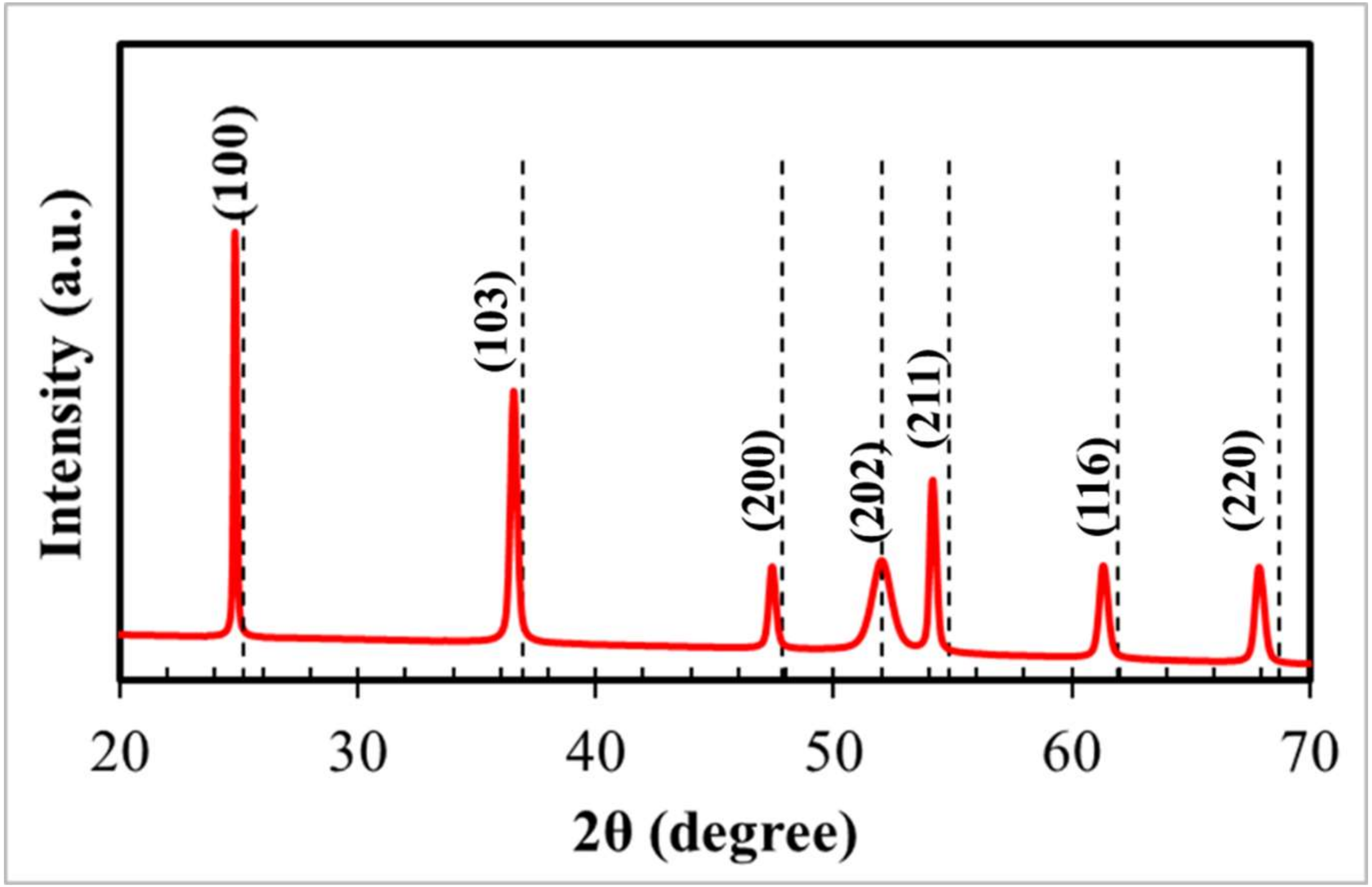
# EDX



| Element | Weight% | Atomic% |
|---|---|---|
| **Ti K** | 53.15 | 68.47 |
| **Zr L** | 33.65 | 22.76 |
| **Nb L** | 13.2 | 8.76 |
| **Totals** | 100 | 100 |

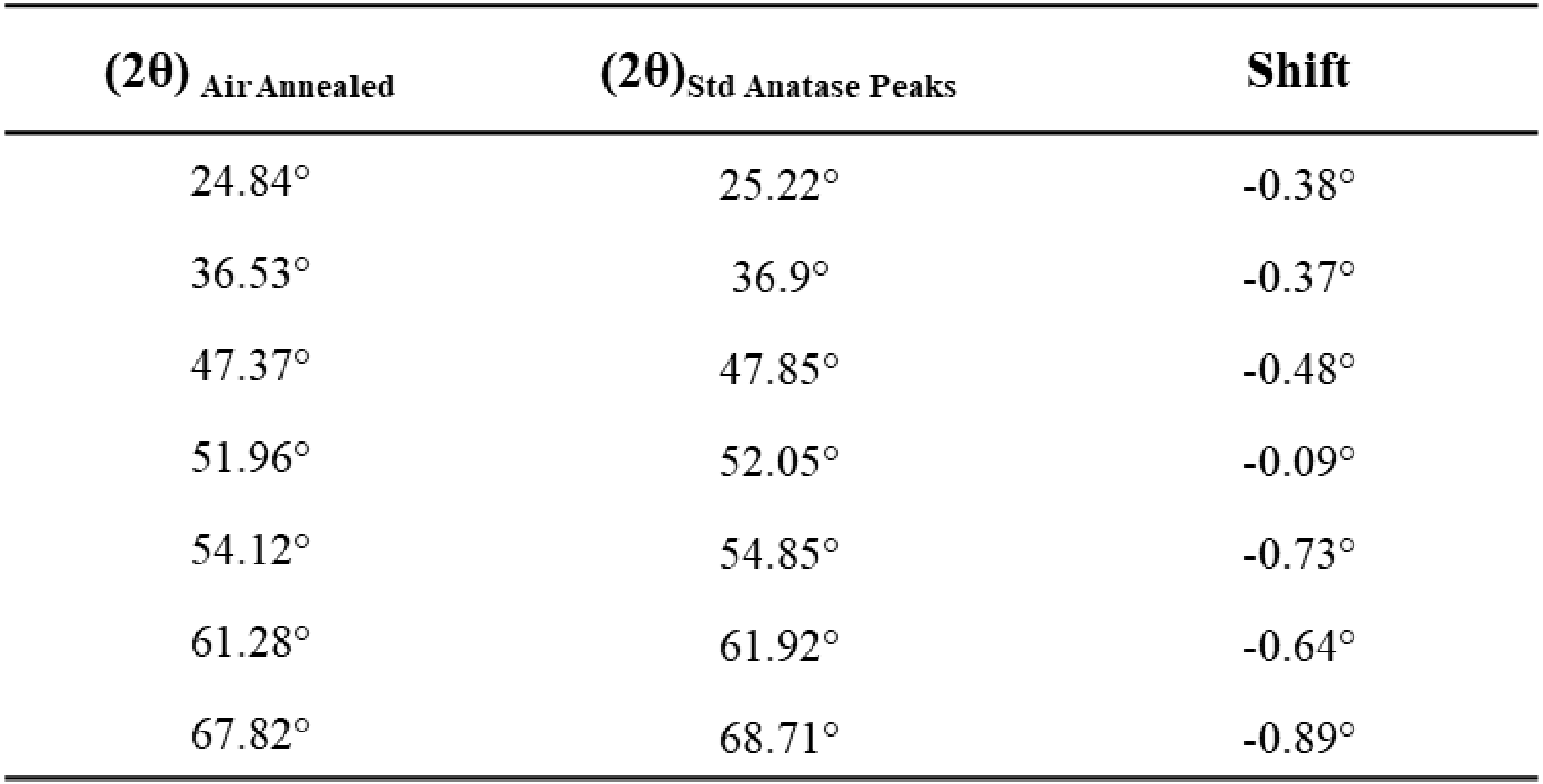
*EDX spectra of the metal alloy before anodization*

# XRD



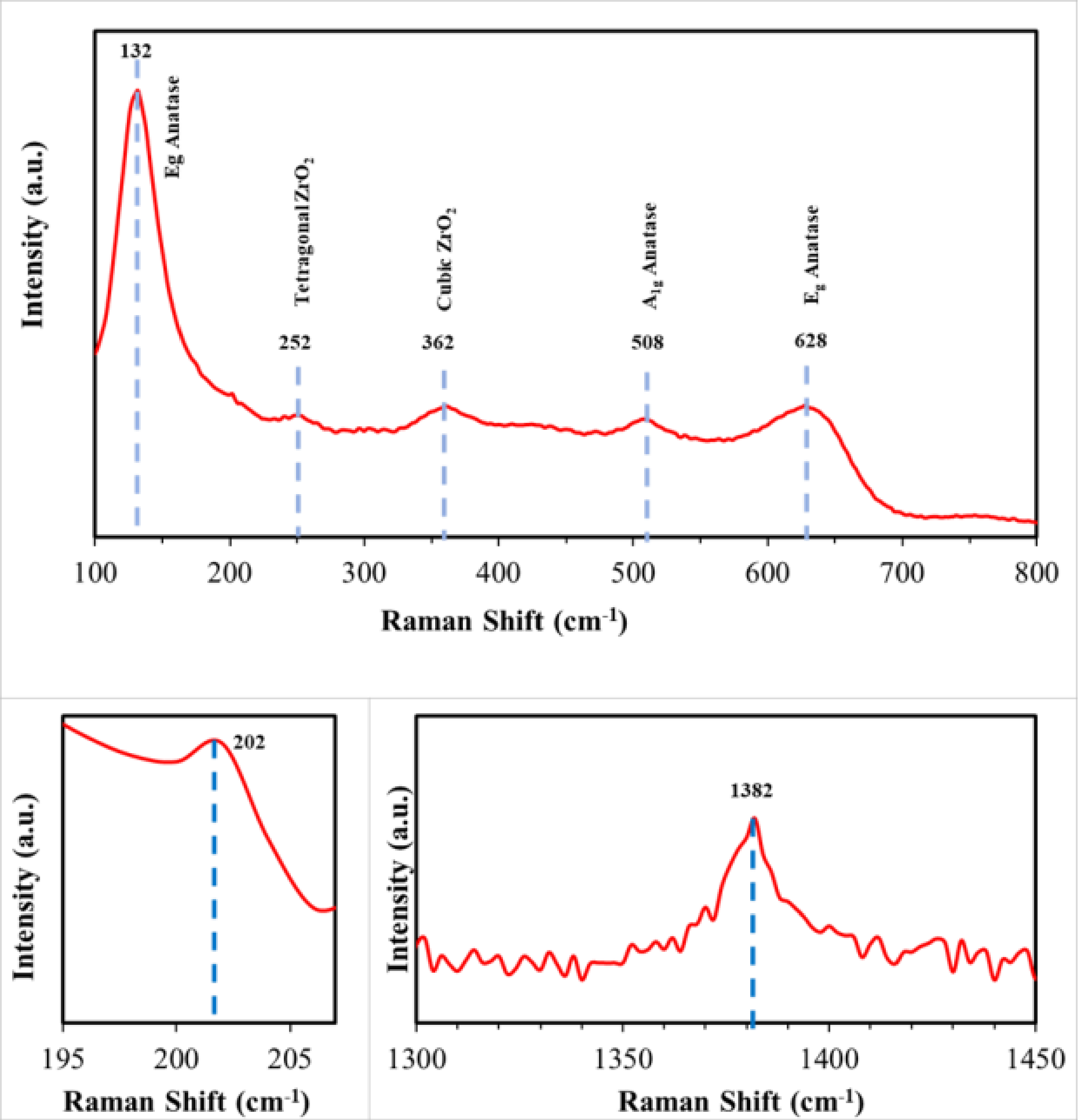
*XRD diffraction patterns of the air-annealed sample. (Vertical lines indicated the positions of the nominal anatase peaks (Ref. code: 01-075-2545)*

# XRD



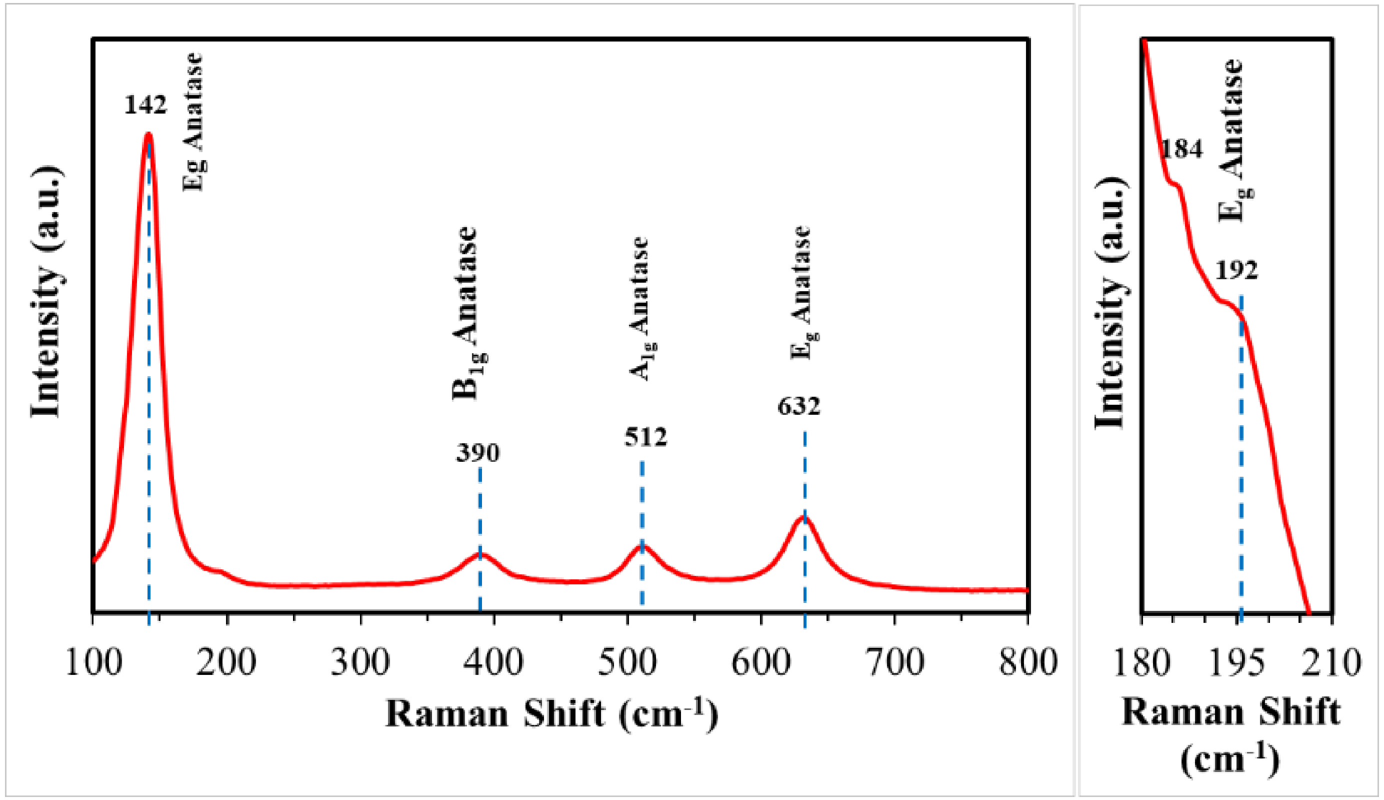
| **$(2\theta)_{\text{Air Annealed}}$** | **$(2\theta)_{\text{Std Anatase Peaks}}$** | **Shift** |
|---|---|---|
| 24.84° | 25.22° | -0.38° |
| 36.53° | 36.9° | -0.37° |
| 47.37° | 47.85° | -0.48° |
| 51.96° | 52.05° | -0.09° |
| 54.12° | 54.85° | -0.73° |
| 61.28° | 61.92° | -0.64° |
| 67.82° | 68.71° | -0.89° |

# Raman Spectroscopy



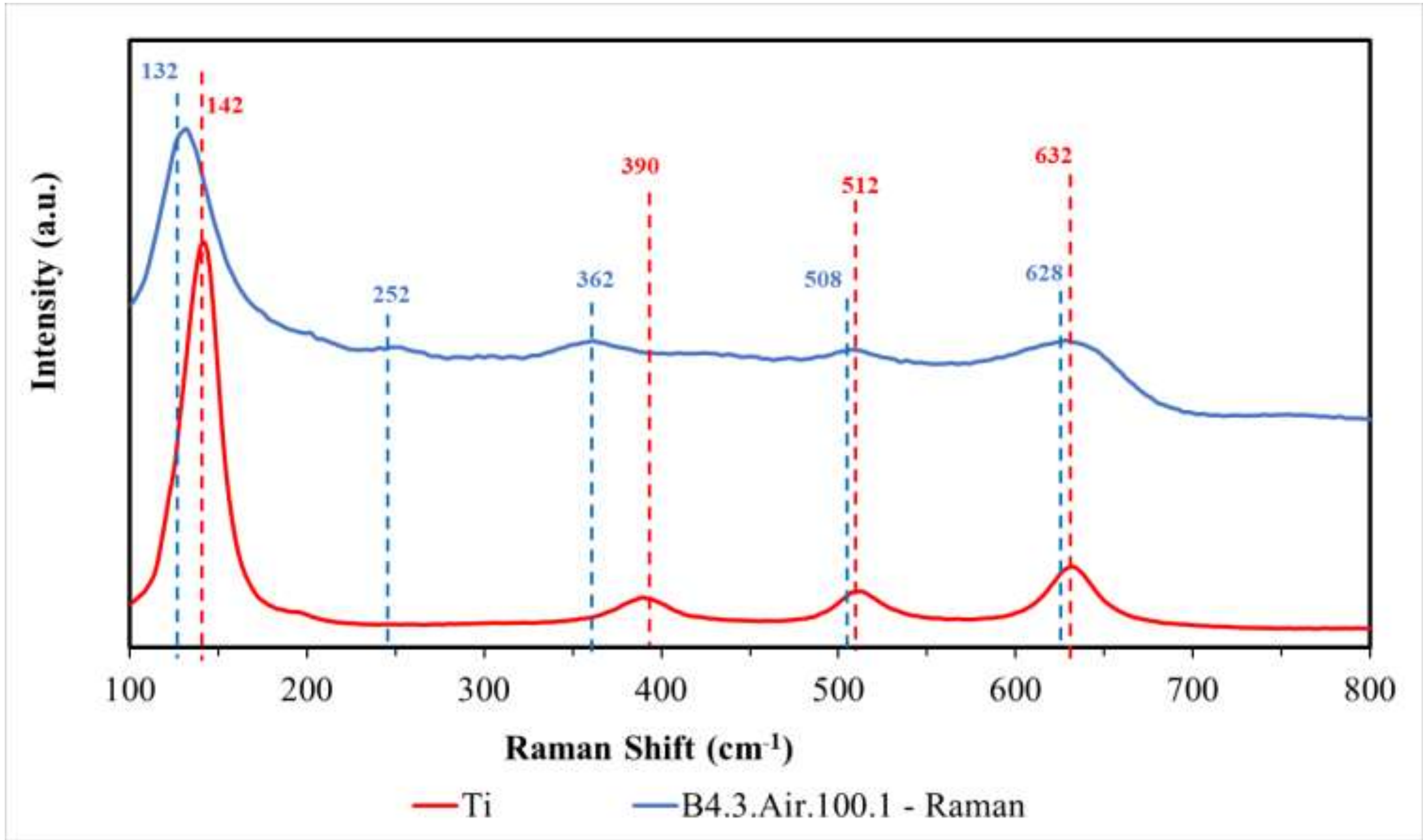
*Raman spectra of a 4 hour annealed samples.*

# Raman Spectroscopy



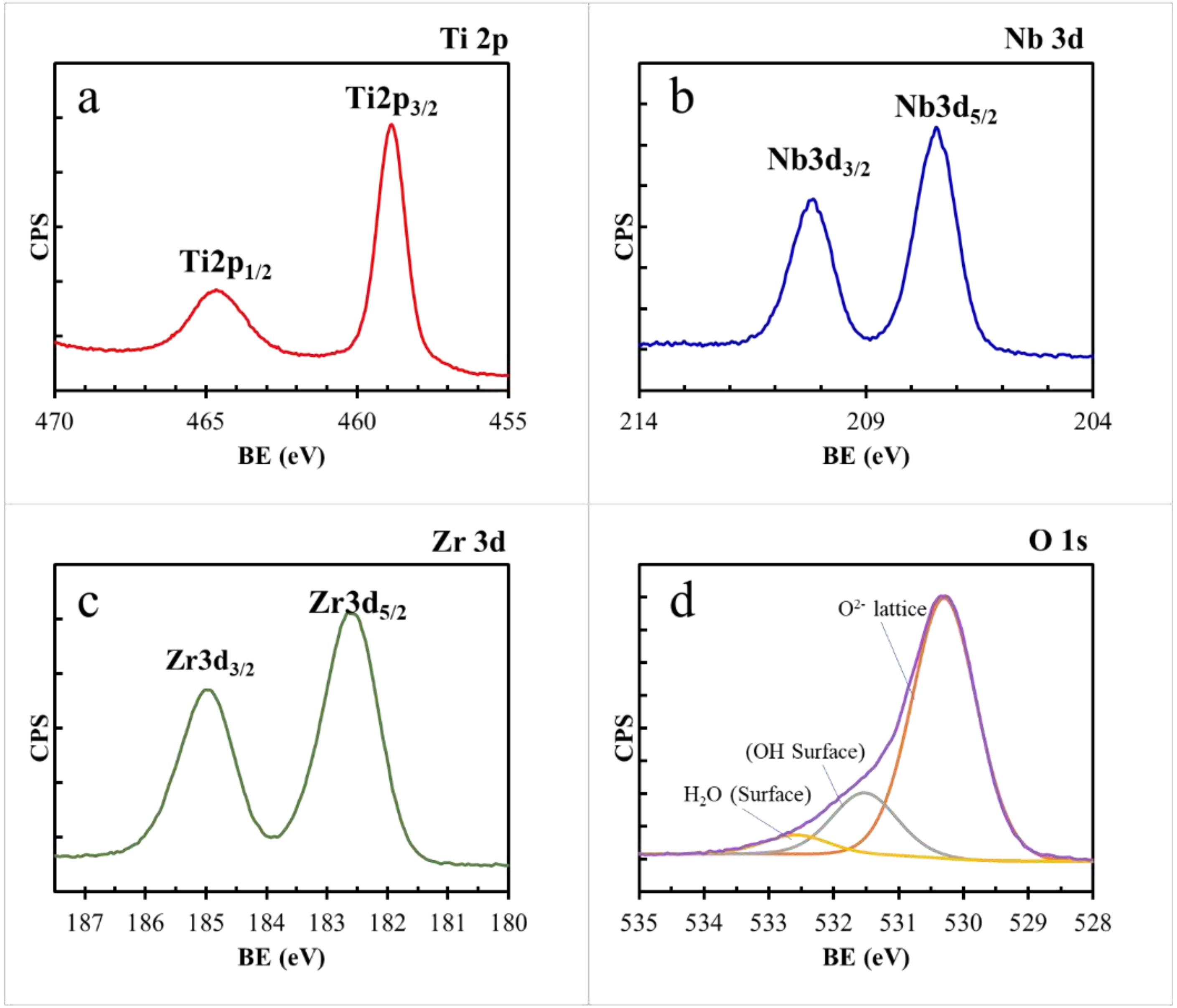
*Pure Ti annealed synthesized at the same conditions of the alloy.*

# Raman Spectroscopy



*The Raman peaks of pure titanium and the air-annealed alloy showing the shift resulting from the alloying effect.*

# XPS

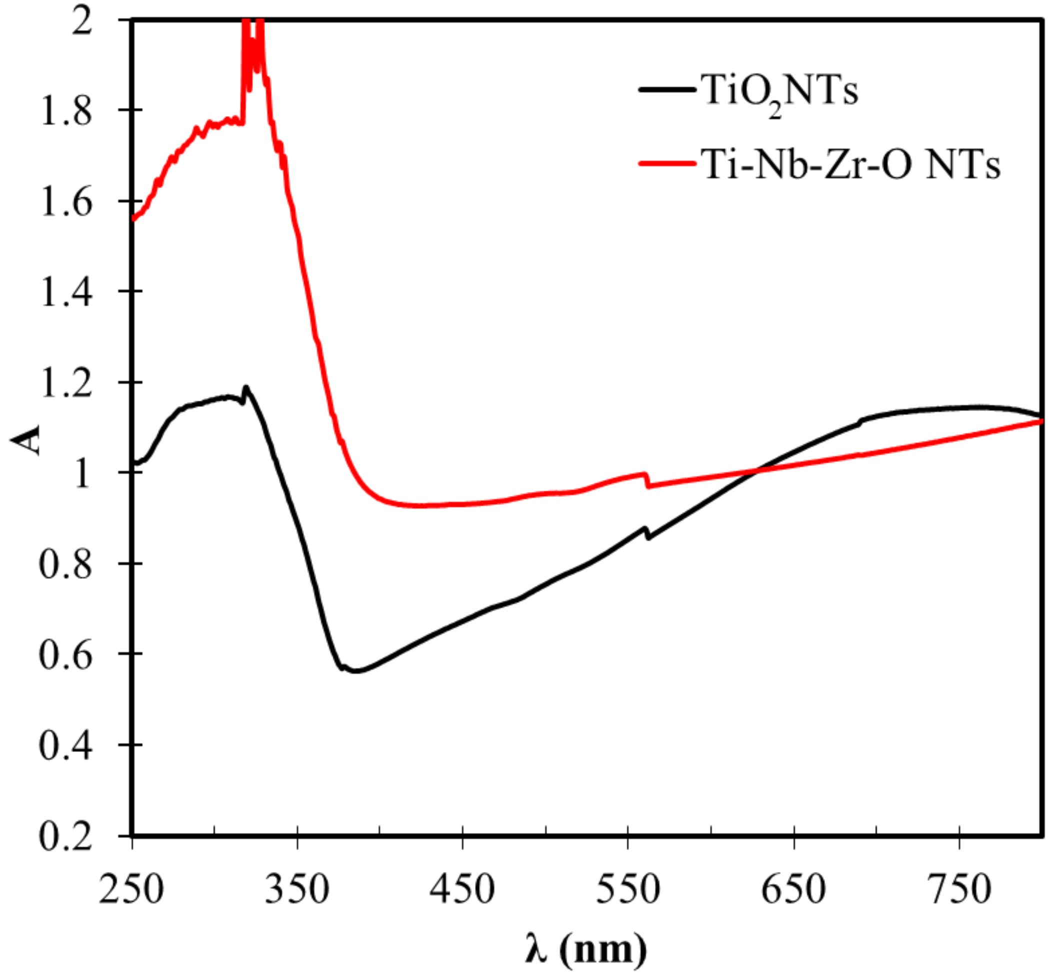


*XPS spectra of (a) Ti, (b) Nb, (c) Zr, and (d) O.*

# Material Characterization

- Structural
- Optical
- PEC

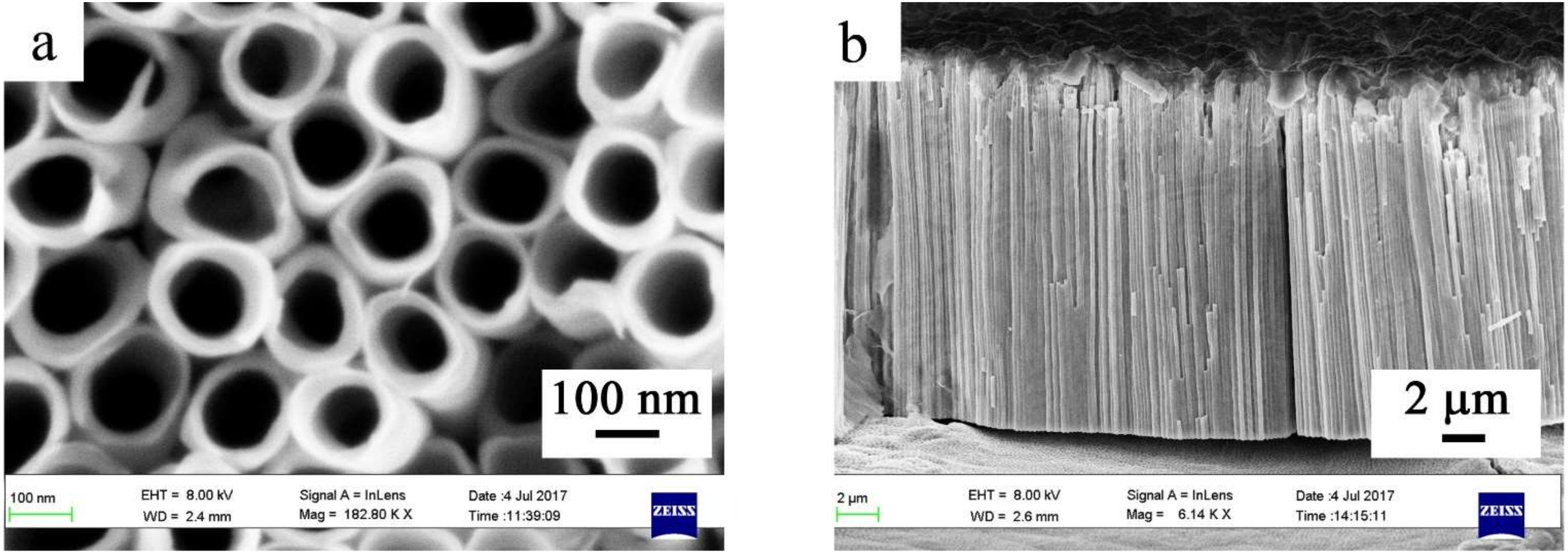
# Absorbance



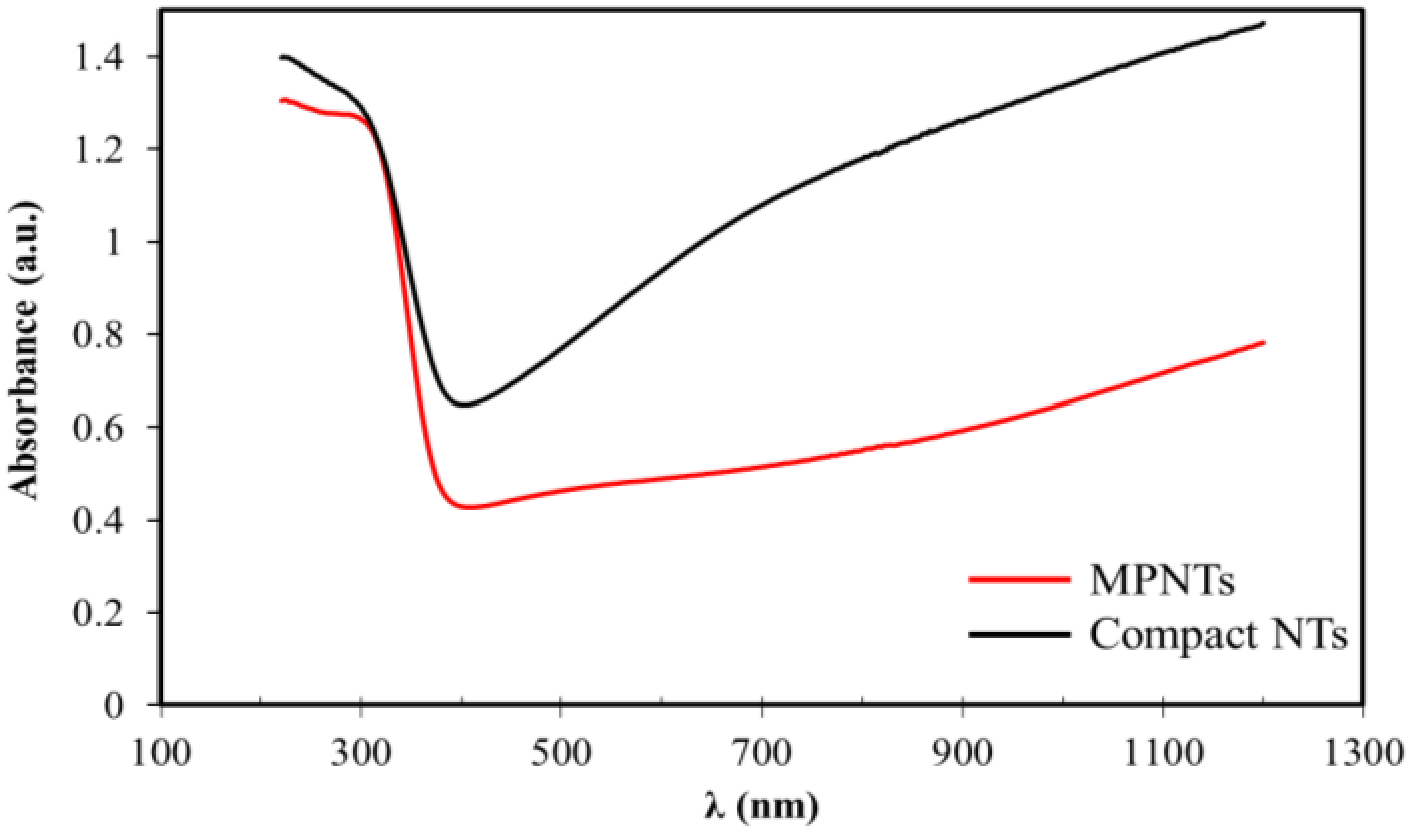
*Absorbance of the $TiO_2$ compared to the formed oxide*

# Studying Multipodality Effect

Vs. Compact NTs



# Absorbance

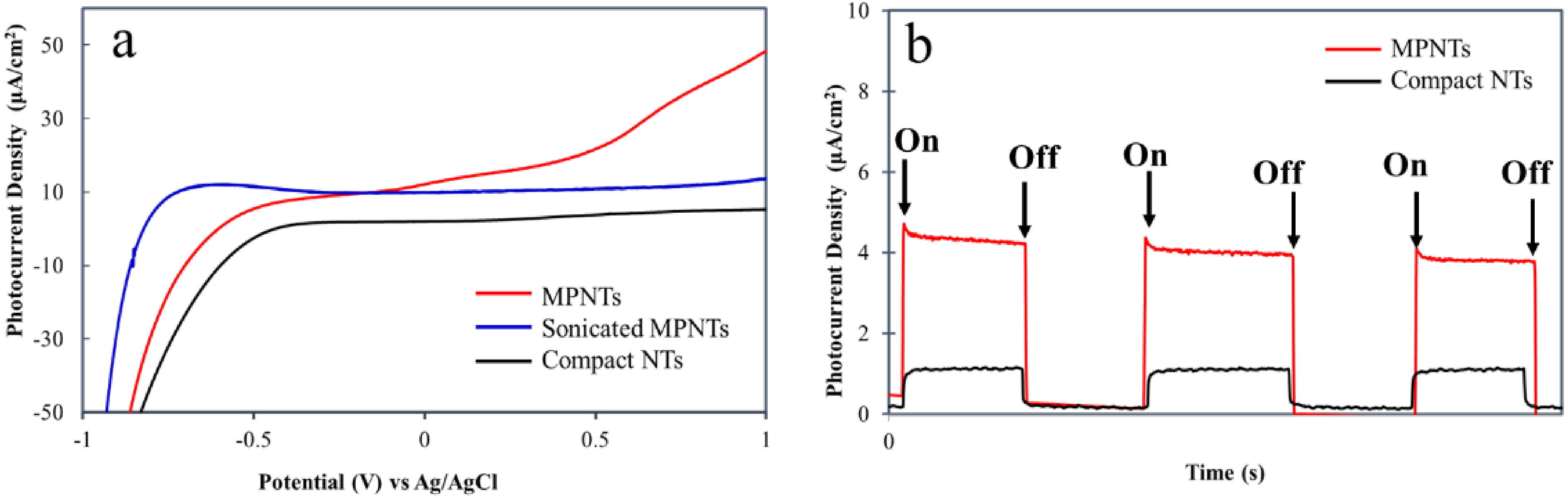


*Absorbance spectra of MPNTs and compact NTs*

# Material Characterization

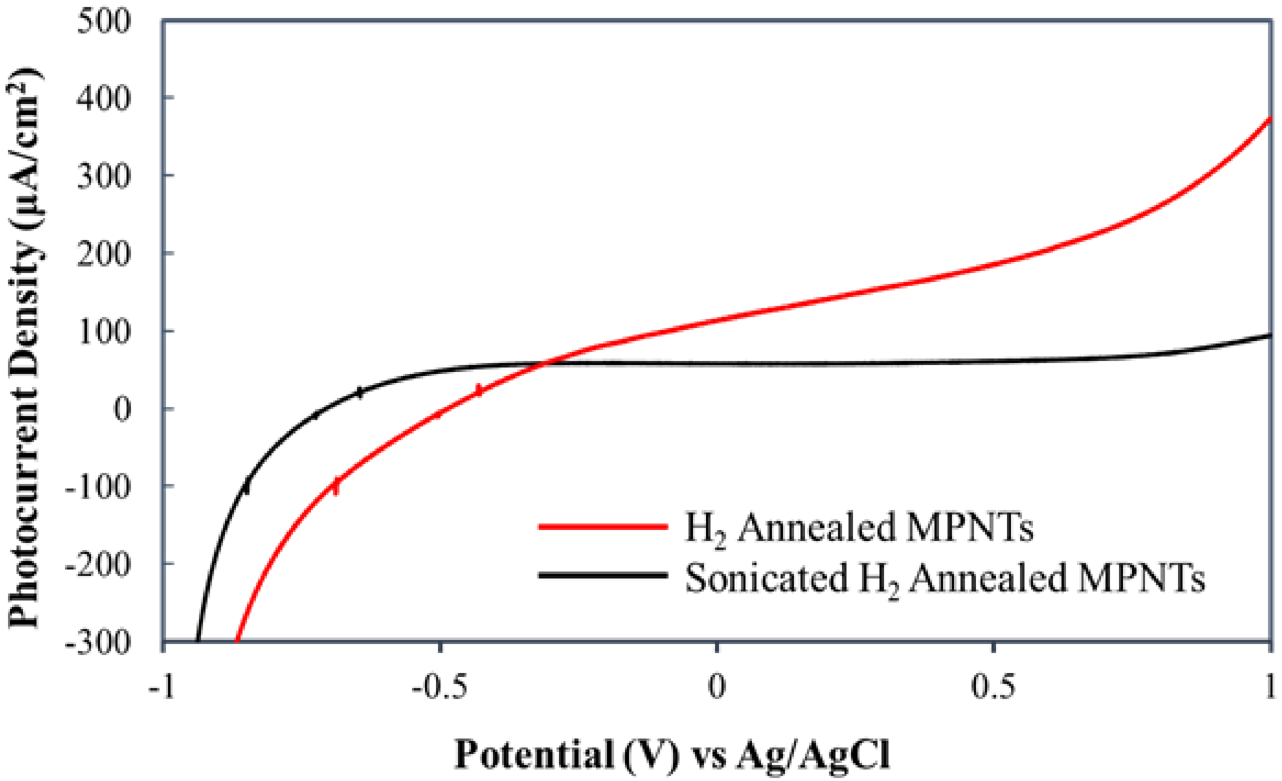
- Structural
- Optical
- PEC

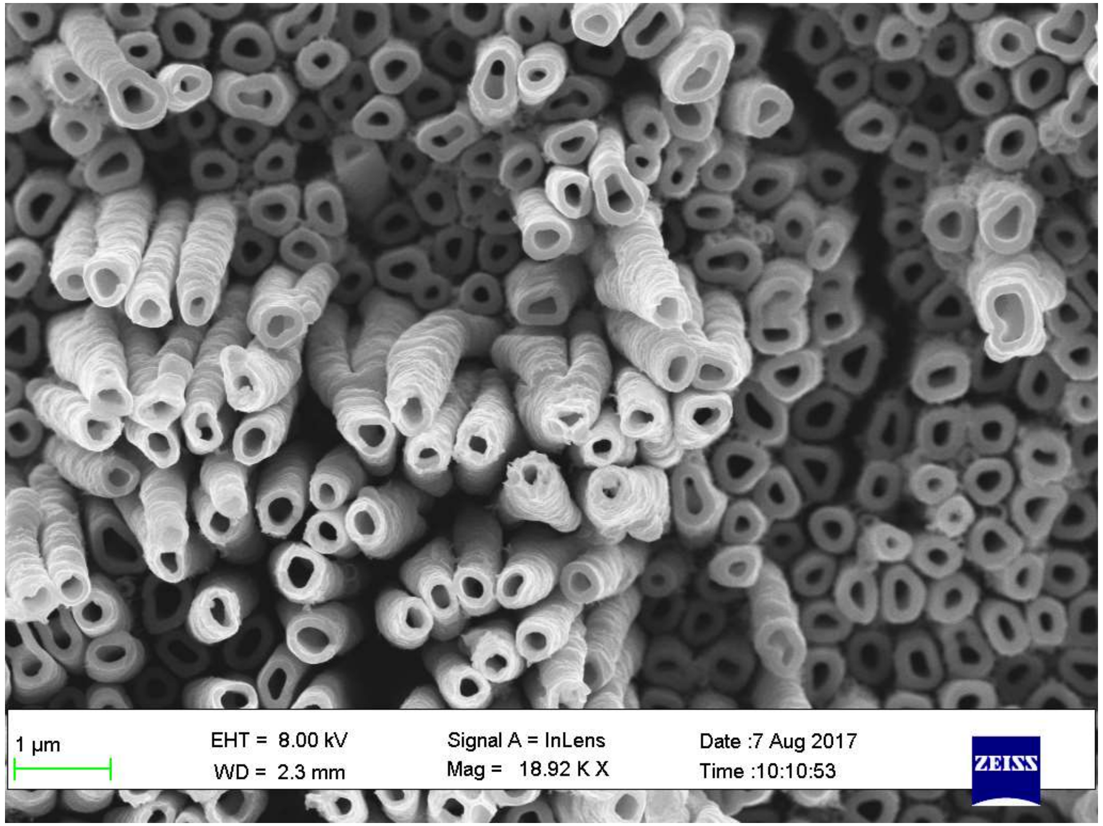
# Linear Sweep Voltametry



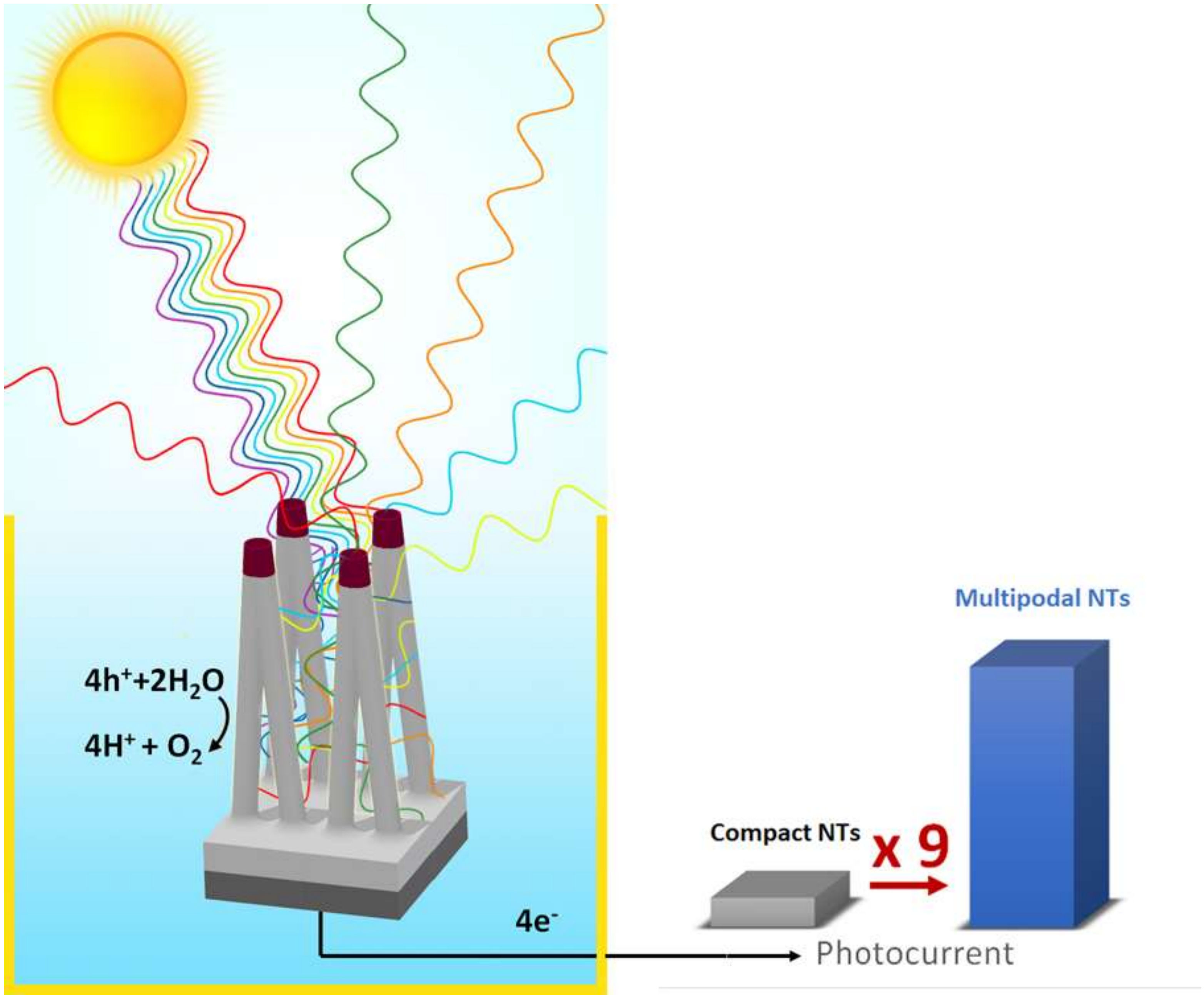
*Photoelectrochemical performance of MPNTs and compact NTs: (a) LSV, (b) normalized Chronoamperometric measurements conducted at 0.5 V.*

# H2 annealing confirming the Multipodal Effect





# Conclusions


$4h^+ + 2H_2O$
$4H^+ + O_2$
$4e^-$
Photocurrent
Compact NTs
x 9
Multipodal NTs

# Thank You