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

Have Questions?

“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
Have you discovered the missing element?


Find the many benefits of ACS membership!

Benefits of ACS Membership

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

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.

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

facebook.com/acswebinars

@acswebinars

Search for “acswebinars” and connect!

How has ACS Webinars® benefited you?

“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
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!
Join GCI in Portland, OR!
June 14-16, 2016

Upcoming ACS Webinars®

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 acswininars@acs.org
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

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

Fuels
- CO₂
- Sugar
- H₂O
- O₂

Electricity
- Light
- SC
- O₂
- H₂
- H₂O

Photosynthesis
Semiconductor/Liquid Junctions
Photovoltaics

Fuel from Sunlight

[Image of fuel production from sunlight]
Lessons from Photosynthesis

Constructing the Pieces of a Solar $H_2$ Fuel Generator
An oxide buffer layer is critical for maintaining pattern fidelity during growth.

Nearly 100% vertically aligned, 75 μm length microwire arrays over areas > 1 cm².
Polymer Embedding of Si Rod Arrays

Silicon rod array on silicon substrate → Cast or grow polymer → Remove from substrate → Silicon rod array in polymer film

PDMS (polydimethylsiloxane)

Polymer Embedding and Wafer Reuse

Silicon rod array on substrate → Polymer embedding → Film removal → Silicon rod array in polymer → Reuse of substrate

Integrated Architectures
Accomplishments and Future Direction

EXAMPLE OF EARLY POLYMER-EMBEDDED MICROWIRE ARRAY

- Scale-up
- Prototypes
- Applied Research
- Use Inspired Research
- Basic Research
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

• Open-circuit potentials are additive:
  - Tandem junction: $E_{oc} = -1.21 \text{ V vs. } E^0 (\text{O}_2/\text{H}_2\text{O})$
  - WO$_3$/liquid junction: $E_{oc} = -0.73 \text{ V vs. } E^0 (\text{O}_2/\text{H}_2\text{O})$
  - n-p+Si junction: $E_{oc} = -0.5 \text{ V vs. } E^0 (\text{O}_2/\text{H}_2\text{O})$

  - Although unassisted water splitting is observed, STH conversion efficiencies remain low (<0.1%) due to the high band-gap of WO$_3$
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

The HER-HDS Hypothesis
Acid-Stable, Earth-Abundant HER Electro-catalysts

- MoS$_2$ is also an HDS catalyst.
- HER and HDS share key hydridic intermediates.
- HDS may be a predictor for HER
- Ni$_2$P was the first target.

Ni$_2$P HER in 1 M H$_2$SO$_4$; 120 mV overpotential at 10 mA/cm$^2$
CoP HER in 1 M H₂SO₄: 85 mV OVERPOTENTIAL AT 10 mA/cm²

Relaxes Catalyst Activity Requirements
Performance Benchmarking of Electrocatalysts in JCAP

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

ACTIVITY AND STABILITY OF HYDROGEN AND OXYGEN EVOLUTION CATALYSTS

Sensitivity analysis of Solar-Fuel Generators

Simulations indicate that photoelectrode improvements provide the greatest efficiency gains.

Current state-of-the-art Earth-abundant catalysts


Development of Alkaline stable photoanodes (cont.)

Protection of unstable photoanodes with thick TiO$_2$ overlayers offers another path to stability.

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. Burschwig, and Nathan S. Lewis “Quantitative, Sustained, Efficient Solar-Diven Oxidation of H$_2$O 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$_x$ Electro catalysts

Blueprint for an Integrated Solar-Fuel Generator
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
Join GCI in Portland, OR!
June 14-16, 2016

www.gcande.org

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

Contact ACS Webinars ® at acswebinars@acs.org
**Artificial Photosynthesis:**
Making Fuels Directly from Sunlight

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

[www.acs.org/acswebinars](http://www.acs.org/acswebinars)

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

---

**How has ACS Webinars® benefited you?**

“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
Benefits of ACS Membership

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

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.

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.

Contact ACS Webinars® at acswebinars@acs.org

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

Contact ACS Webinars® at acswebinars@acs.org