
FAB5: The Fifth International Fab Lab Forum
and Symposium on Digital Fabrication
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Guiding principle: Biomimicry

• *Bio* (from Greek “βιος”) = 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 same laws of physics as biological evolution.

• Evolution took billions of years to achieve spectacular machines of various sizes

• But we can take a shortcut…
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 surpass evolution
# Proteins are the hardware

**Made by Human** (macro)  **Made by Nature** (nano)

**Machines**

- Electric Fences
- Transportation
- Assembly lines
- Digital database
- Copy machines
- Bulldozer/Destroyer
- Chain couplers
- Train control center
- Train tracks
- Internet nodes
- Gates/keys & passes
- Chemical & gas sensors
- Electrolysis machine
- Photovoltaics

**Molecular machines**

- Membranes
- Hemoglobin
- Ribosomes
- Nucleosomes
- Polymerases
- Proteases/proteosome
- Ligases
- Centrosome
- Actin filament network
- Neuronal synapse (MP + membr)
- Ion channels (MP)
- Olfactory receptors (MP)
- Photosystem II (MP)
- Photosystem I (MP)
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
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
Peptides detergents stabilize membrane proteins through hydrophobic interactions
Ru Dye-Sensitized Solar Cells inspired by PS-I

Prof. Michael Graetzel EPFL

Record: $\eta \approx 11.5\%$ in the laboratory

“Commercially” (Konarka etc.) $\sim 6\%$ 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
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*,†
1st Generation (flat) Devices now in the Boston Museum of Science

Biomimicry resonates with people

Nature, Boston Globe, AP, Reuters, CNN, NYT, FT, BBC, etc.
Just how inexpensive is the photosynthetic raw material?

Paper & Pulp industry
Turn waste into solar energy collecting nanomachines
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
and even more…

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

Water $T=8^\circ C$!
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
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.”
Biomimicry: Look at Forest

- Immobilize PS1 on transparent, conducting “tree trunks”

- Ideally would be spaced such that a monolayer of photosynthetic protein can be immobilized on them.
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?
Increasing efficiency by ZnO nanowires
transparent, conducting ‘tree-trunks'

High surface area, transparent, conducting, bio-friendly, enhancement factor $\sim 20-2000$

$$\kappa = \frac{A_{\text{old}}}{A_{\text{new}}} = 1 + 2\pi Rh \left( \frac{1}{(R + g)^2} \right) \approx 200 - 2000$$
0.25mm thickness ZnO Foil
1-Step Unseeded ZnO NW
$T_{\text{max}} = 20^\circ \text{C}$

3mm Glass with ITO coat
Multi-step Seeded ZnO NW
$T_{\text{max}} = 350^\circ \text{C}$
ZnO Nanowires grown on flexible, 0.1mm thick Zn Foil
1-step, inexpensive process, T=20 - 60°C

a), b) Flat substrate
c), d) Rifts when folding into tube
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
‘Periodic Table’ of ZnO Nanowires

Jing Han

T vs pH
ZnO nanowires are easy!
TiO$_2$ and ZnO Photoanodes

ρ TiO$_2$ ~ x50 per µm

ρ ZnO ~ x10 per µm
Replacing natural redox mediators with electrolyte and TiO$_2$ or ZnO
Combine printing process, Flex ZnO and PS-I in a roll-to-roll

Low temperature 60°C ZnO patterning

ZnO affinity tagged PsAD Subunits

Crude Leaf Extract

PS-I self-assembling on ZnO

Organic semiconductor painting

Sealing

Plant Solar Battery Sheet
Ideal Case Scenario: flex inexpensive substrate, paint-like sensitizer
Many competing schemes (plastic SC etc.)
Niche bio-sensitized solar cells

$V_{oc} \sim 0.5V$, $J_{sc}^{Norm} \sim 362 \mu A/cm^2$

lifetime $>3$ weeks $P \sim 81 \mu W/cm^2$

- 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
Inspire Children to Innovation, Creativity, Knowledge

www.moleClues.org
www.molecularfrontiers.org
Molecular Frontier Inquiry Prize, “Nobel For Kids”