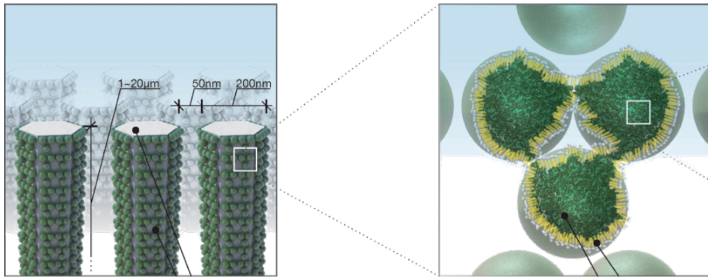
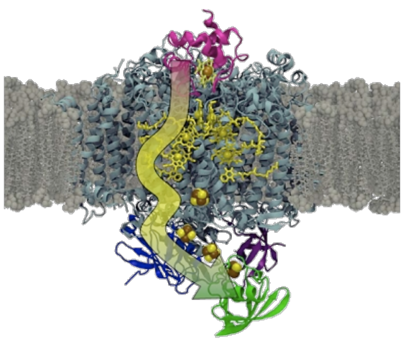
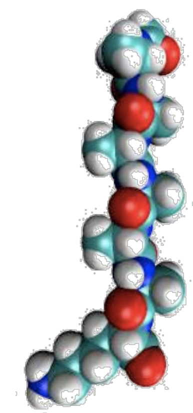


Bio-Nano-Mechanics: Using Nature's Templates

FAB5: The Fifth International Fab Lab Forum and Symposium on Digital Fabrication
August 20th 2009





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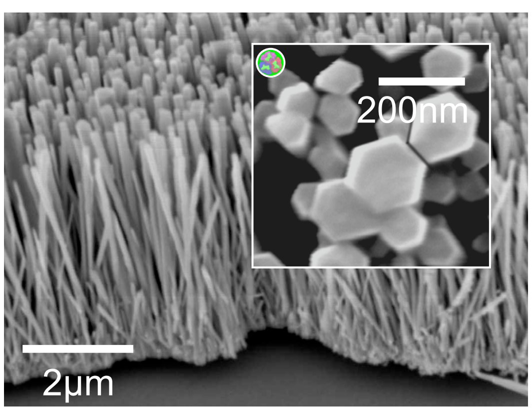
mershin@mit.edu



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Massachusetts Institute of Technology,

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http://web.mit.edu/lms/www/

Guiding principle: Biomimicry

- *Bio* (from Greek "βιοs") = life
- *Mimicry* (from Greek "μιμηση") = to copy, to emulate

A socio-technological example of mimicry: Japan in the last century: first copying the West then surpassing the West. Now, the West copies Japan!

- Biomimicry = To copy, mimic, or be inspired by living things.
- Human intellect and design are constrained by the <u>same laws of physics</u> as biological evolution.
- Evolution took billions of years to achieve spectacular machines of various sizes
- But <u>we</u> can take a shortcut…

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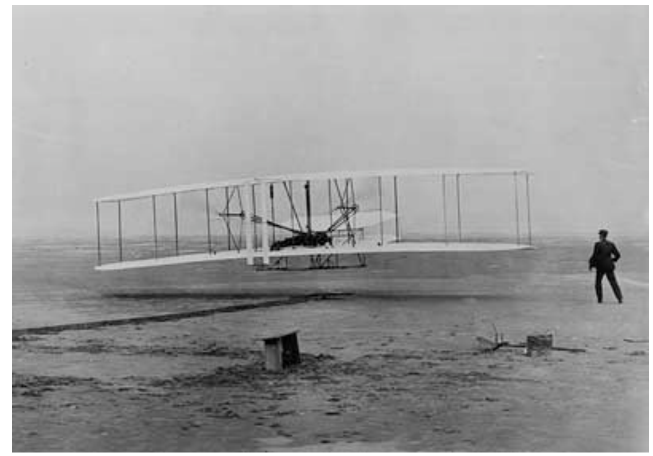
Sometimes unavoidable: powered flight

The same principle of an airfoil creating lift is behind bird and insect flight and powered aircraft flight



Inspired by biology

Human design can <u>surpass</u> evolution

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Proteins are the hardware

Made by Human (macro) Machines	Made by Nature (nano) Molecular machines
Electric Fences	Membranes
Transportation	Hemoglobin
Assembly lines	Ribosomes
Digital database	Nucleosomes
Copy machines	Polymerases
Bulldozer/Destroyer	Proteases/proteosome
Chain couplers	Ligases
Train control center	Centrosome
Train tracks	Actin filament network
Internet nodes	Neuronal synapse (MP + membr)
Gates/keys & passes	Ion channels (MP)
Chemical & gas sensors	Olfactory receptors (MP)
Electrolysis machine	Photosystem II (MP)
Photovoltaics	Photosystem I (MP)

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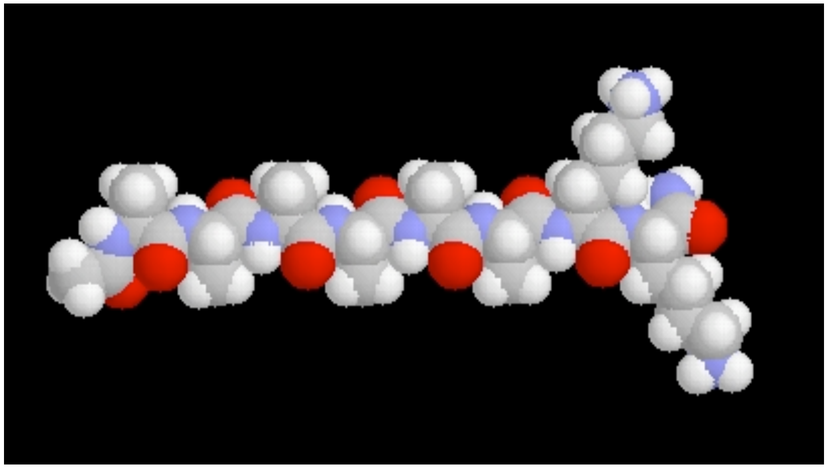
Domesticating Molecules

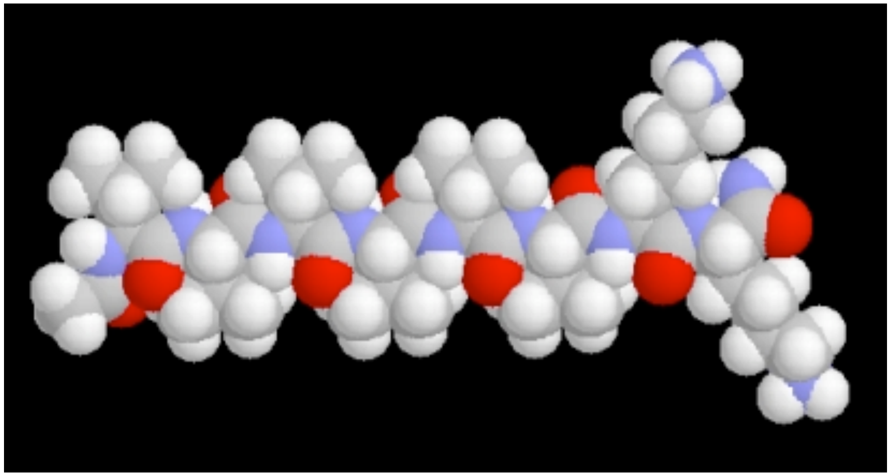
“About 10,000 years ago, man began to domesticate plants and animals. Now it's time to domesticate molecules”

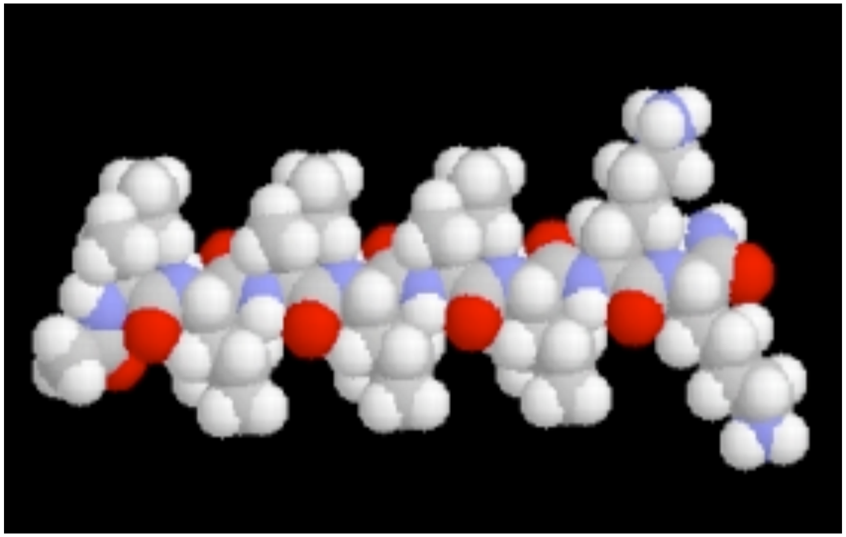
Prof. ***Susan Lindquist***, MIT Biology,

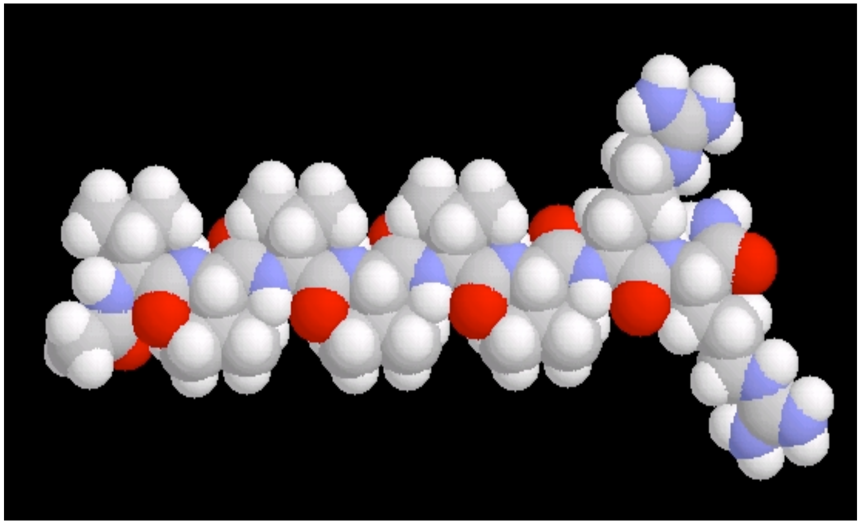
at Shuguang Zhang’s Crete Conference 2003

Intellectual "connective tissue": Designed Peptides









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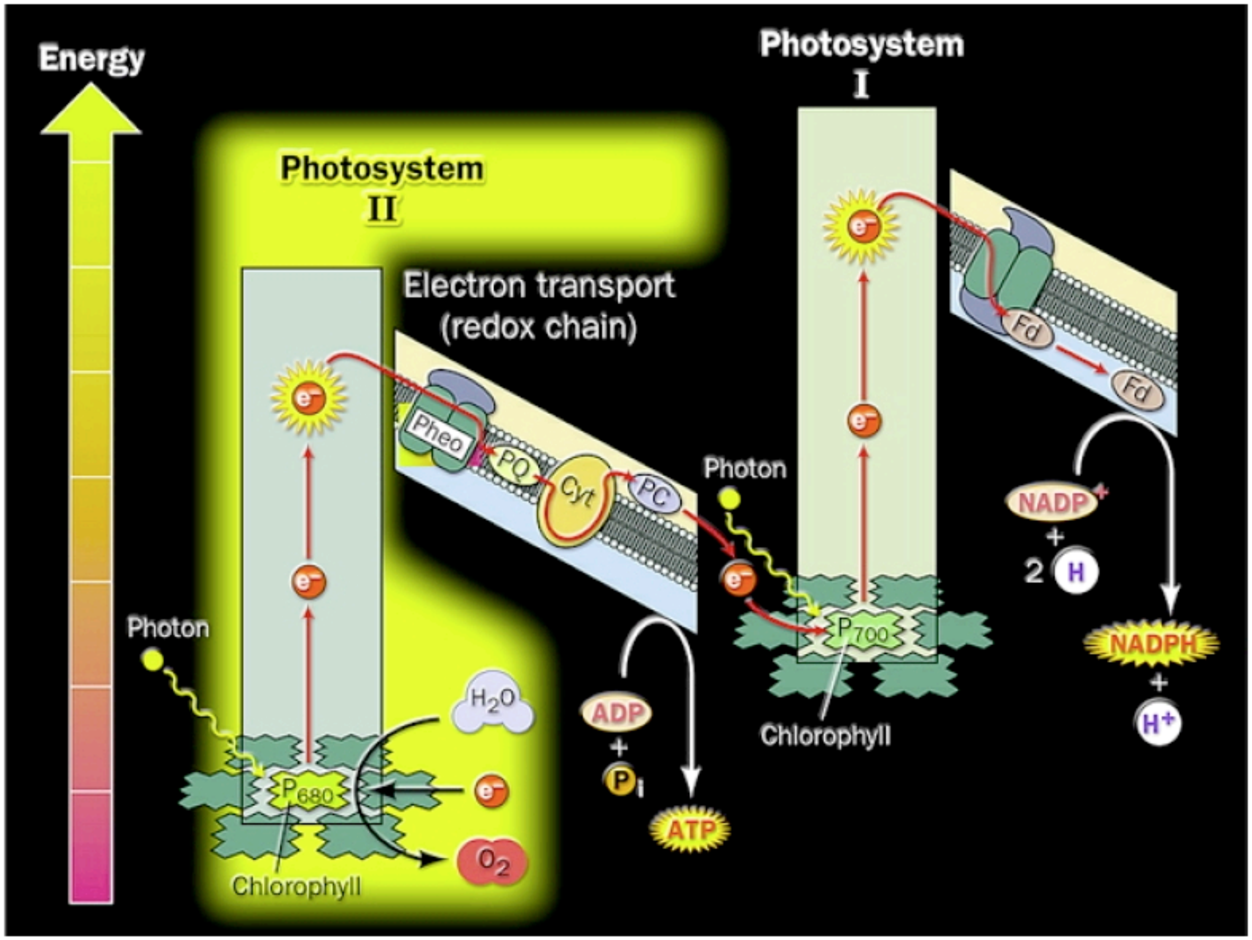
Plants make electricity!
(and hydrogen) via membrane proteins



Idea to harvest this energy has been around for three decades

no one could do it before because membrane proteins "die" quickly

until now…

PS-II is the most efficient water splitter in the world

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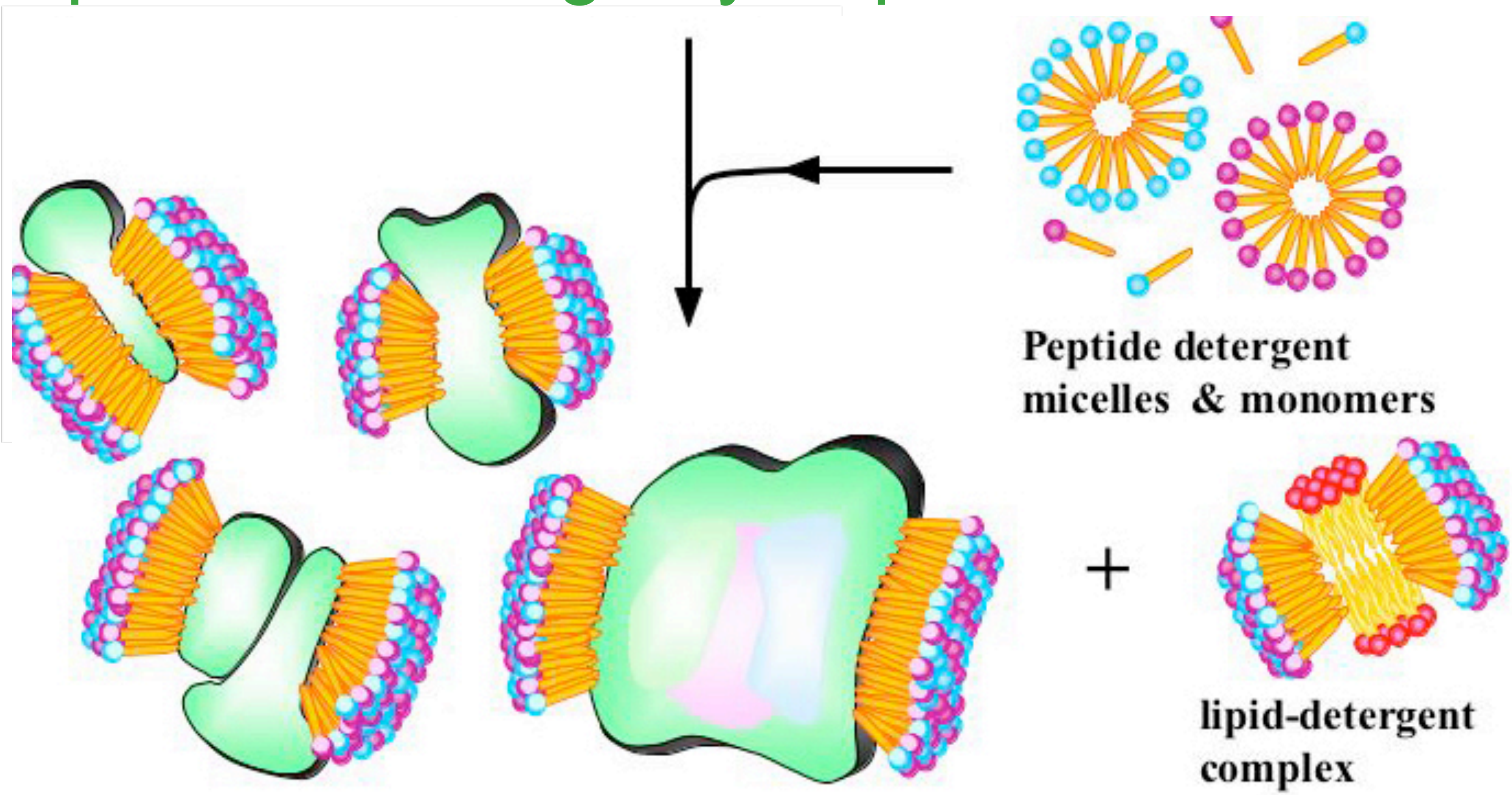
Peptides detergents stabilize membrane proteins through hydrophobic interactions



Open access, freely available online PLoS BIOLOGY

Self-Assembling Peptide Detergents
Stabilize Isolated Photosystem I
on a Dry Surface for an Extended Time

Patrick Kiley[1,2], Xiaojun Zhao[1], Michael Vaughn[3], Marc A. Baldo[2], Barry D. Bruce[3], Shuguang Zhang[1,4*]

July 2005 | Volume 3 | Issue 7 | e230

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Ru Dye-Sensitized Solar Cells inspired by PS-I

Prof. Michael Graetzel EPFL

NATURE | VOL 414 | 15 NOVEMBER 2001 |

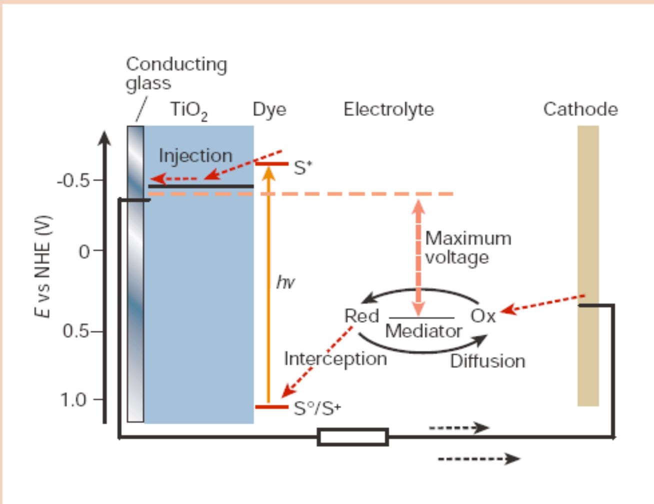

Figure 3 Schematic of operation of the dye-sensitized electrochemical photovoltaic cell. The photoanode, made of a mesoporous dye-sensitized semiconductor, receives electrons from the photo-excited dye which is thereby oxidized, and which in turn oxidizes the mediator, a redox species dissolved in the electrolyte. The mediator is regenerated by reduction at the cathode by the electrons circulated through the external circuit. Figure courtesy of P. Bonhôte/EPFL-LPI.

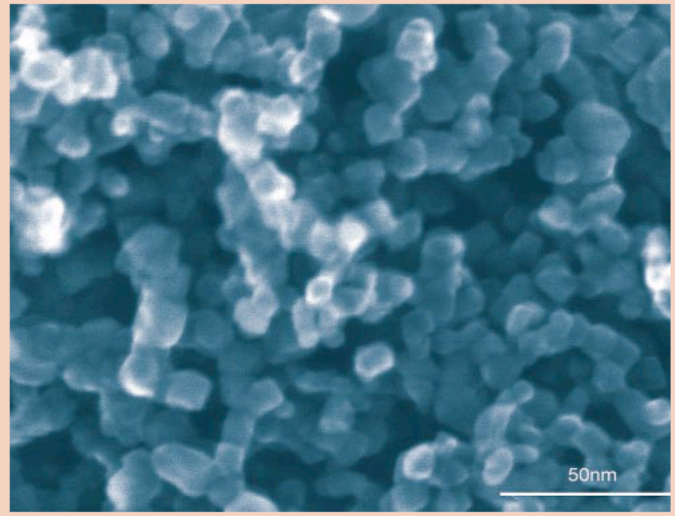

Figure 4 Scanning electron micrograph of the surface of a mesoporous anatase film prepared from a hydrothermally processed TiO_2 colloid. The exposed surface planes have mainly {101} orientation.

<u>Record: η~11.5% in the laboratory</u>

"Commercially" (Konarka etc.) ~ 6% for tandem cells

DNP claims 7.1% for single cell with transfer method

Ru is expensive and toxic

TiO_2 is expensive and difficult to work with

Efficient Tandem Polymer Solar Cells Fabricated by All-Solution Processing
Jin Young Kim, *et al.*
Science **317**, 222 (2007);
DOI: 10.1126/science.1141711

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Efficiency is important but ¢/kWh is even more important

DSSC game will be won by making the manufacturing process easy and cheap not by adding the last 1% and month of lifetime

Biology offers a potentially very cheap way to niche solar power

Photosynthetic Solar Power

Step 1: Show that it can be done (proof of principle)

Nanoletters 2004 Vol.4 No.6 1079-1083

Integration of Photosynthetic Protein Molecular Complexes in Solid-State Electronic Devices

Rupa Das,[†] Patrick J. Kiley,[†,‡] Michael Segal,[†] Julie Norville,[†] A. Amy Yu,[§] Leyu Wang,[||] Scott A. Trammell,[||] L. Evan Reddick,[⊥] Rajay Kumar,[†] Francesco Stellacci,[§] Nikolai Lebedev,[||] Joel Schnur,[||] Barry D. Bruce,[⊥,#] Shuguang Zhang,[‡,▼] and Marc Baldo*,[†]

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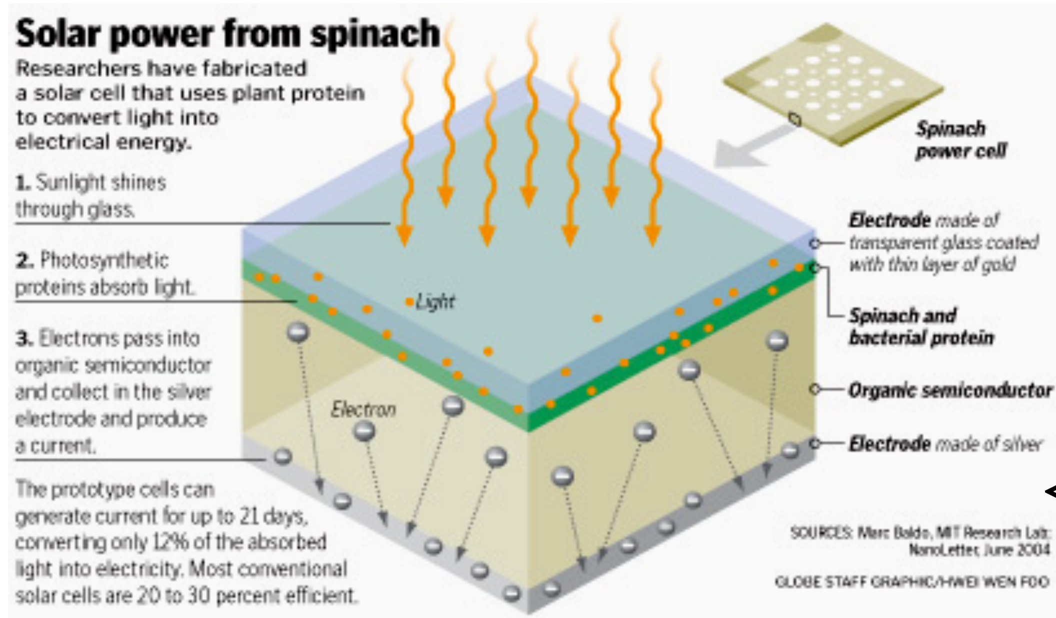
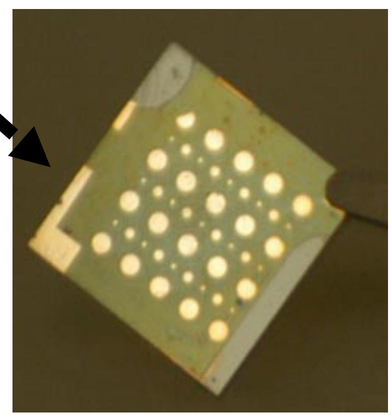
1st Generation (flat) Devices now in the Boston Museum of Science



$<1\mu m$



Nature,
Boston Globe
AP,Reuters,
CNN,
NYT, FT,
BBC, etc.

Biomimicry resonates with people

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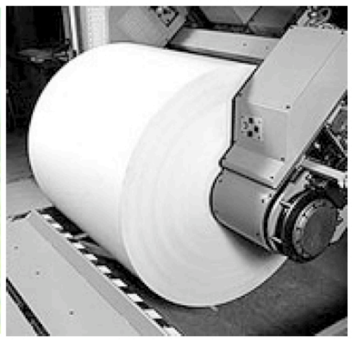
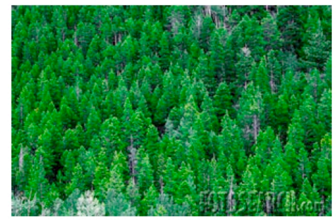
Just how inexpensive is the photosynthetic raw material ?

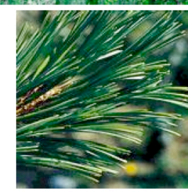
Paper & Pulp industry

Turn waste into solar energy collecting nanomachines



Pine forest





Oak forest

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…even more sources

Plants leaves (Kentucky Coffee tree, Sourwood, Baldcypress, Pine)

↓ homogenized in a food processor

Homogenate

↓ strained through four layers of cheesecloth and Miracloth

Filtrate

↓ washed and solubilized by 0.7-4.0% of Triton X-100

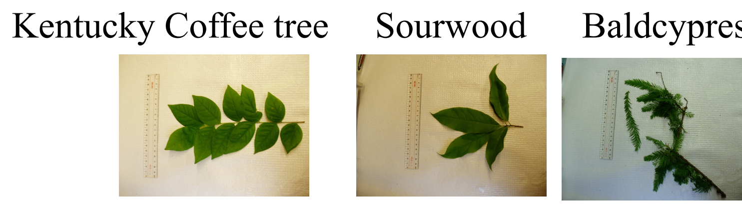
Chloroplast suspension

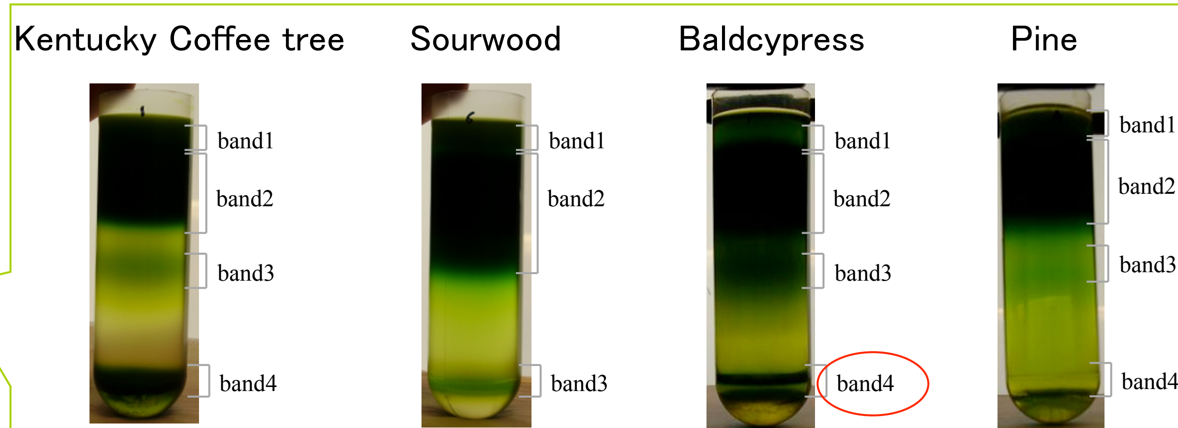
↓ purified by sucrose gradient (0.1–1.0 M)

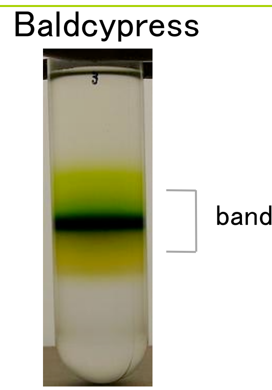
PS-I (LHC mixture)

↓ purified by sucrose gradient (0.5–2.0 M)

PS-I







The other samples are insoluble.

Select the most efficient PS-I

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and even more…

Water T=8^{o}C !

Hidehito Takayama, Yusuke Nagai, Aki Nagai, Andreas Mershin, Shuguang Zhang
May 2005, Ft. Wetherhill, Rhode Island

Photosynthetic Solar Power Step 1 Completed

- Long term stability of PS-I on dry surface using peptides
- Orientation using his- tags and current harvesting using evaporated flat electrodes
- Good publicity

- To get more power we need to solve efficiency and lifetime problems

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Photosynthetic Solar Power

Step 2: Make it efficient

Solution contains dilemma

Thicker photosynthetic layer = better light absorption but worse charge extraction

- How to get thin, ordered layer yet more of it per cm^2?
- Linus Pauling: “ The best way to have a good idea is to have a lot of ideas. ”

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Biomimicry: Look at Forest

Heita Kamaishi, Japan March 11 05

- Immobilize PS1 on transparent, conducting “tree trunks”

- Ideally would be spaced such that a monolayer of photosynthetic protein can be immobilized on them.

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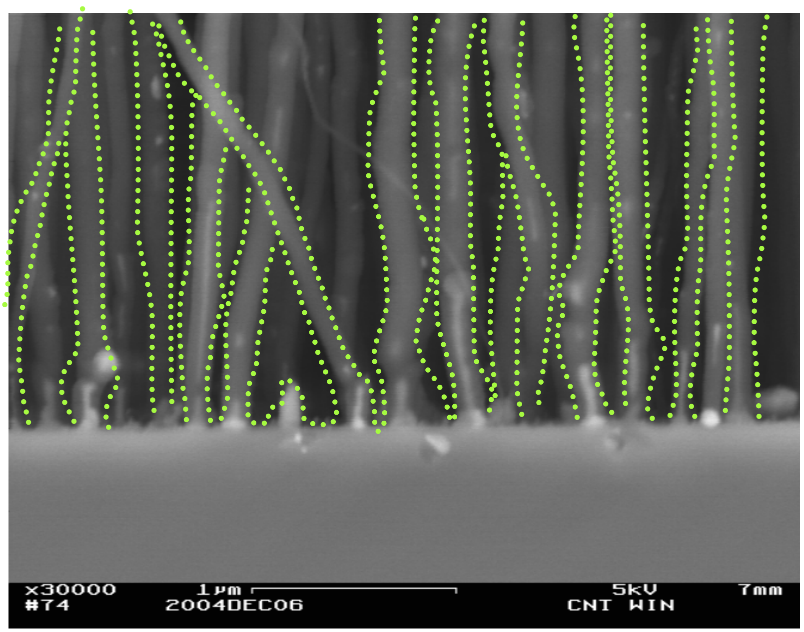
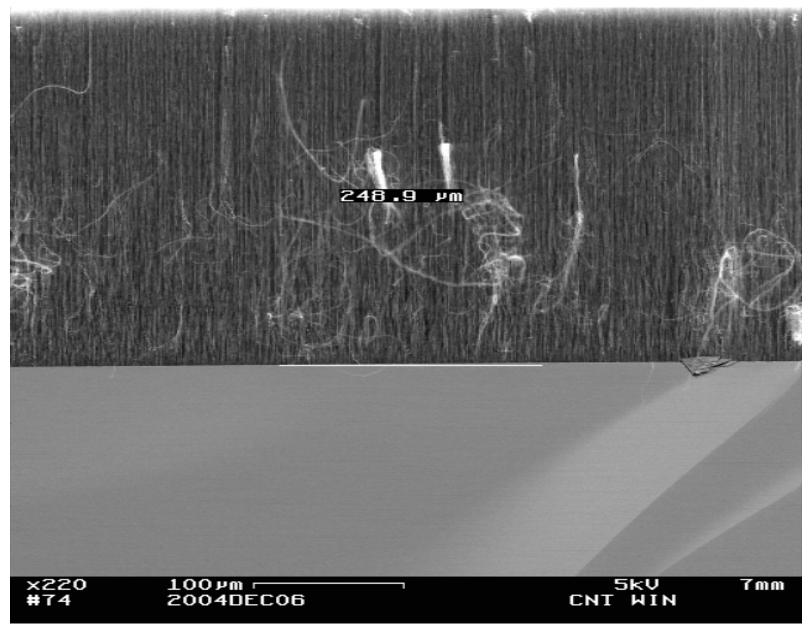
Carbon Nanotube Mats SEM

•MW CNTs from Prof. Alan Windle's group in University of Cambridge





Conducting, Ordered, high aspect ratio, functionizable.
Just what the doctor ordered?

Black…

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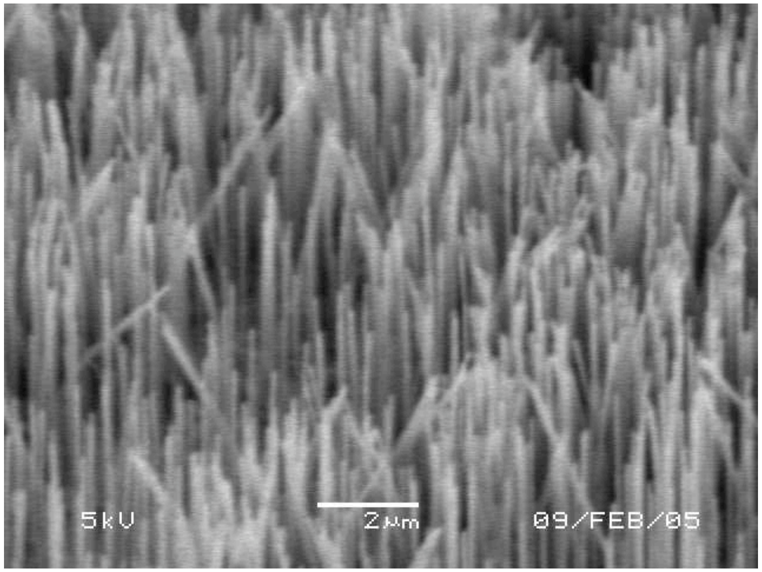
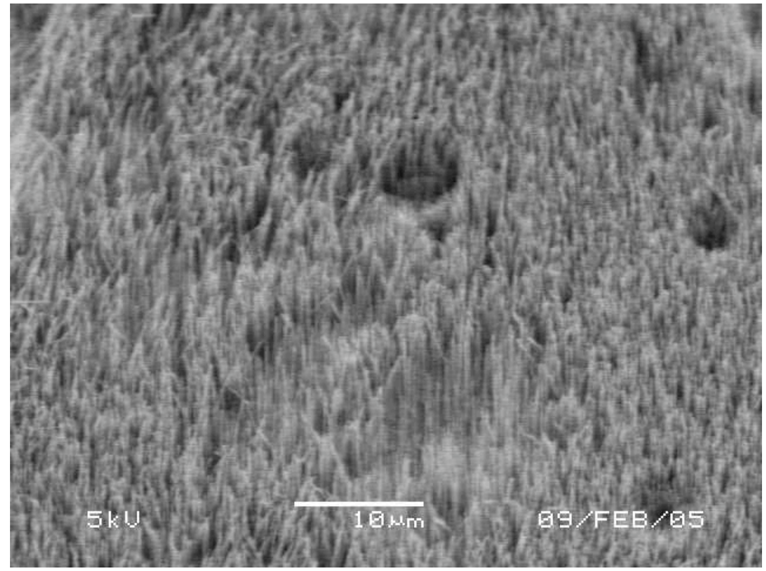
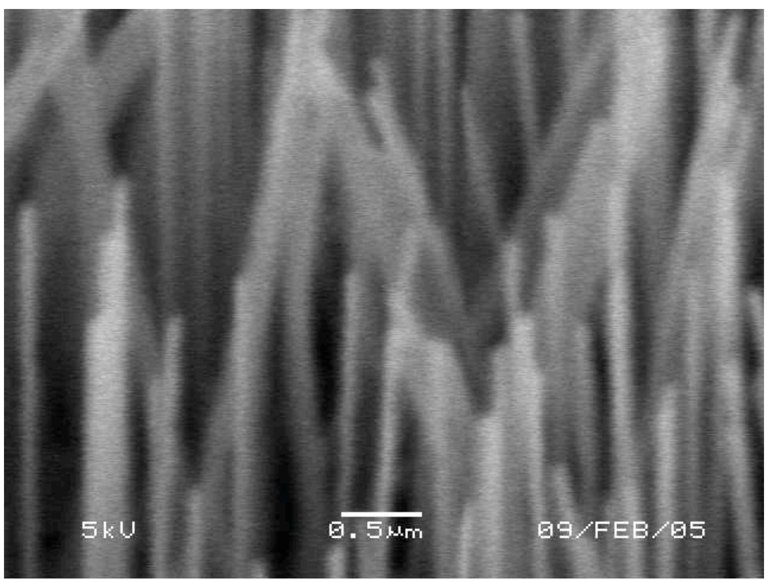
Increasing efficiency by ZnO nanowires transparent, conducting 'tree-trunks'







High surface area, transparent, conducting, bio-friendly, enhancement factor ~20-2000

$$\kappa = \frac{A_{old}}{A_{new}} = 1 + 2\pi R h \left\{ \frac{1}{(R+g)^2} \right\} \approx 200 - 2000$$

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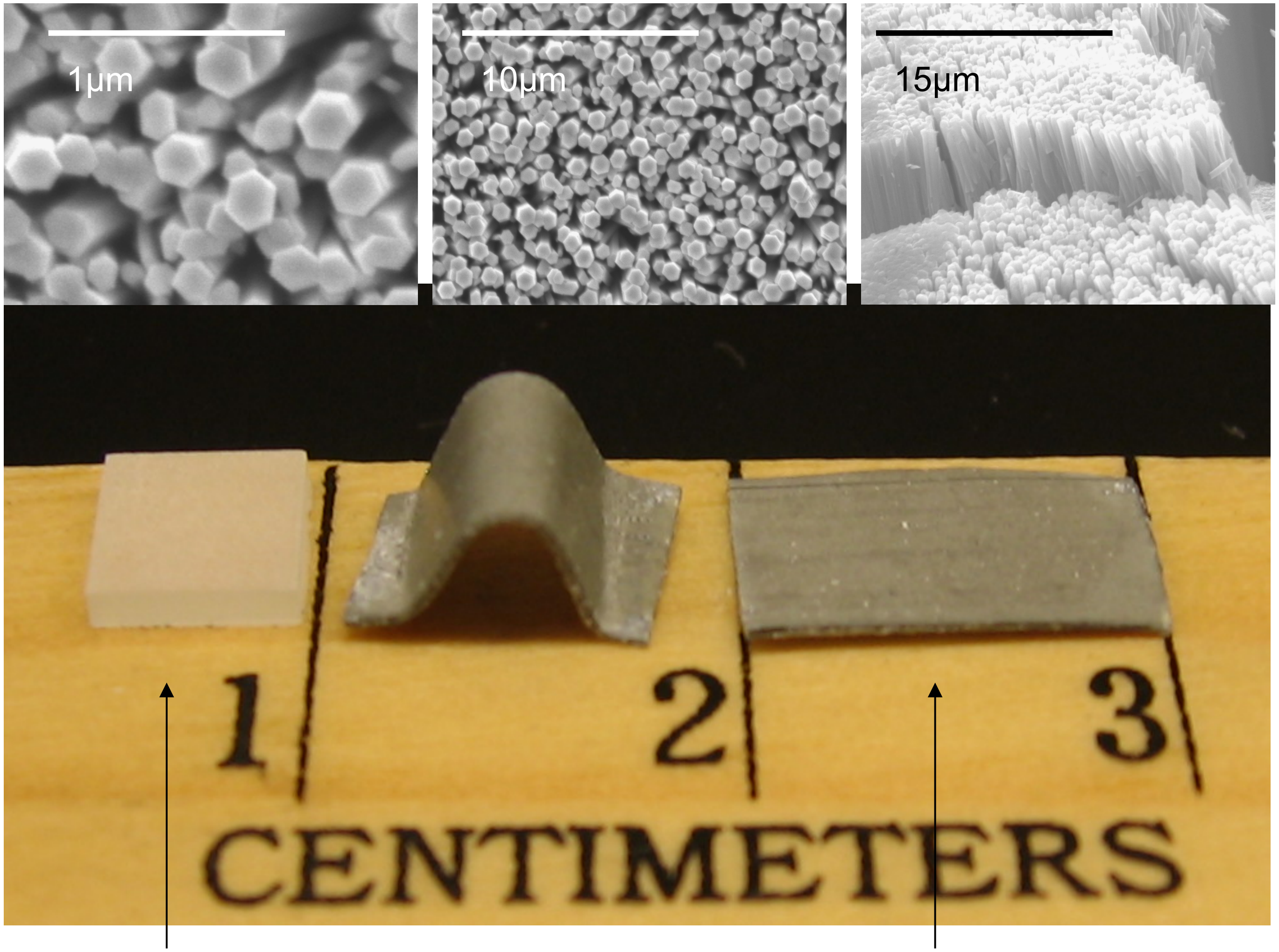

3mm Glass with ITO coat
Multi-step Seeded ZnO NW
T_{max} = 350°C

0.25mm thickness ZnO Foil
1-Step Unseeded ZnO NW
T_{max} = 20°C

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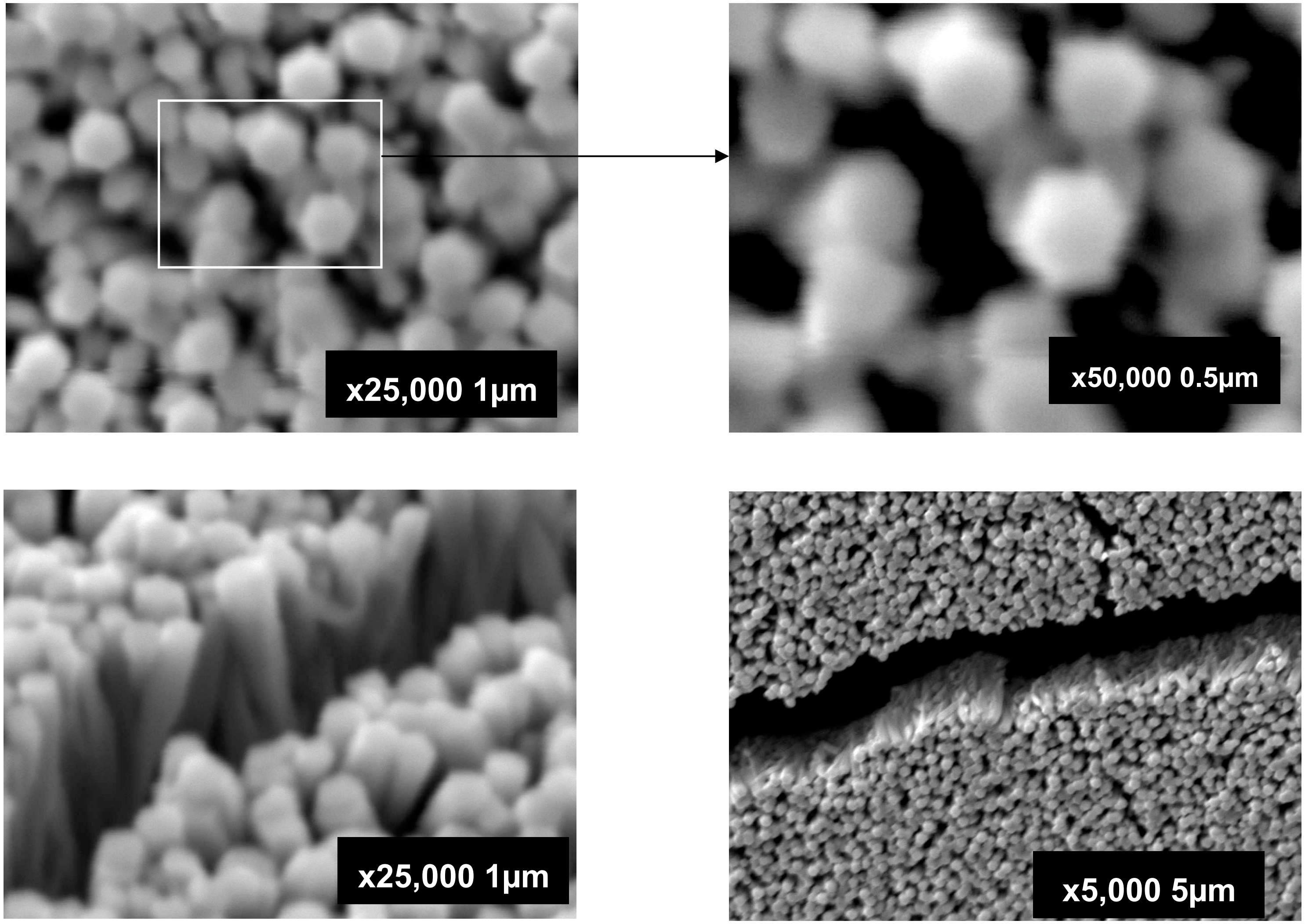
ZnO Nanowires grown on flexible, 0.1mm thick Zn Foil
1-step, inexpensive process, T=20 - 60^{o}C



a), b) Flat substrate
c), d) Rifts when folding into tube

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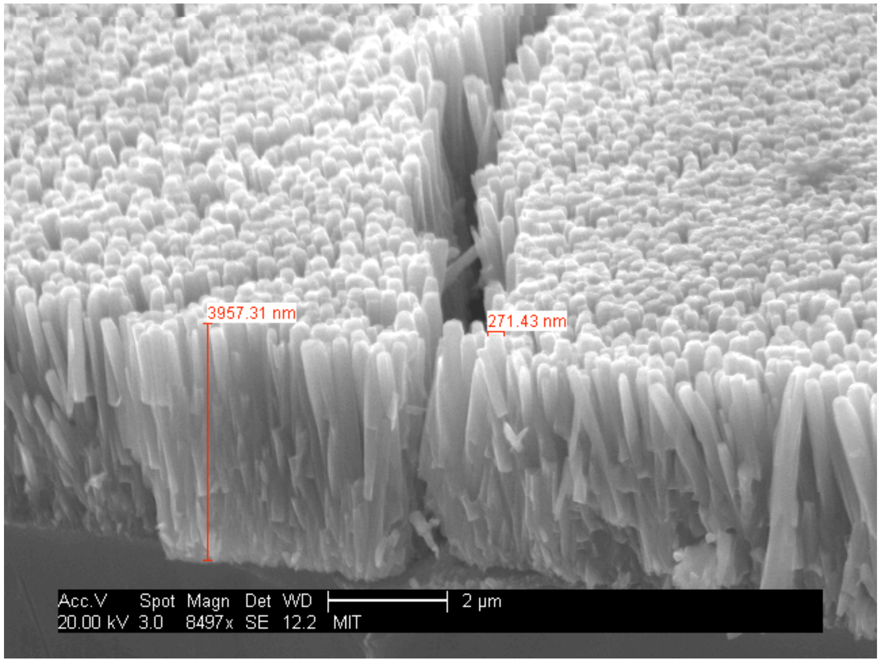
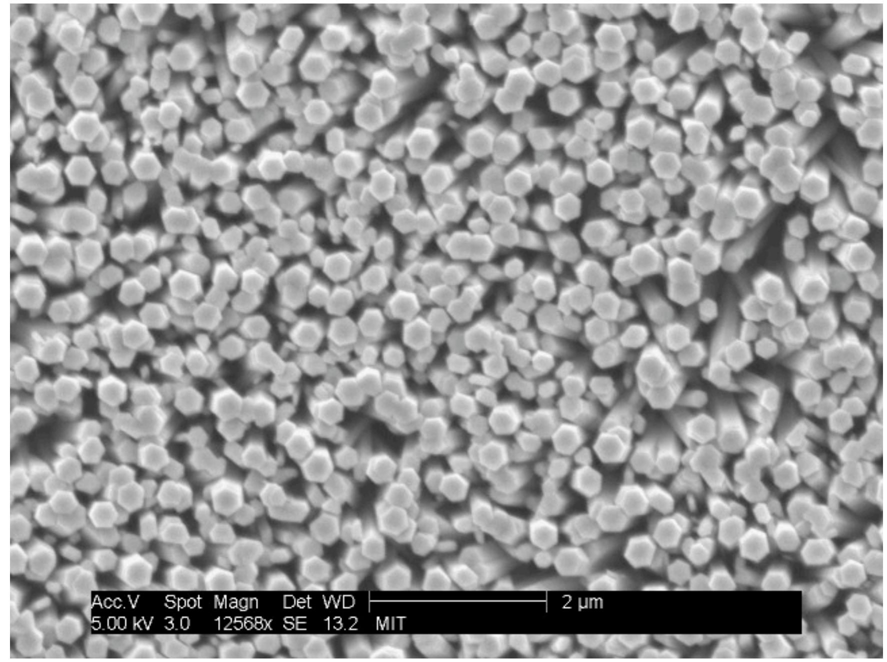
11.7pH Zn foil, 15h, 60°C





Ideal for D/B-SSC

Flexible substrate
Simple growth
100nm thickness
Inexpensive

100-200nm spacing
Tallest possible (currently 18µm)

Explore parameter space

T°C , t, pH, molar ratios, more?

To optimize

Spacing and height

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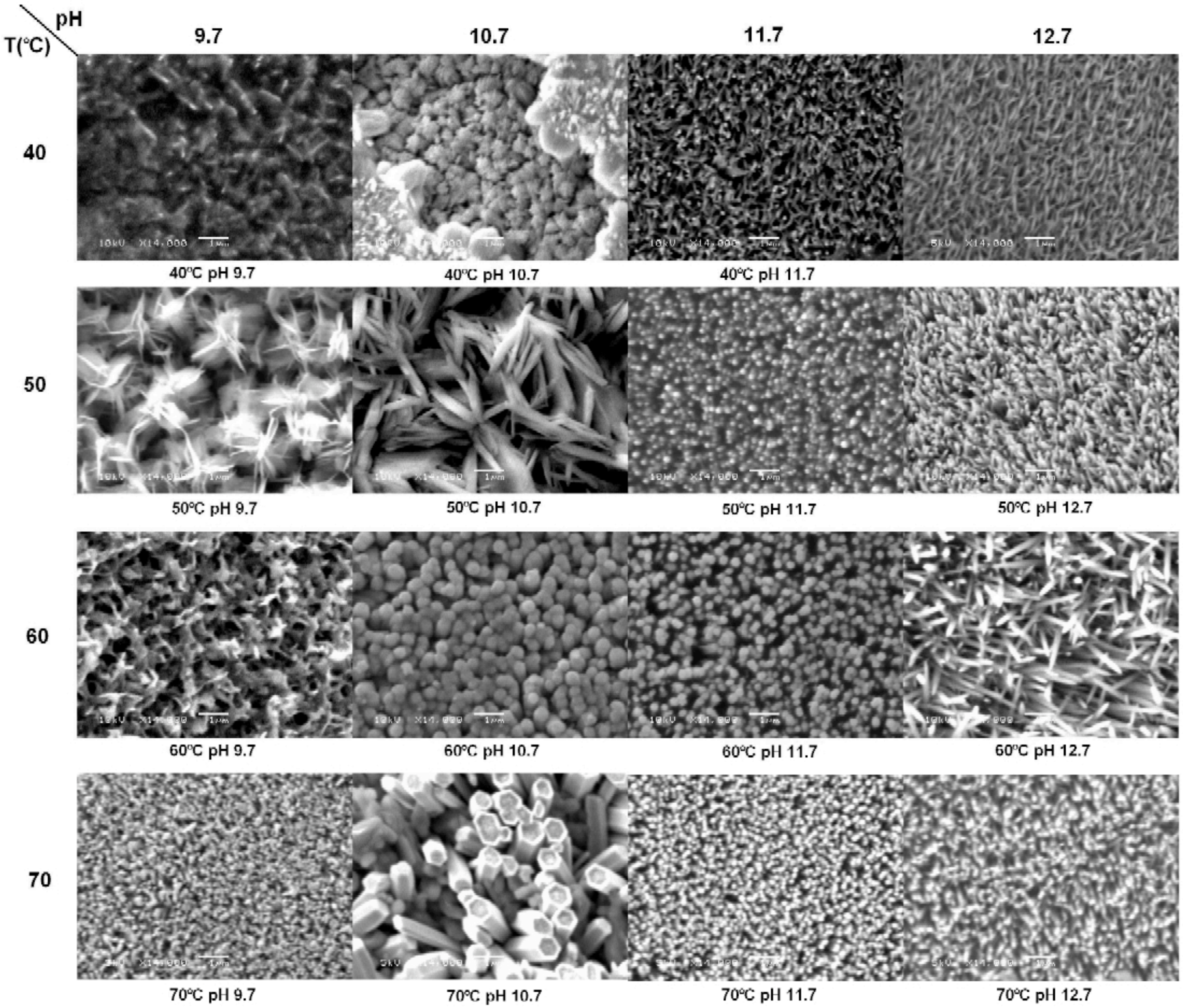
‘Periodic Table’ of ZnO Nanowires



Jing Han

T vs pH

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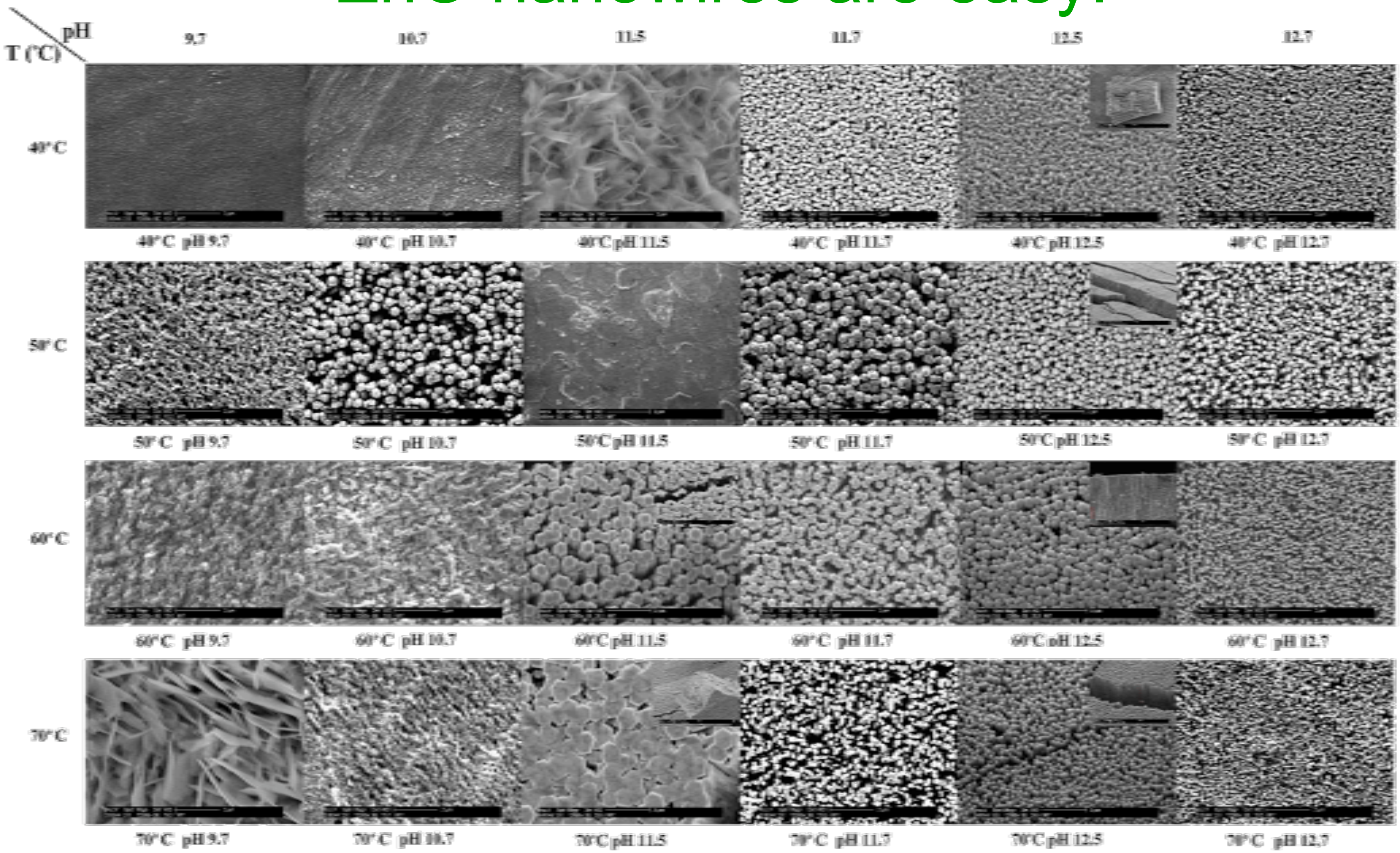
ZnO nanowires are easy!



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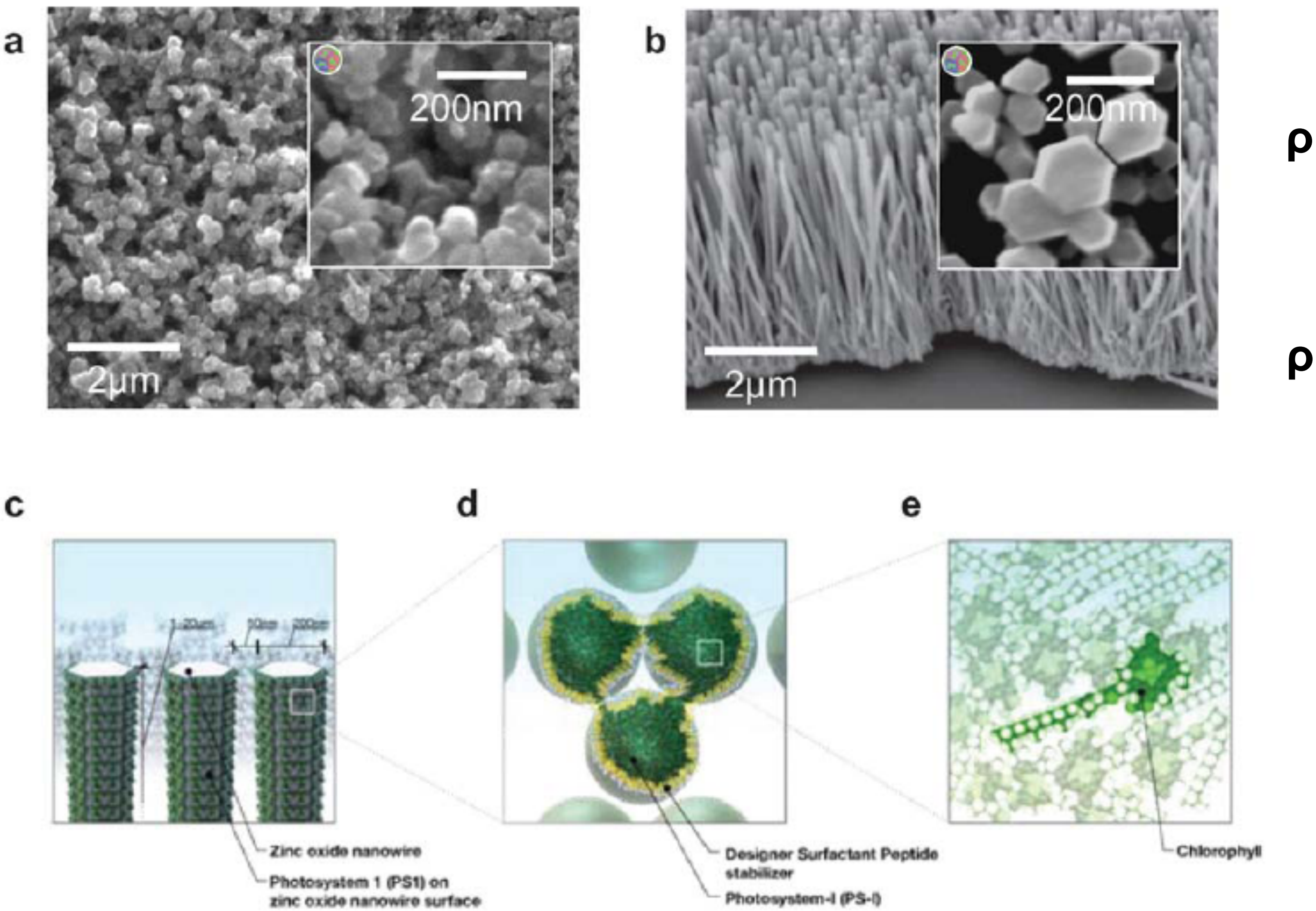
TiO_2 and ZnO Photoanodes



ρ TiO_2 ~ x50 per µm

ρ ZnO ~ x10 per µm

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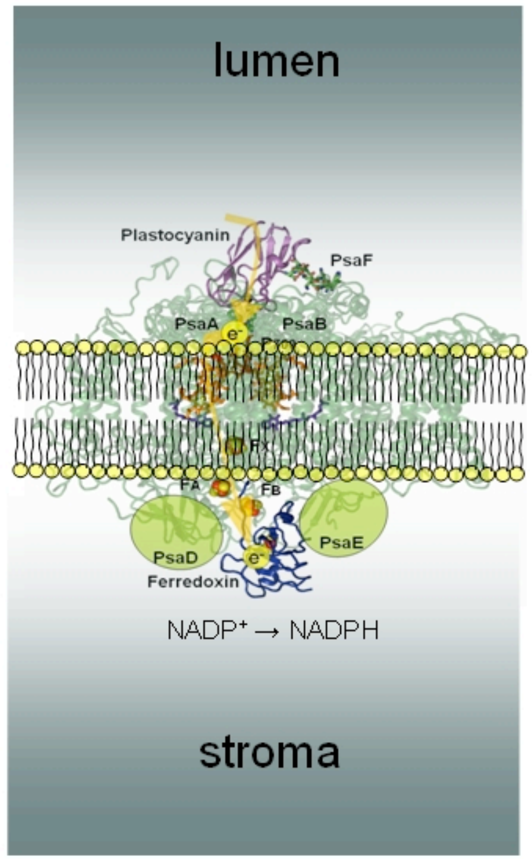
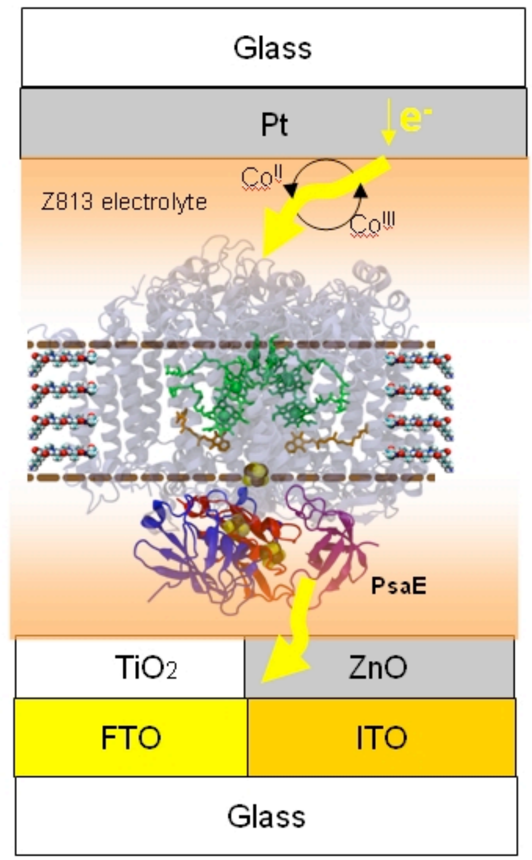
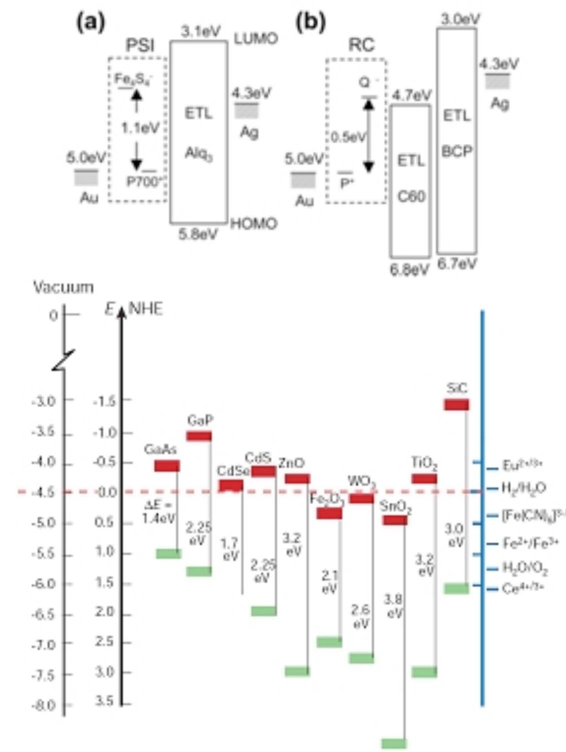
Replacing natural redox mediators with electrolyte and TiO_2 or ZnO

a



b





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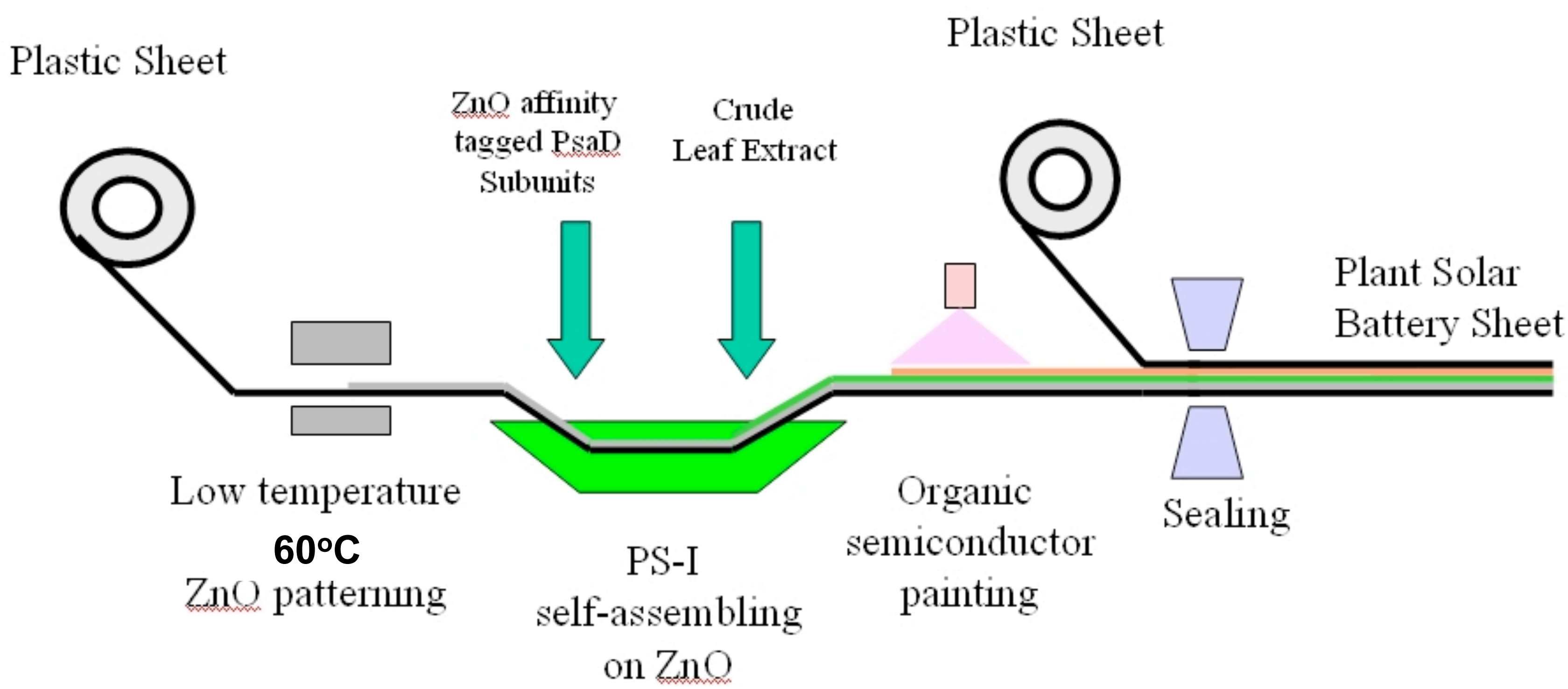
Combine printing process, Flex ZnO and PS-I in a roll-to-roll



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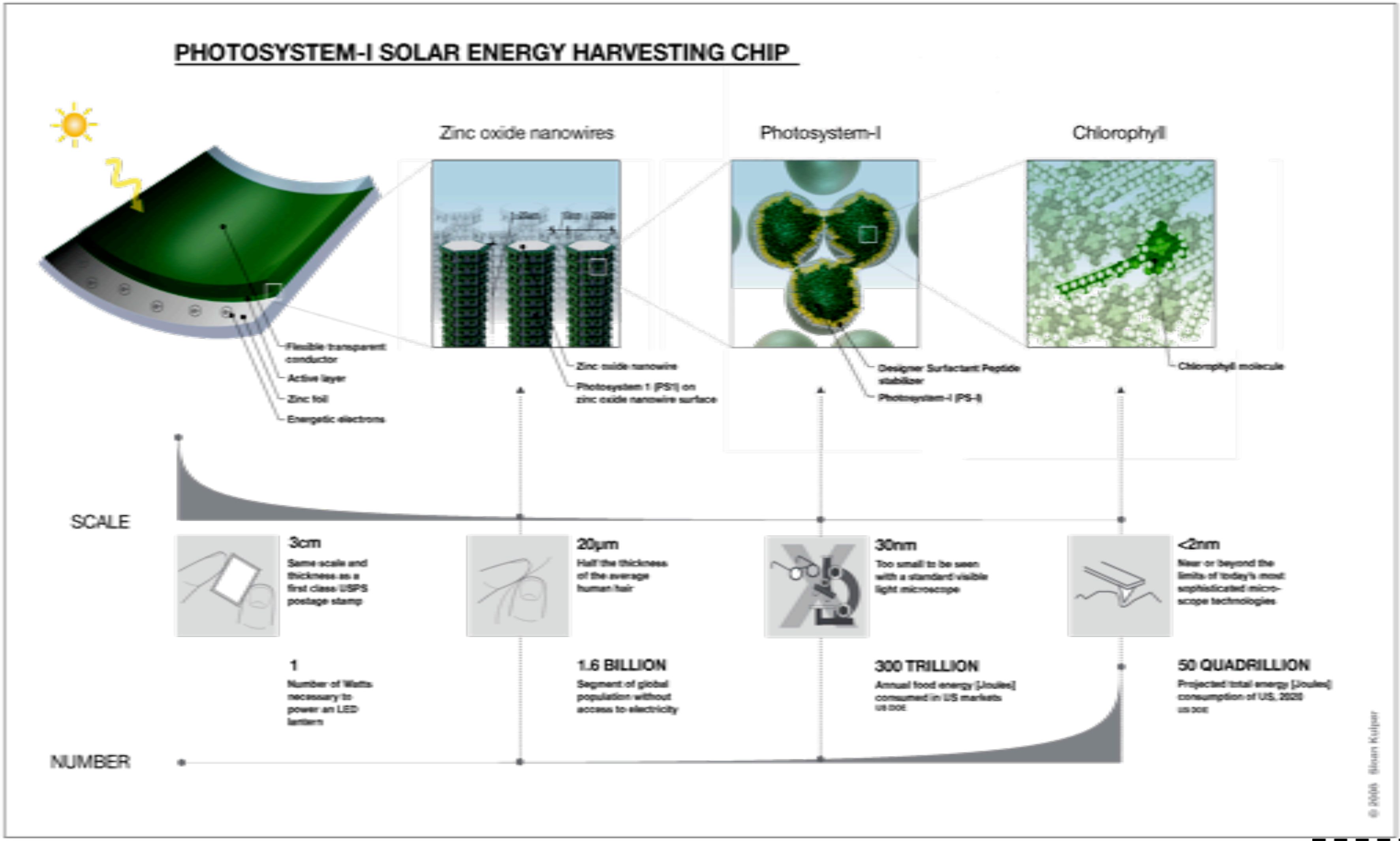
Ideal Case Scenario: flex inexpensive substrate, paint-like sensitizer
Many competing schemes (plastic SC etc.)



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Niche bio-sensitized solar cells

$V_{oc} \sim 0.5V$, $J_{sc}^{Norm} \sim 362\mu A/cm^2$
lifetime >3 weeks $P \sim 81\mu W/cm^2$

Obvious

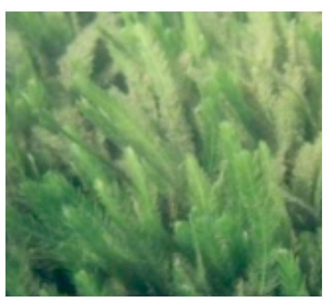
- Unlikely to compete with rooftop Silicon

- Likely to compete with portable silicon (mobile devices, chargers)

- New market for disposable "solar stickers" that extend battery life of mobile devices

- ***"Make your own photovoltaic" (developing world)***
Using locally available materials + simple processing + easily transportable, non-perishable, harmless chemicals + unskilled labor

Radical

 +  +  =  ?

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Inspire Children to Innovation, Creativity, Knoweldge

www.moleClues.org

www.molecularfrontiers.org

Molecular Frontier Inquiry Prize, “Nobel For Kids”