ACS Webinars
CLICK • WATCH • LEARN • DISCUSS

ACS Chemistry for Life®

We will begin momentarily at 2pm ET

Slides available now! Recordings will be available to ACS members after one week.

www.acs.org/acswebinars

Contact ACS Webinars ® at acswebinars@acs.org

1

Have Questions?

ACS Chemistry for Life®

"Why am I muted?"
Don't worry. Everyone is muted except the presenter and host. Thank you and enjoy the show.

Type them into questions box!

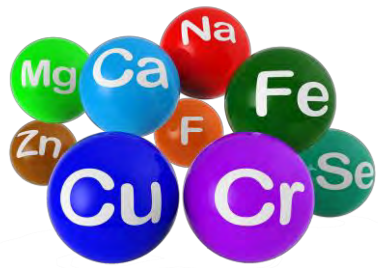
Contact ACS Webinars ® at acswebinars@acs.org

2

ACS Webinars
CLICK • WATCH • LEARN • DISCUSS

ACS Chemistry for Life®

Have you discovered the missing element?



http://bit.ly/ACSjoin

Find the many benefits of ACS membership!

3

ACS Webinars
CLICK • WATCH • LEARN • DISCUSS

ACS Chemistry for Life®

Benefits of ACS Membership

C&EN
CHEMICAL & ENGINEERING NEWS

Chemical & Engineering News (C&EN)
The preeminent weekly news source.

ACS Presentations on Demand
YOUR SOURCE FOR RECORDED MEETING CONTENT

NEW! Free Access to ACS Presentations on Demand®
ACS Member only access to over 1,000 presentation recordings from recent ACS meetings and select events.

NEW! ACS Career Navigator
Your source for leadership development, professional education, career services, and much more.

http://bit.ly/ACSjoin

4

Let's get Social…post, tweet, and link to ACS Webinars during today's broadcast!

ACS Chemistry for Life®

facebook.com/acswebinars

@acswebinars

LinkedIn Search for "acswebinars" and connect!

5

How has ACS Webinars® benefited you?

ACS Chemistry for Life®

"ACS Webinars benefits me by informing me about trends in industry so that I can relay the information to my undergraduate students. This particular webinar [about Base Metal Catalysis] also provided me with great ideas for lab experiments that can be developed for my inorganic chemistry course."

Fan of the Week

Lindsey A. Welch, Ph.D.
Assistant Professor
Dept. of Chemical and Physical Sciences
Cedar Crest College

Be a featured fan on an upcoming webinar! Write to us @ acswebinars@acs.org

6

7

Learn from the best and brightest minds in chemistry!
Hundreds of webinars presented by subject matter experts in the chemical enterprise.

Recordings are available to current ACS members one week after the Live broadcast date. **www.acs.org/acswebinars**

Broadcasts of ACS Webinars® continue to be available to the general public LIVE every Thursday at 2pm ET!

www.acs.org/acswebinars

8

Join GCI in Portland, OR!

June 14-16, 2016

ACS Chemistry for Life®

www.gcande.org

9

Upcoming ACS Webinars®

www.acs.org/acswebinars

ACS Chemistry for Life®

Thursday, March 10, 2016

Chemistry of Hello: Lithium Ion Batteries

Challenges and Opportunities for Personal Electronics Applications

Dee Strand, Chief Scientific Officer, Wildcat Discovery Technologies

Mark Jones, Executive External Strategy and Communications Fellow, Dow Chemical

Thursday, March 24, 2016

Chemistry Champs: Soaking in Solar Energy

Tierra Range, 2015 Chem Champs Runner Up and Student, Centenary College of Louisiana

Chris McCarthy, Social Media & Multimedia Manager, American Chemical Society

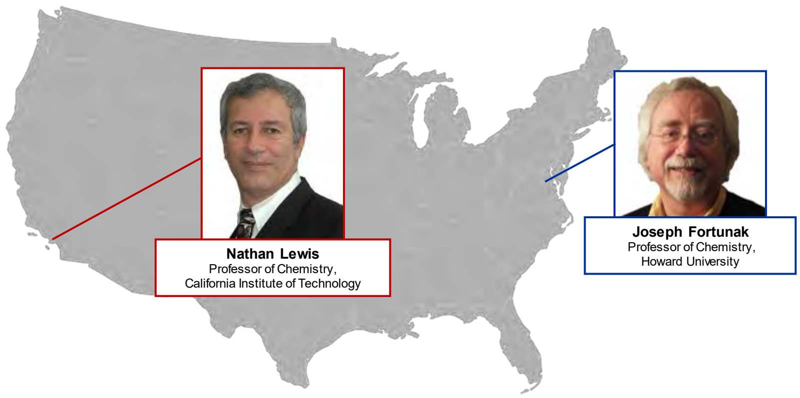
Contact ACS Webinars ® at acswebinars@acs.org

10

ACS Webinars
CLICK · WATCH · LEARN · DISCUSS

ACS Chemistry for Life®

Artificial Photosynthesis:
Making Fuels Directly from Sunlight



Slides available now! Recordings will be available to ACS members after one week

www.acs.org/acswebinars

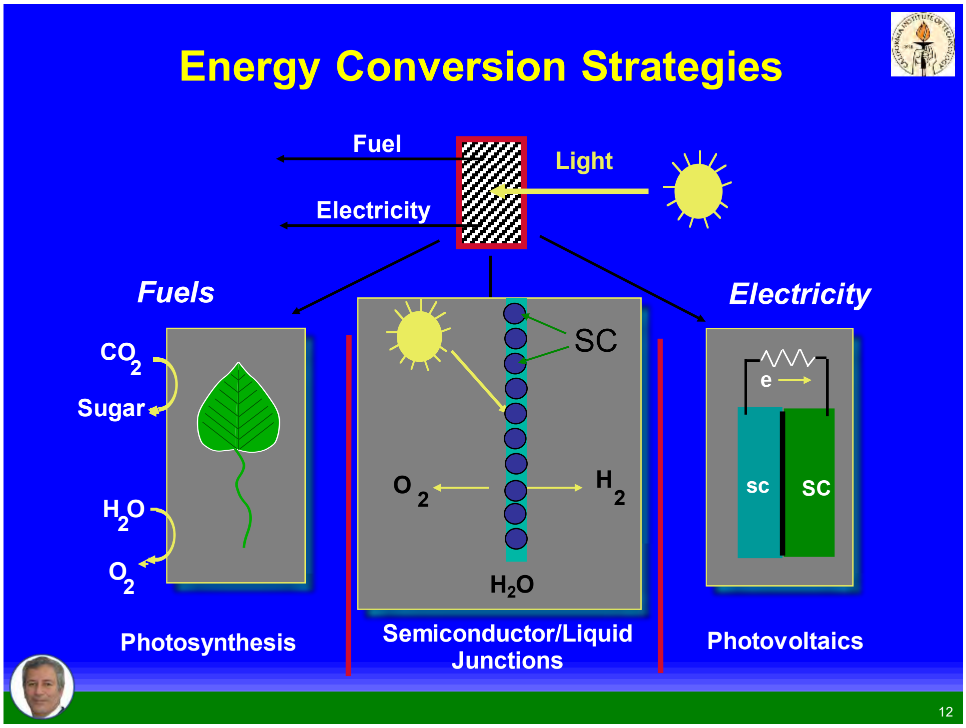
This ACS Webinar is being co-produced with ACS Green Chemistry Institute

JCAP
JOINT CENTER FOR ARTIFICIAL PHOTOSYNTHESIS

NSF CCI, DOE BES, AFOSR, Moore Foundation

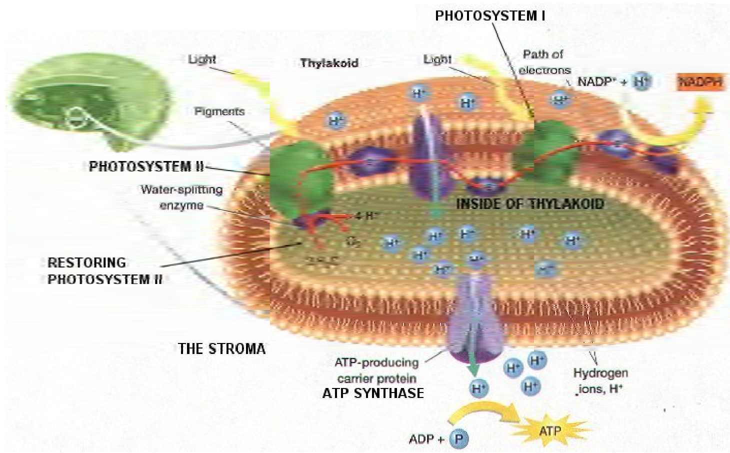
"Artificial Photosynthesis:
Direct Production of Fuels from Sunlight"

Nathan S. Lewis
Division of Chemistry and Chemical Engineering
California Institute of Technology


Energy Conversion Strategies
Fuel
Light
Electricity
Fuels
Electricity
CO2
Sugar
H2O
O2
SC
O 2
H 2
H2O
e
sc
SC
Photosynthesis
Semiconductor/Liquid Junctions
Photovoltaics
12

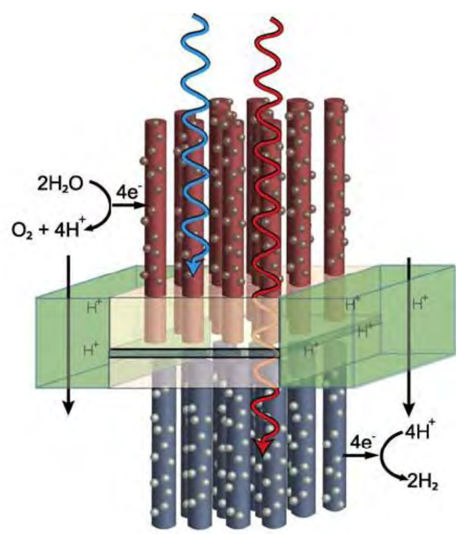

Fuel from Sunlight
13

Lessons from Photosynthesis



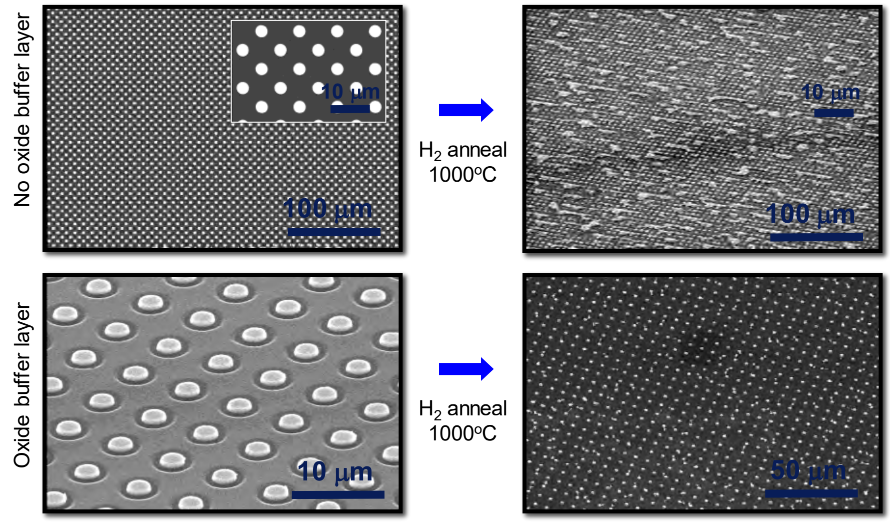
14

Constructing the Pieces of a Solar H_2 Fuel Generator



15

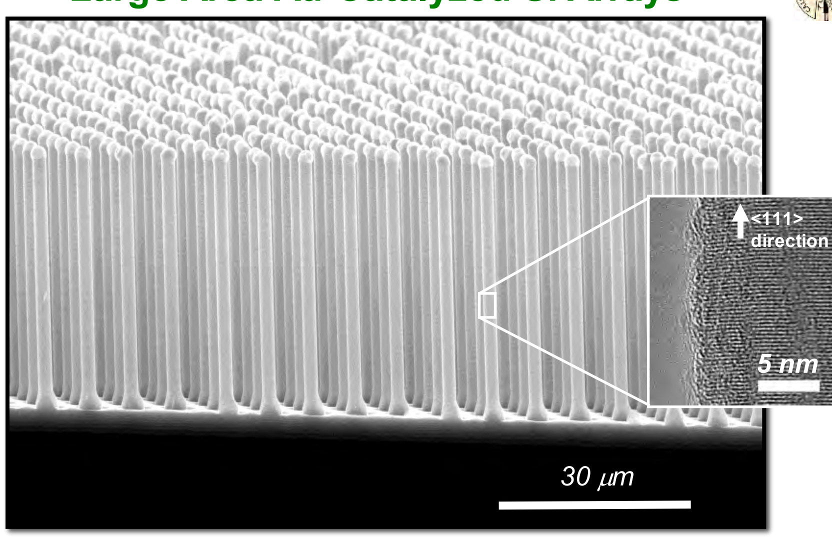
Oxide Buffer Layer - Pattern Fidelity



3 µm array, 500 nm Au, T_{growth} = 1000ºC, P_{growth} = 760 Torr

An oxide buffer layer is critical for maintaining pattern fidelity during growth.

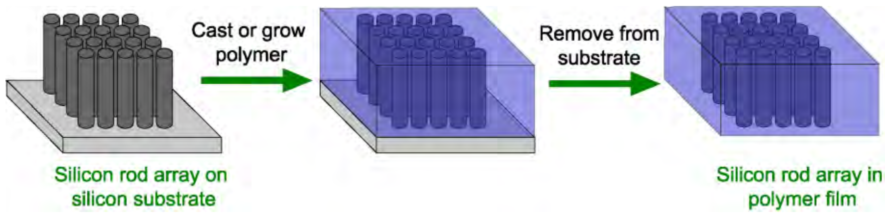
Large Area Au-Catalyzed Si Arrays

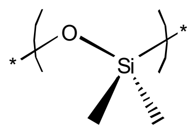


3 µm array, 500 nm Au, T_{growth} = 1000ºC, P_{growth} = 760 Torr, 30 min growth, 2 mole % $SiCl_4$ in H_2

Nearly 100% vertically aligned, 75 µm length microwire arrays over areas > 1 cm^2.

Polymer Embedding of Si Rod Arrays

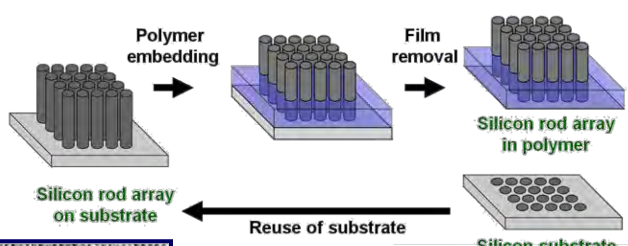


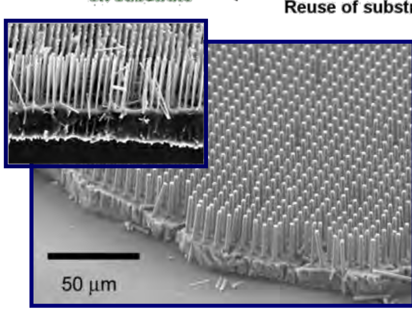


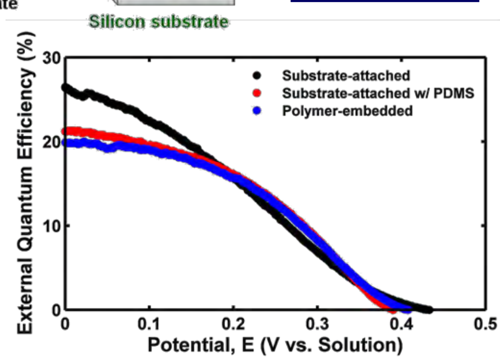
PDMS
(polydimethylsiloxane)

18

Polymer Embedding and Wafer Reuse

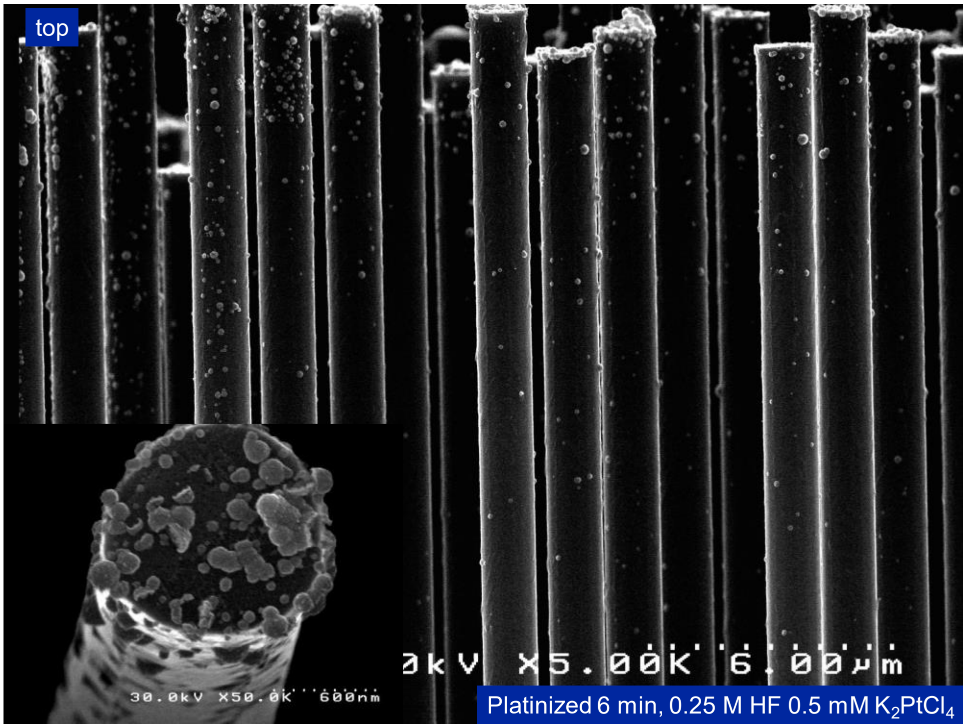






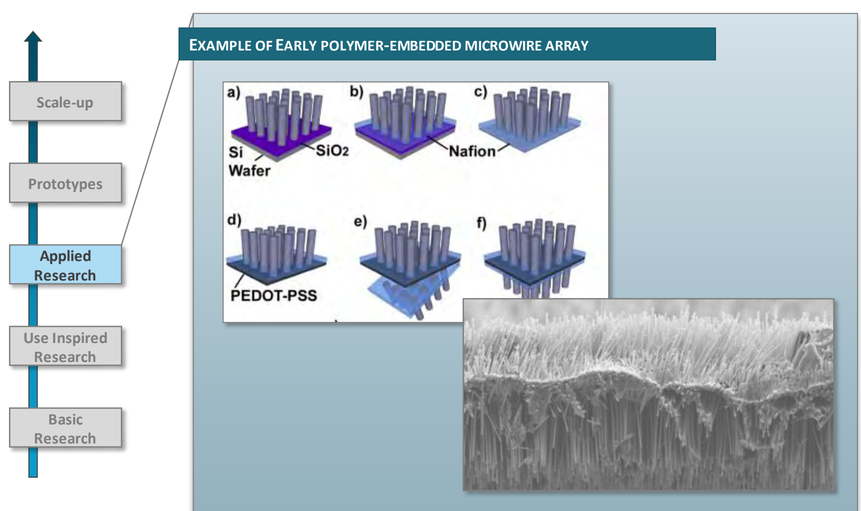
Spurgeon, Boettcher et al., *Energy. Env. Sci.*
Spurgeon, et al., *Appl Phys. Lett.* 93 (3) (2008).
Plass, et al., *Adv. Mater.* **21** (325) (2009).

19



Integrated Architectures

Accomplishments and Future Direction



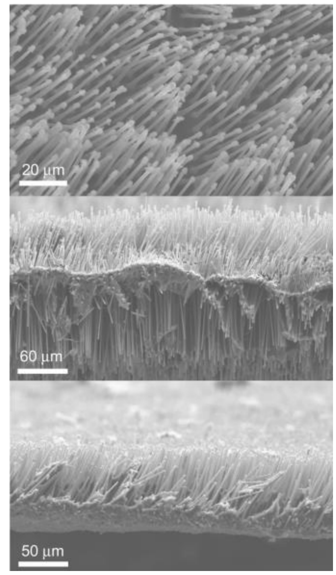
21

Si Wire/Ionomer Morphology

Dual (Si Wire Array/Nafion)/PEDOT-PSS

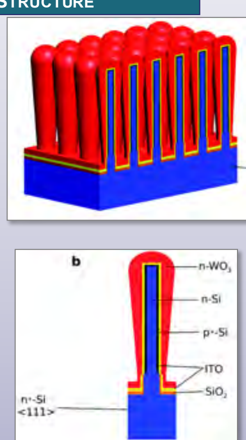
Dual (Si Wire Array/Nafion)/PEDOT-PSS

Si wire/QAPSF

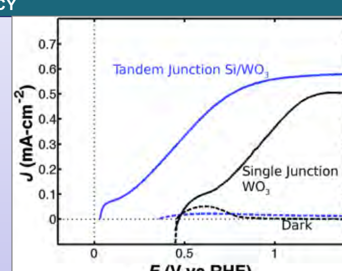


Development of a microwire architecture capable of solar-driven water splitting

CORE-SHELL STRUCTURE



CURRENT-VOLTAGE BEHAVIOR AND CONVERSION EFFICIENCY

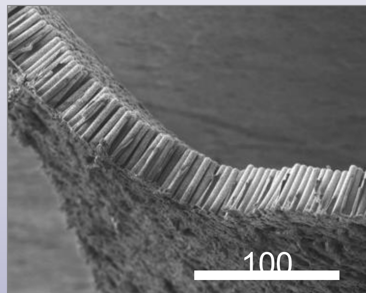


- *Open-circuit potentials are additive:*
  - *Tandem junction: E_{oc} = -1.21 V vs. $E^{o'}(O_2/H_2O)$*
  - *WO_3/liquid junction: E_{oc} = -0.73 V vs. $E^{o'}(O_2/H_2O)$*
  - *n-p+-Si junction: E_{oc} = -0.5 V vs. $E^{o'}(O_2/H_2O)$*
- *Although unassisted water splitting is observed, STH conversion efficiencies remain low (<0.1%) due to the high band-gap of WO_3*

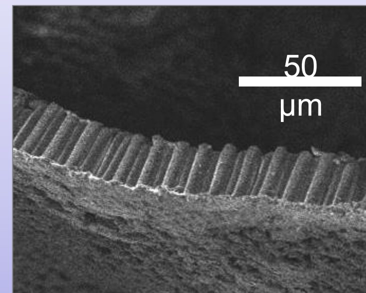
Matthew M. Shaner, Katherine T. Fountaine, Shane Ardo, Rob H. Cordian, Harry A. Atwater, Nathan S. Lewis
Energy Environ. Sci. **2014**, 7, 779-790. (10.1039/c3ee43048k)

Core-Shell Tandem Junction Microwire Arrays

ACID-STABLE EMBEDDED MICROWIRE ARRAY

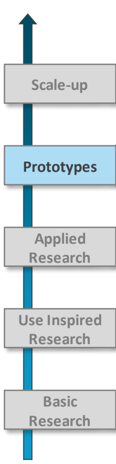


ALKALINE-STABLE EMBEDDED MICROWIRE ARRAY

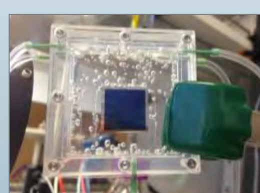


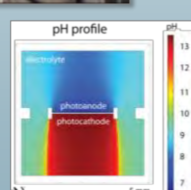
Integrated Prototyping Approach in JCAP (cont.)

JCAP's research prototypes are fully integrated systems



EXAMPLE: MEMBRANE AND MEMBRANE-FREE SOLAR-FUEL GENERATORS





- *Identified requirements of the membrane (e.g. crossover rates, ion conductivity, etc.) needed to ensure intrinsically safe operation*
- *Revealed operational pH of the electrode surfaces even in 1 M buffer*
- *Revealed intrinsic concentration-polarization based energy losses in this configuration*
- *Validated the modeling effort with a real experimental system*

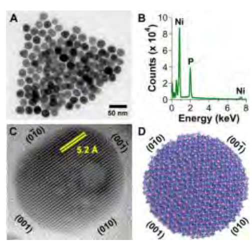
Near neutral pH testing

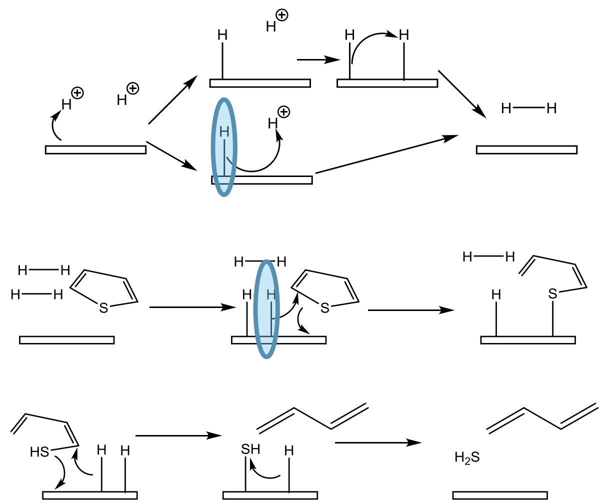
Jin, J.; Walczak, K.; Singh, M. R.; Karp, C.; Lewis, N. S.; Xiang, C., "An Integrated Membrane-free Solar-Fuel Generator with Solar-to-Hydrogen Conversion Efficiency of 3.2% and product Cross-over" *Energ Env Sci*, **2014**

The HER-HDS Hypothesis

Acid-Stable, Earth-Abundant HER Electrocatalysts

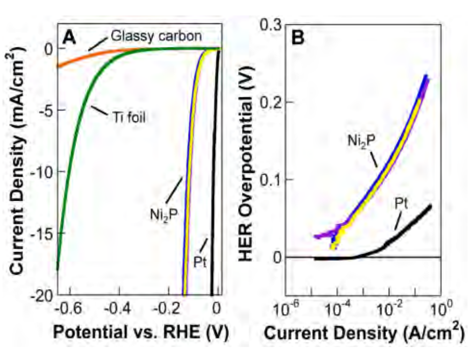
- MoS_2 is also an HDS catalyst.
- HER and HDS share key hydridic intermediates.
- HDS may be a predictor for HER
- Ni_2P was the first target.

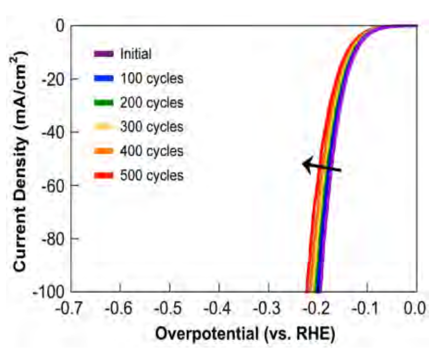




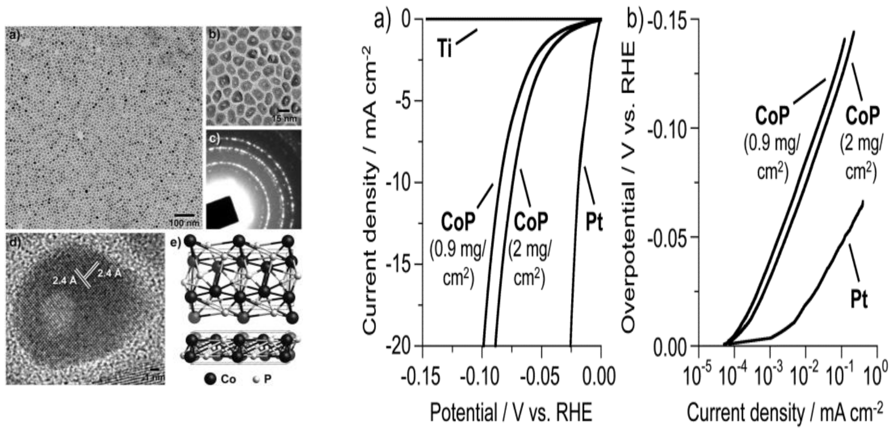
J. Am. Chem. Soc., **2013**, *135* (25), pp 9267–9270

Ni_2P HER in 1 M H_2SO_4; 120 mV overpotential at 10 mA/cm^2

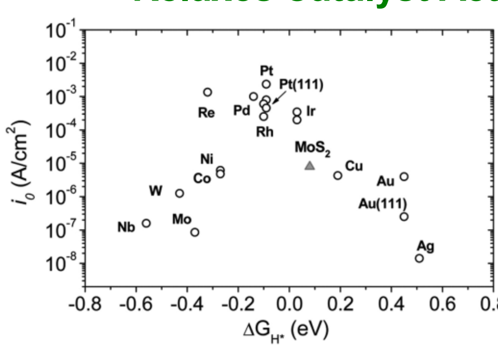


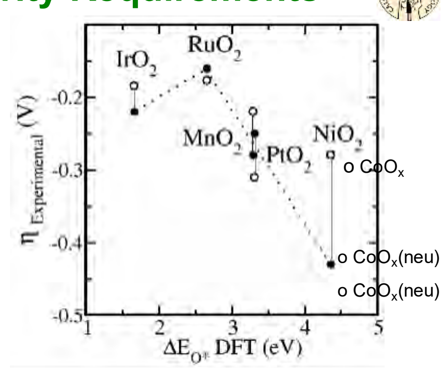


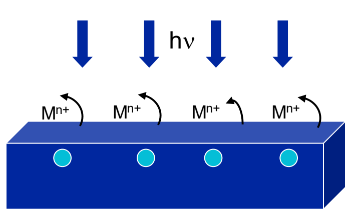
CoP HER in 1 M H_2SO_4; 85 mV overpotential at 10 mA/cm^2

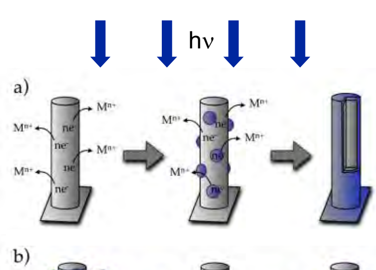


Relaxes Catalyst Activity Requirements

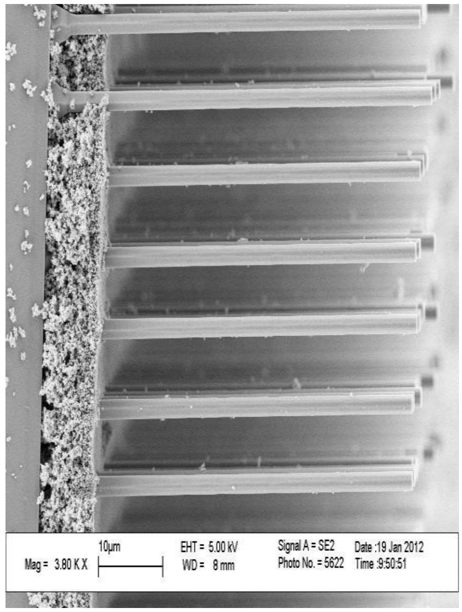






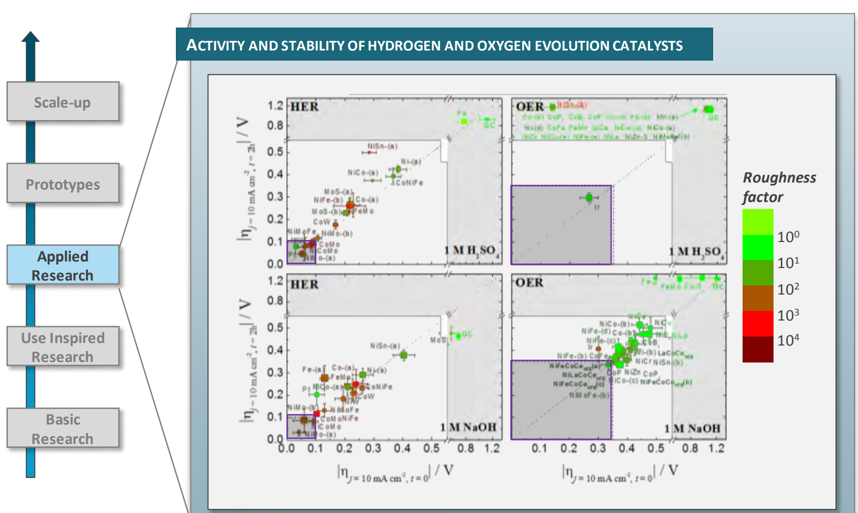


Ni-Mo HER Catalyst at Base of Si Wires



Performance Benchmarking of Electrocatalysts in JCAP

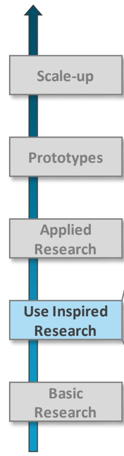
JCAP's benchmarking facility allows for consistent performance evaluation of catalysts



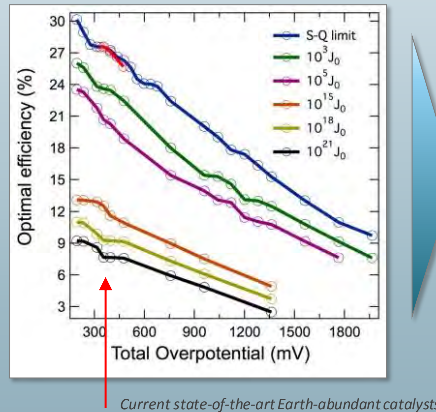
Charles C. L. McCrory, Suho Jung, Jonas C. Peters, and Thomas F. Jaramillo "Benchmarking Heterogeneous Catalysts for the Oxygen Evolution Reaction" *J. Am. Chem. Soc.* **2013**, *135*, 16977-16987. (DOI: 10.1021/ja407115p)

Sensitivity analysis of Solar-Fuel Generators

Simulations indicate that photoelectrode improvements provide the greatest efficiency gains



MODELING OF EFFICIENCY FOR LIGHT ABSORBER/CATALYST COMBINATIONS

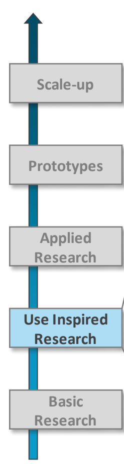


Improvements in photon capture and conversion efficiency can offer larger solar-to-hydrogen efficiency gains than reductions in catalyst overpotential

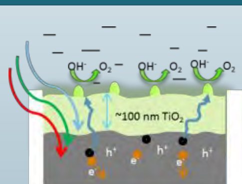
Chengxiang, Xiang, Katie Chen, and Nathan Lewis, *Energy Env. Sci.*, **2015**.

Development of Alkaline stable photoanodes (cont.)

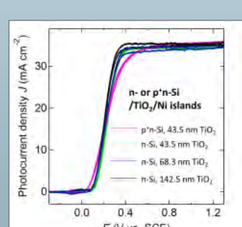
Protection of unstable photoanodes with thick TiO_2 overlayers offers another path to stability

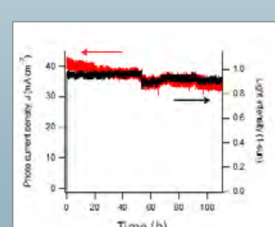


PROTECTION OF SILICON PHOTOANODES WITH THICK TiO_2 OVERLAYERS



- *Efficiency is equivalent to a 9.5% efficient photovoltaic in series with an electrolyzer*
- *Photocurrent is stable for more than 100 hours*

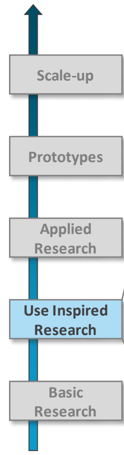




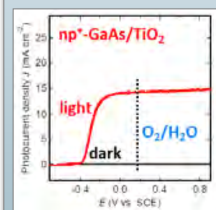
Shu Hu, Matthew Shaner, Joseph Beardslee, Michael Lichterman, Bruce S. Brunschwig, and Nathan S. Lewis "Quantitative, Sustained, Efficient Solar-Driven Oxidation of H_2O to O_2(g) Using Thin Ni Electrocatalytic Films on TiO_2-Coated Si, GaAs, and GaP Semiconductor Photoanodes" **2014**, *Science*

Development of Alkaline stable photoanodes (cont.)

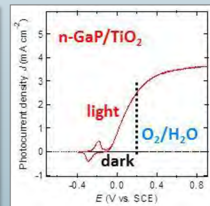
Thick TiO_2 overlayers are also compatible with III-V semiconductors that have near ideal band gaps



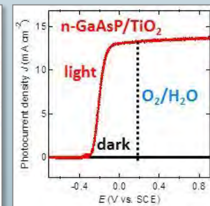
PERFORMANCE OF III-V SEMICONDUCTORS WITH THICK TiO_2 LAYERS



GaAs
1.4 eV bandgap



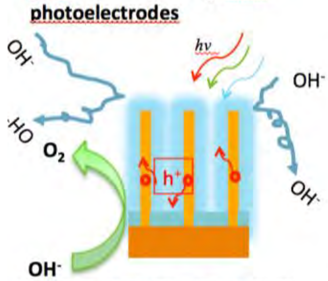
GaP
2.3 eV bandgap

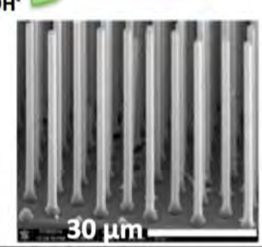


$GaAs_{0.6}P_{0.4}$
1.7 eV bandgap

Wire-shape photoanodes stabilized by atomic layer deposited TiO_2

Schematic and SEM image of GaAs or Si wire/TiO_2/NiOx photoelectrodes

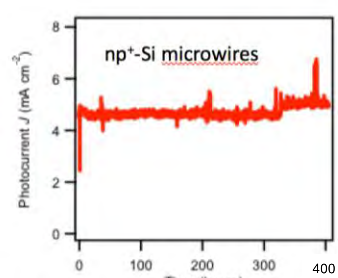




PEC performance and stability

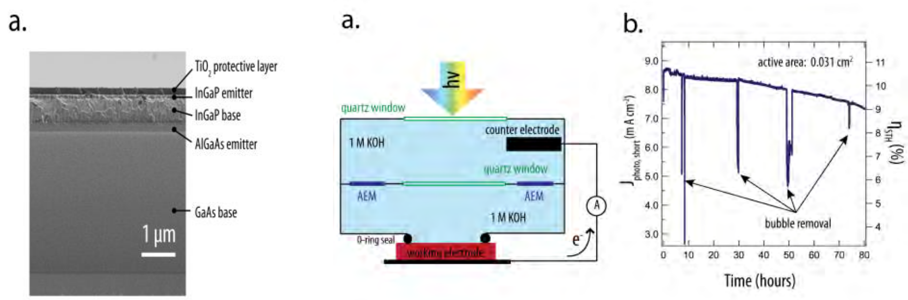
in 1 M KOH

Stability: >400 hours
FF remains the same.

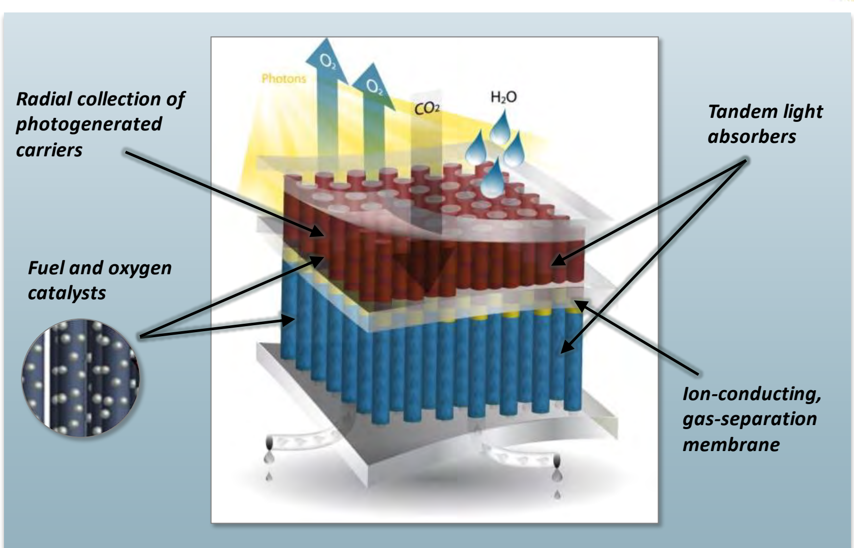


M. Shaner et al., *Energy Env Sci.* 2014.

An Intrinsically Safe, 10% Efficient Solar-to-Hydrogen System with TiO_2-Stabilized III-V Tandem and Ni-Mo/NiO_x Electrocatalysts



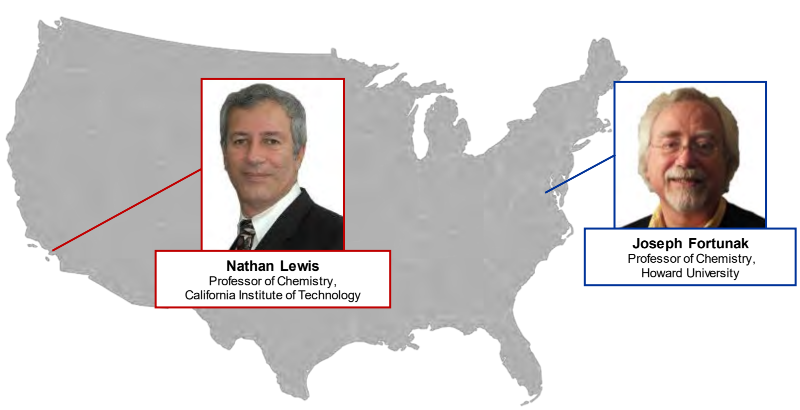
Blueprint for an Integrated Solar-Fuel Generator



ACS Webinars
CLICK • WATCH • LEARN • DISCUSS

ACS Chemistry for Life®

Artificial Photosynthesis:
Making Fuels Directly from Sunlight



Slides available now! Recordings will be available to ACS members after one week
www.acs.org/acswebinars

This ACS Webinar is being co-produced with ACS Green Chemistry Institute 40

Join GCI in Portland, OR!

June 14-16, 2016

ACS Chemistry for Life®

www.gcande.org

Upcoming ACS Webinars®

www.acs.org/acswebinars

ACS Chemistry for Life®

Thursday, March 10, 2016

Chemistry of Hello: Lithium Ion Batteries

Challenges and Opportunities for Personal Electronics Applications

Dee Strand, Chief Scientific Officer, Wildcat Discovery Technologies

Mark Jones, Executive External Strategy and Communications Fellow, Dow Chemical

Thursday, March 24, 2016

Chemistry Champs: Soaking in Solar Energy

Tierra Range, 2015 Chem Champs Runner Up and Student**,** Centenary College of Louisiana

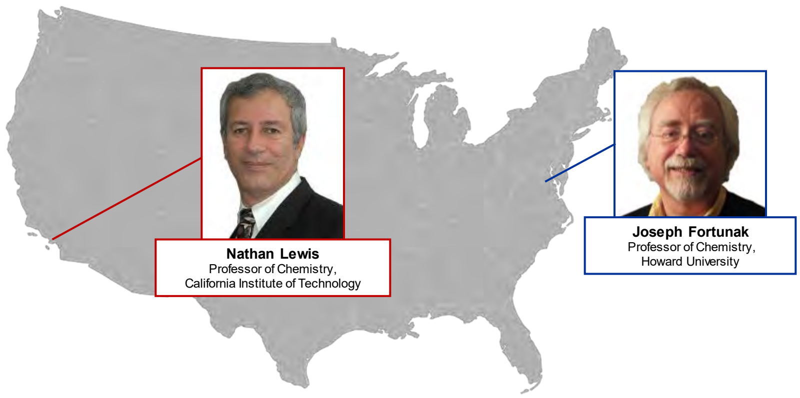
Chris McCarthy, Social Media & Multimedia Manager, American Chemical Society

Contact ACS Webinars ® at acswebinars@acs.org

ACS Webinars
CLICK • WATCH • LEARN • DISCUSS

ACS Chemistry for Life®

Artificial Photosynthesis:
Making Fuels Directly from Sunlight



Slides available now! Recordings will be available to ACS members after one week
www.acs.org/acswebinars

This ACS Webinar is being co-produced with ACS Green Chemistry Institute

43

How has ACS Webinars® benefited you?

ACS Chemistry for Life®

"ACS Webinars benefits me by informing me about trends in industry so that I can relay the information to my undergraduate students. This particular webinar [about Base Metal Catalysis] also provided me with great ideas for lab experiments that can be developed for my inorganic chemistry course."

Fan of the Week
Lindsey A. Welch, Ph.D.
Assistant Professor
Dept. of Chemical and Physical Sciences
Cedar Crest College

Be a featured fan on an upcoming webinar! Write to us @ acswebinars@acs.org

44

ACS Webinars
CLICK • WATCH • LEARN • DISCUSS

ACS Chemistry for Life®

45

ACS Webinars
CLICK • WATCH • LEARN • DISCUSS

ACS Chemistry for Life®

Benefits of ACS Membership

C&EN
CHEMICAL & ENGINEERING NEWS

Chemical & Engineering News (C&EN)
The preeminent weekly news source.

ACS Presentations on Demand
YOUR SOURCE FOR RECORDED MEETING CONTENT

NEW! Free Access to ACS Presentations on Demand®
ACS Member only access to over 1,000 presentation recordings from recent ACS meetings and select events.

NEW! ACS Career Navigator
Your source for leadership development, professional education, career services, and much more.

http://bit.ly/ACSjoin

46

ACS Webinars® does not endorse any products or services. The views expressed in this presentation are those of the presenter and do not necessarily reflect the views or policies of the American Chemical Society.

Upcoming ACS Webinars®

www.acs.org/acswebinars

Thursday, March 10, 2016

Chemistry of Hello: Lithium Ion Batteries

Challenges and Opportunities for Personal Electronics Applications

Dee Strand, Chief Scientific Officer, Wildcat Discovery Technologies

Mark Jones, Executive External Strategy and Communications Fellow, Dow Chemical

Thursday, March 24, 2016

Chemistry Champs: Soaking in Solar Energy

Tierra Range, 2015 Chem Champs Runner Up and Student**,** Centenary College of Louisiana

Chris McCarthy, Social Media & Multimedia Manager, American Chemical Society