Nanoscale Materials for Sustainable Energy

STACEY F. BENT

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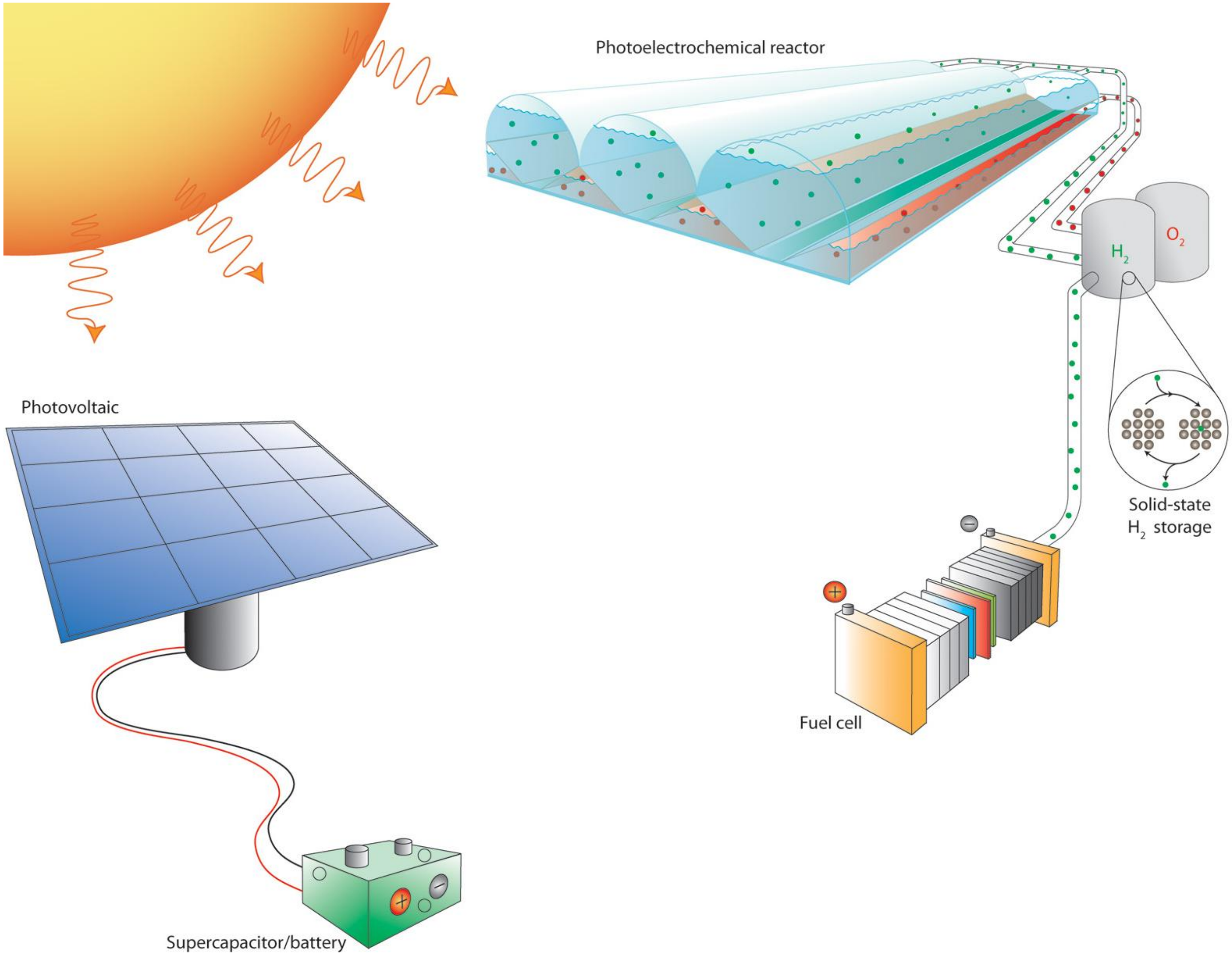
STANFORD UNIVERSITY

One vision for a sustainable energy future



by Zhebo Chen

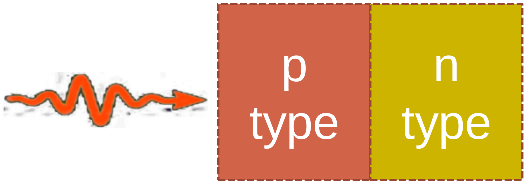
Same Underlying Phenomena

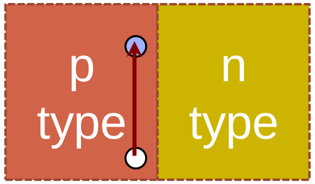
- The diverse energy devices needed, such as photovoltaics, fuel cells, and batteries, all exploit **similar physical and chemical phenomena**.
- By identifying and exploiting common threads, we can lay the groundwork for new generations of many families of devices.

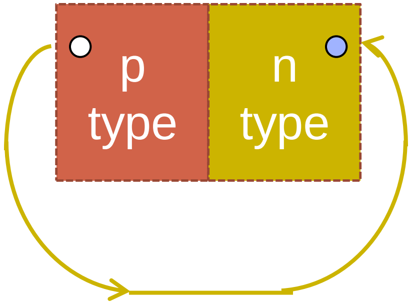
- Each process
  - Creates a positive and negative charge carrier (e.g. electron and hole)
  - Moves the charge
  - Recombines charge

A Photovoltaic Device Separates, Transports, and Recombines Charge

- Photovoltaic devices convert light into electrical energy
- Typically consist of semiconductor materials
  - Light is absorbed
  - Charge carriers (electrons and holes) are created
  - Charge carriers are separated
  - Current flows in a circuit



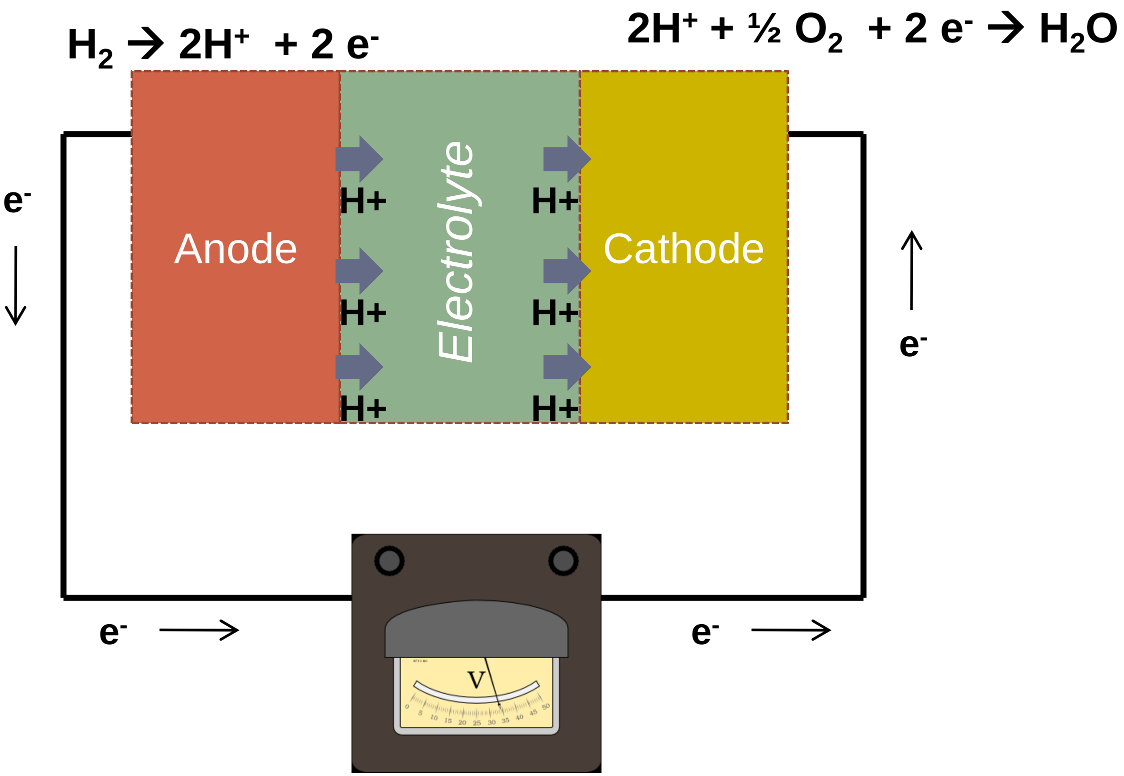




Fuel cells do the same

Fuel cells are devices that convert chemical energy into electrical energy

- Generate charged species (ions, electrons)
- Move the charged species (ions, electrons)
- Recombine



$H_2 \rightarrow 2H^+ + 2e^-$

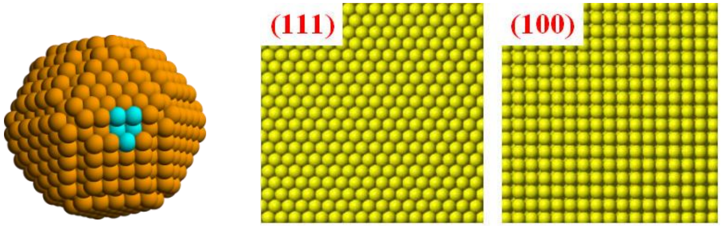
$2H^+ + \frac{1}{2} O_2 + 2e^- \rightarrow H_2O$

How can we improve this process?

Answer: **Make things smaller**

- Charges don’t have as far to move

- More light may be absorbed
  - If induced by light, may get better absorption by tuning bandgap through quantum confinement
- Separation and recombination of charge may improve
  - If chemical reaction, can get more active surfaces for better reaction rates (kinetics)



One vision for a sustainable energy future

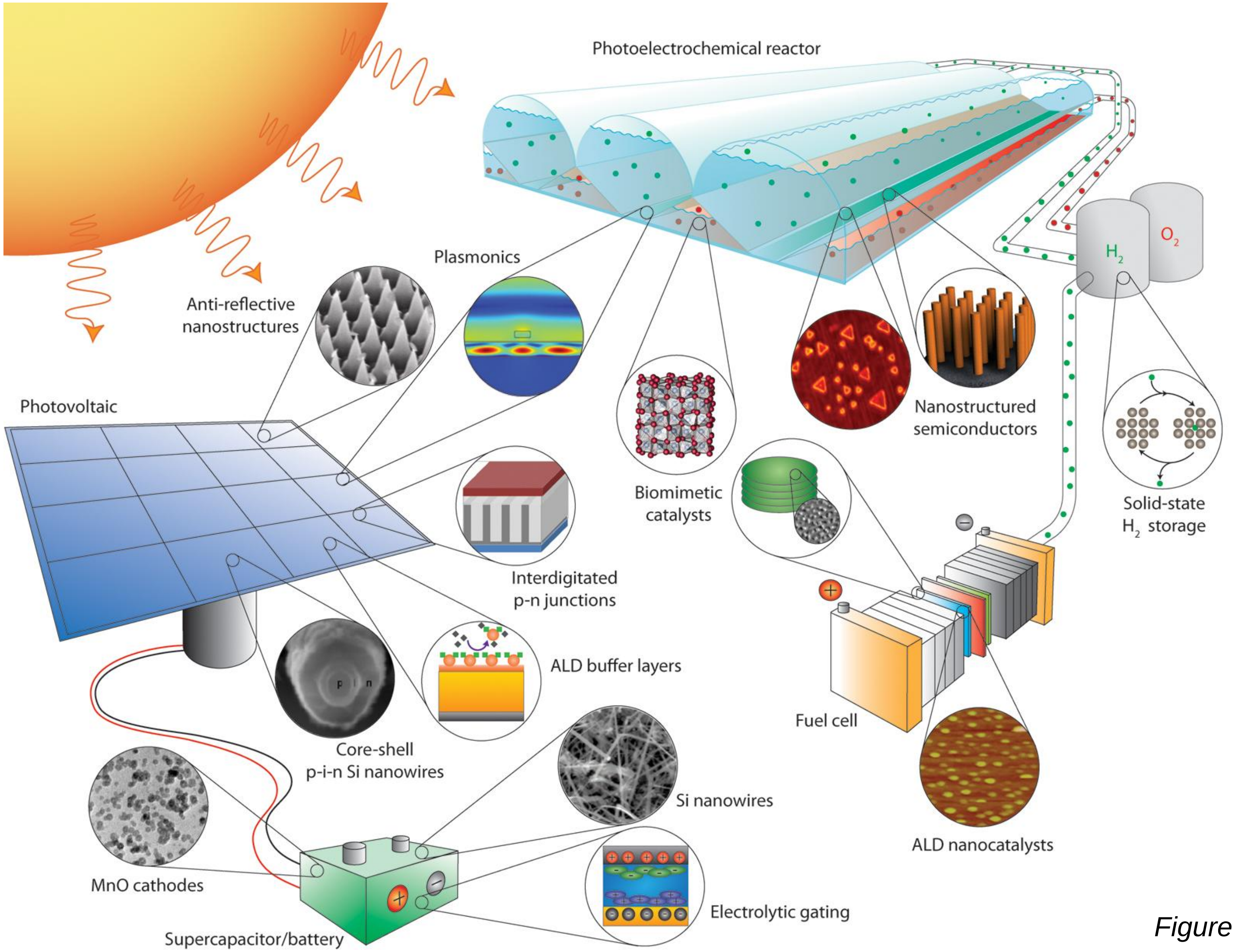


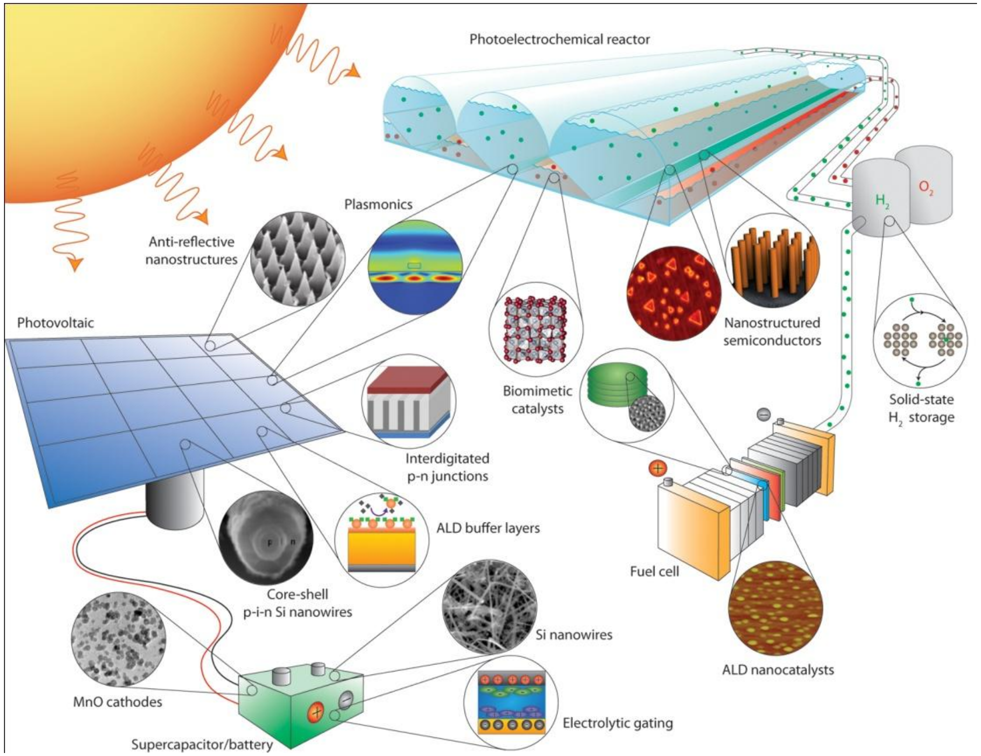
Figure by Zhebo Chen

U.S. DEPARTMENT OF ENERGY

Center on Nanostructuring for Efficient Energy Conversion (CNEEC)

Stacey Bent and Fritz Prinz (Stanford)

CNEEC seeks to understand how nanostructuring can enhance efficiency of energy conversion, and solve cross-cutting fundamental problems at the nanoscale to improve materials properties such as light absorption, charge transport, and catalytic activity. These efforts are aimed at efficient energy conversion and storage in advanced systems.



RESEARCH PLAN AND DIRECTIONS

We use nanostructuring to tune thermodynamic potentials, enhance kinetics, manage photonics, and accelerate charge transport in materials, each of which contributes to improved efficiency and performance in energy conversion.

DTU

HRL LABORATORIES

CARNEGIE INSTITUTION FOR SCIENCE

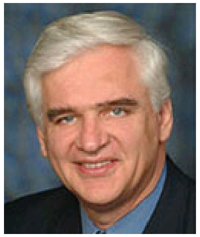
an Office of Basic Energy Sciences

Energy Frontier Research Center

The CNEEC Team of PIs

Co-Directors


Stacey Bent
(ChE)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(ME)

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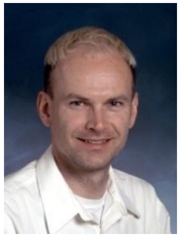
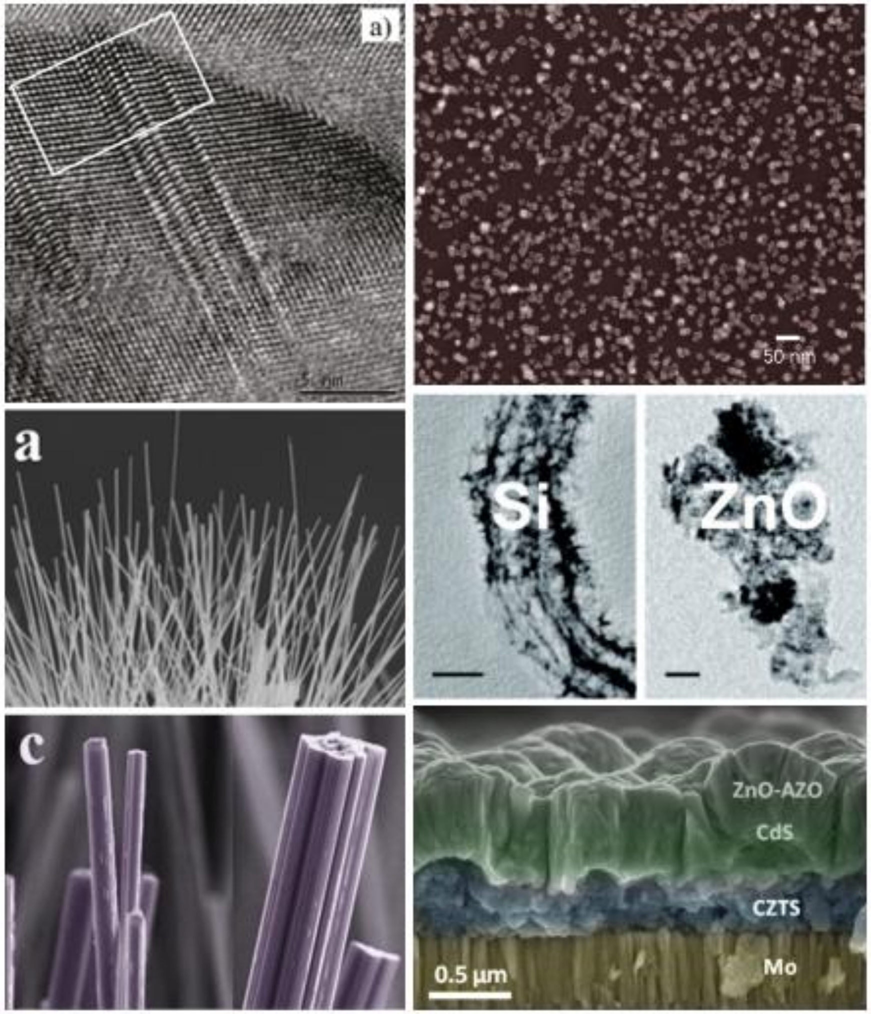

John Vajo
HRL


Arthur Grossman
Carnegie


Jen Wilcox
(ERE) SEED

Examples of Nanomaterials



Examples of nanostructures fabricated in CNEEC. Clockwise from top left: Atomic layer deposited CdS,[1] size-controlled MnO_x nanoparticles, porous Si nanowires and ZnO nanorods,[2] CZTS in a photovoltaic device structure,[3] and tungsten oxide nanostructures.[4]

[1]Bakke et al., Chem. Mater. **2010**, 22, 4669-4678; [2]Choi et al., Nano Lett. **2010,** 10, 1409-1413; [3]Wangperawong et al., Thin Solid Films **2011**, 519 2488–2492;[4]Rao et al., Proceedings of the Combustion Institute **2011**, 33, 1891–1898.

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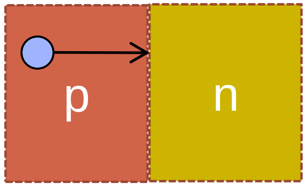
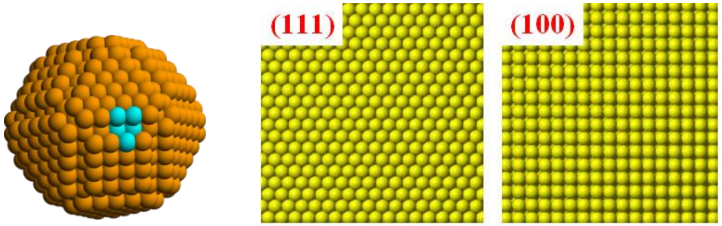
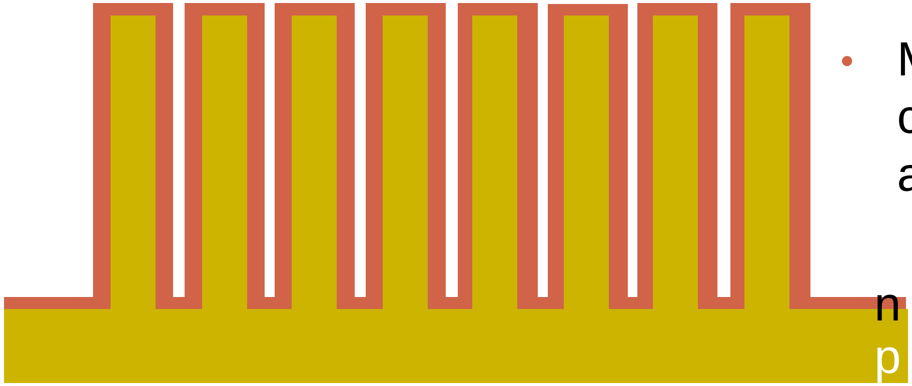


- More light may be absorbed
    - If induced by light, may get better absorption by tuning bandgap through quantum confinement
- Separation and recombination of charge may improve
    - If chemical reaction, can get more active surfaces for better reaction rates (kinetics)

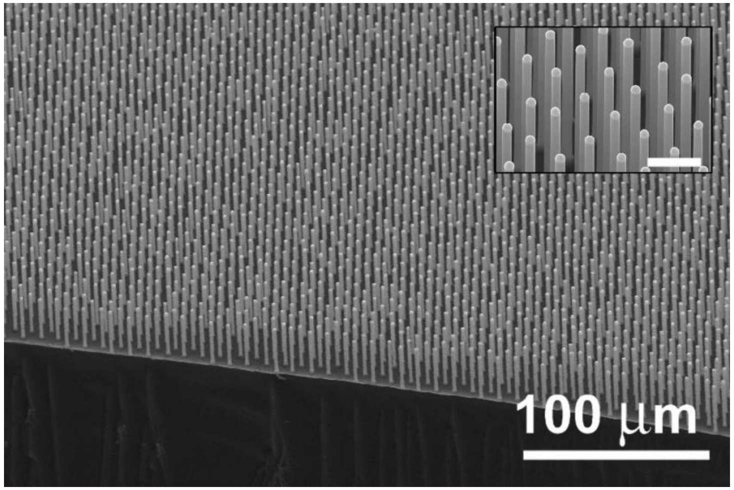


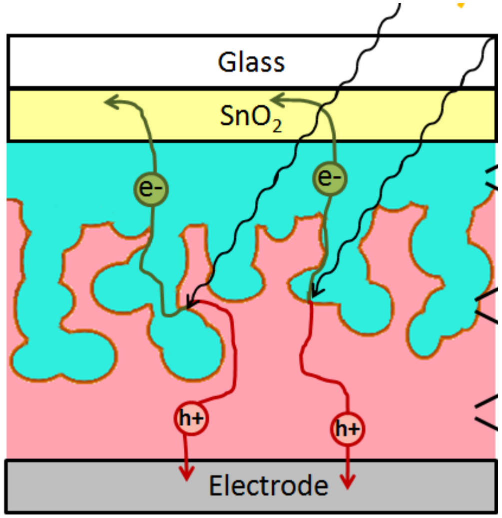
Nanostructured Architecture for PV



- Minimizes required diffusion length of charge carriers while maximizing absorption of incident photons with $E \geq E_g$

Array of Si nanowires
Kayes et al., Appl. Phys. Lett. 91, 103110 (2007)



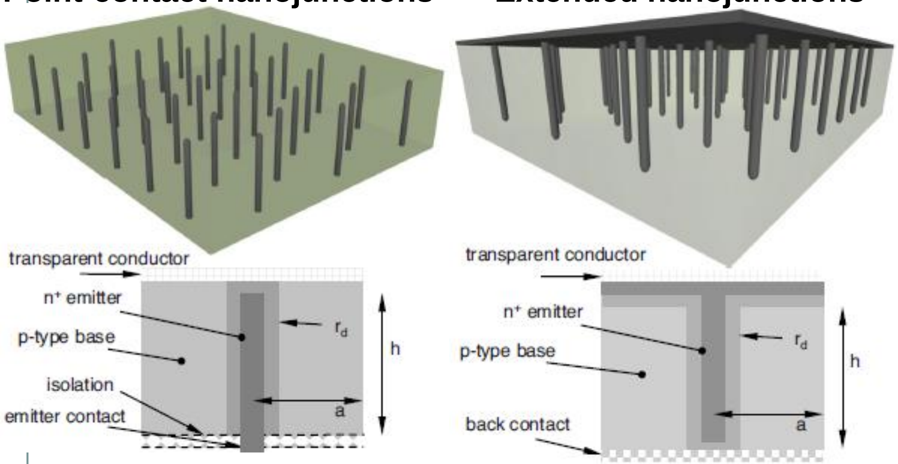


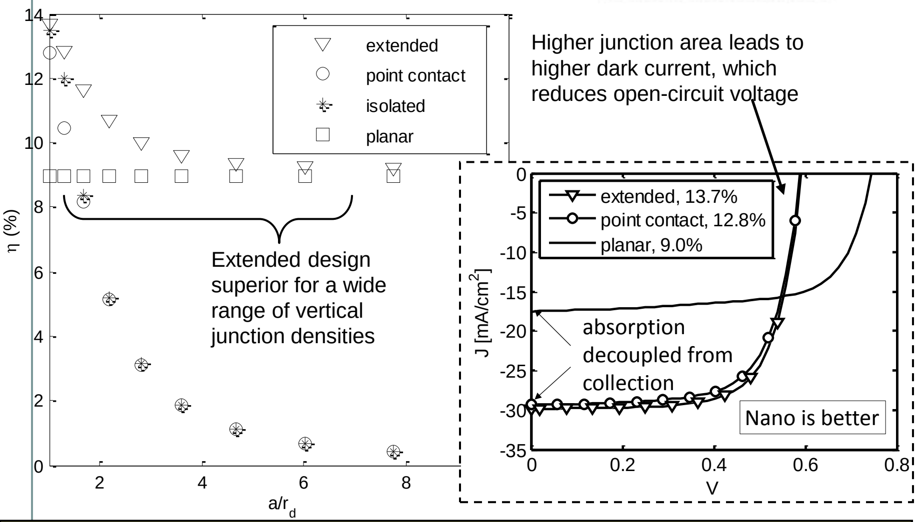
Dye sensitized solar cell

3D Nanojunction Designs to Enhance Efficiency of Solar Cells Using Low-Cost Materials

Artit Wangperawong and Stacey F. Bent, Depts. of Electrical and Chemical Engineering, Stanford Univ.

Point-contact nanojunctions **Extended nanojunctions**





Higher junction area leads to higher dark current, which reduces open-circuit voltage

Extended design superior for a wide range of vertical junction densities

absorption decoupled from collection

Nano is better

A. Wangperawong and S. F. Bent, Appl. Phys. Lett. 98, 1 (2011)

✓***Achievement*:**

We have developed a new analytical approach that describes the device performance of nanostructured solar cells in three dimensions, distinguishing between isolated and interdigitated nanojunctions.

Both designs at left incorporate vertical nanojunctions in order to decouple light absorption from charge carrier collection.

For the data plots below, material properties of inexpensive, low-quality CdTe are incorporated into the model. The higher surface area from nanostructuring reduces the cell's maximum possible voltage, but the increase in current from superior charge collection provides an overall net benefit in energy conversion efficiency.

✓ ***Significance*:**

Our achievements here provide a powerful tool to design nanostructured solar cells that can be both efficient and cheap.

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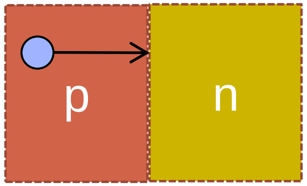

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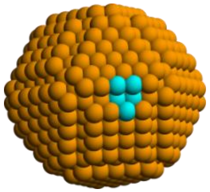
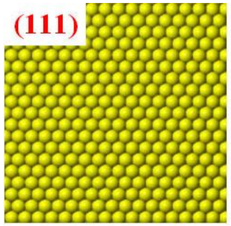
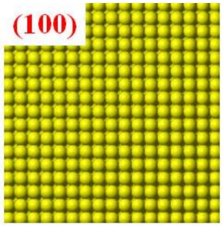
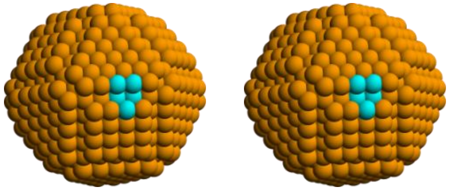






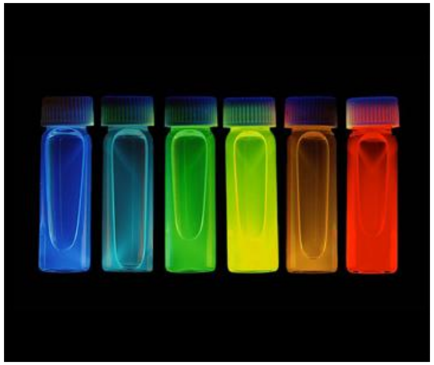
Quantum Dots



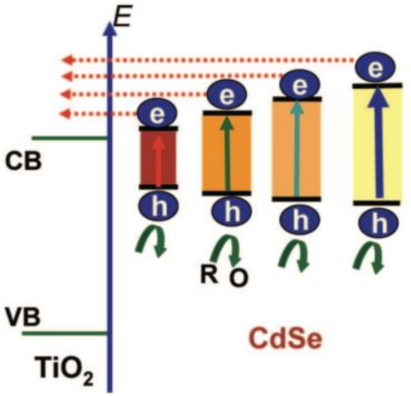
Semiconductor particles a few nanometers in size

Benefits to quantum dots:

- Size quantization effect
  - band gap is tunable by the size of the QD
  - Their absorption spectrum can be tailored by changing their size
- Stability (inorganic)
- Multiple exciton generation (MEG) from a single incident photon
  - *Nozik, A. J., Inorg. Chem., 2005 (44), 6893*
- Solution processable



nanoe.ece.drexel.edu



Kamat, P. J. Phys. Chem. C, 2008, 112 (48), 18737

CdS Quantum Dots by ALD

Photo credit: L.A. Cicero

Increasing size of the quantum dots (ALD cycles)

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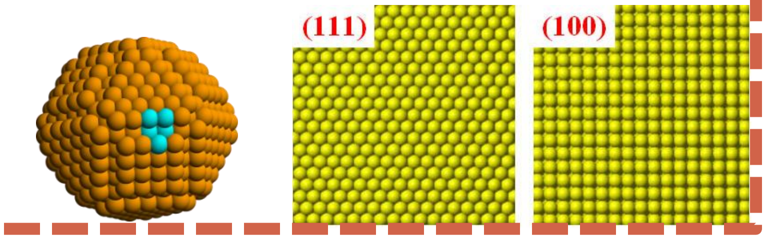
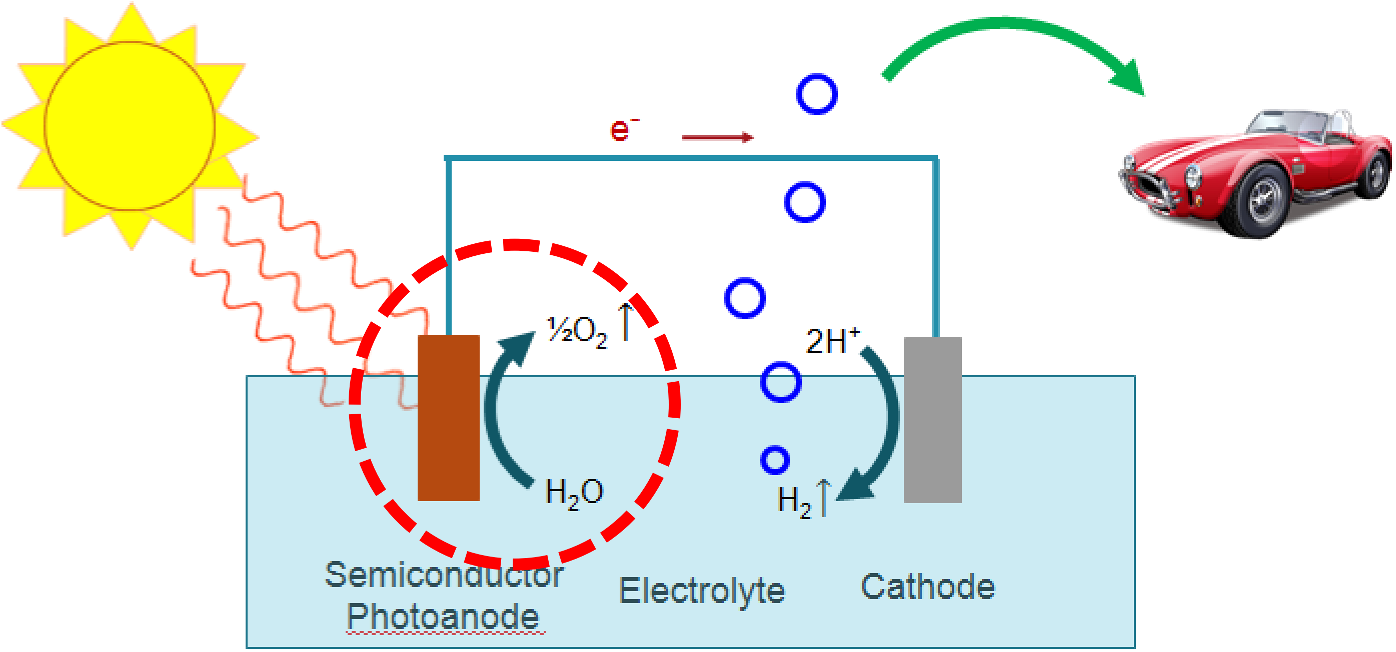


Photoelectrochemical Splitting of Water

- Can we fabricate improved photoelectrocatalysts for the splitting of water by using nanoscale materials?

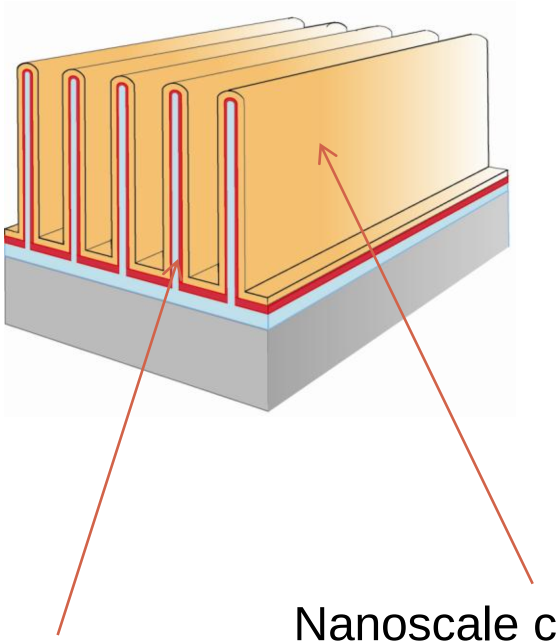
$$H_2O \longrightarrow H_2 + ½\,O_2$$



- Challenge: the material must absorb solar light (semiconductor), catalyze the reaction at its surface, and remain stable

Possible Nanoscaled PEC Geometry

- Propose to nanostructure semiconducting light absorber to decouple material requirements
- Best catalysts for OER are IrO_2 and RuO_2
- MnO_x good candidate
  - Cheap and abundant
  - Low overpotential
  - Activity dependent on phase and preparation

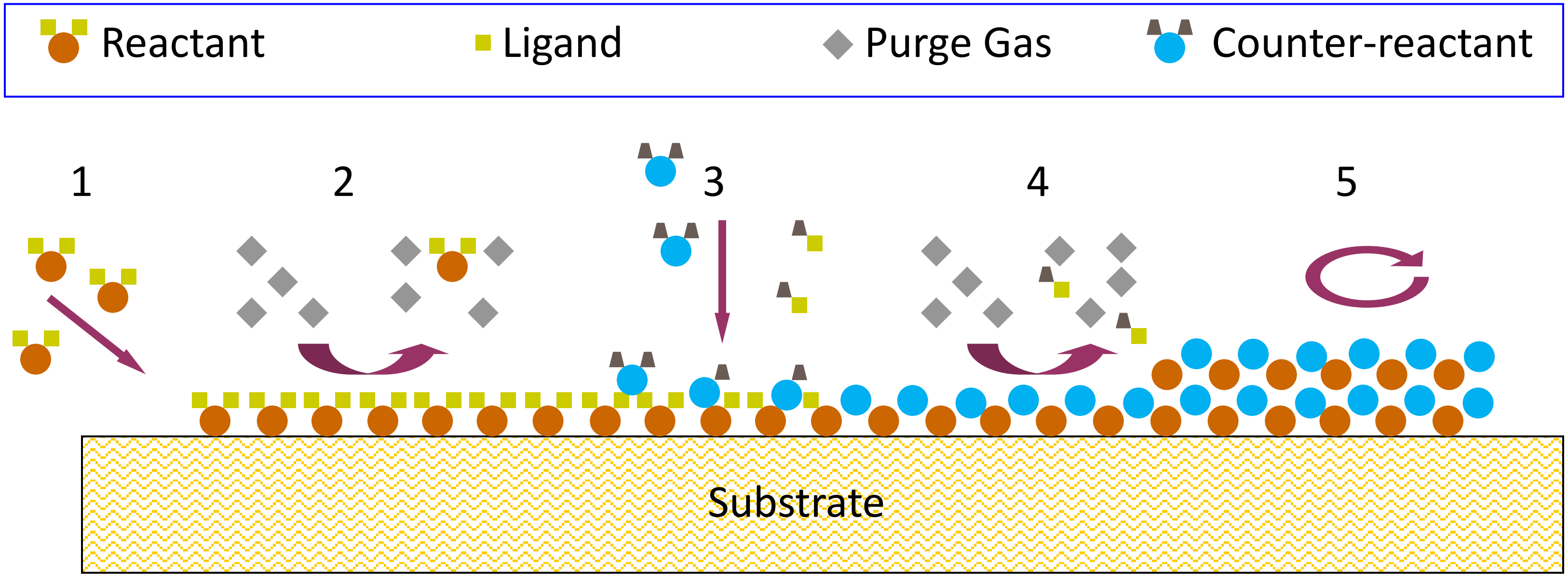


Nanostructured semiconductor for light absorption, high surface area

Nanoscale coating for stability and catalysis

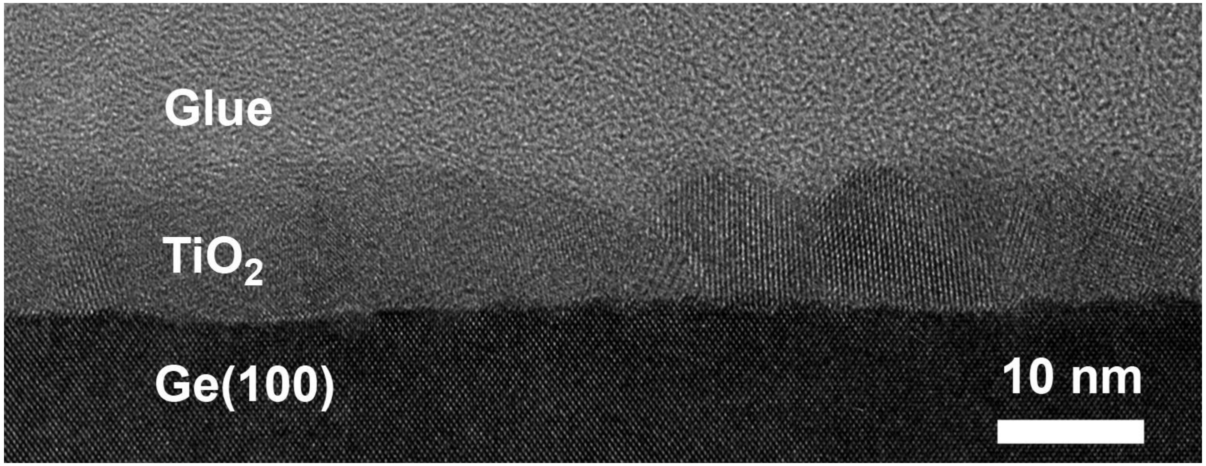
Atomic Layer Deposition (ALD)

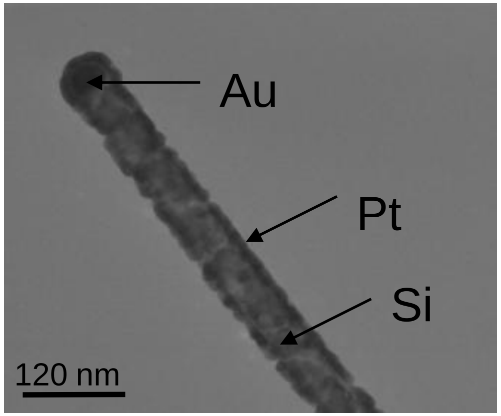
1) Pulse reactant into the reactor
2) Purge to remove excess reactant
3) Pulse counter-reactant
4) Purge to remove products/excess counter-reactant
5) Repeat 1-4 as many times as desired



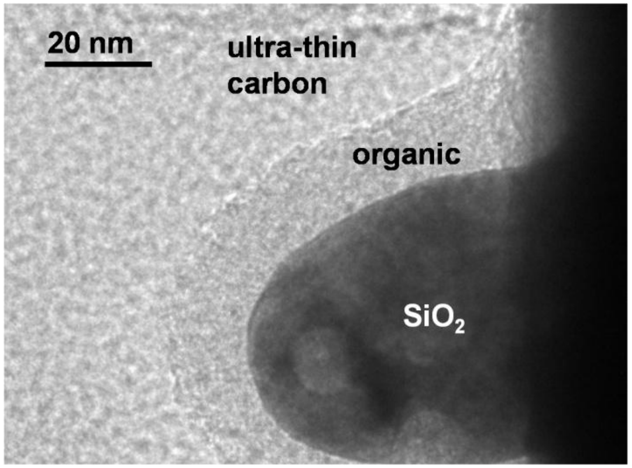
Atomic Layer Deposition

Excellent thickness control and conformality





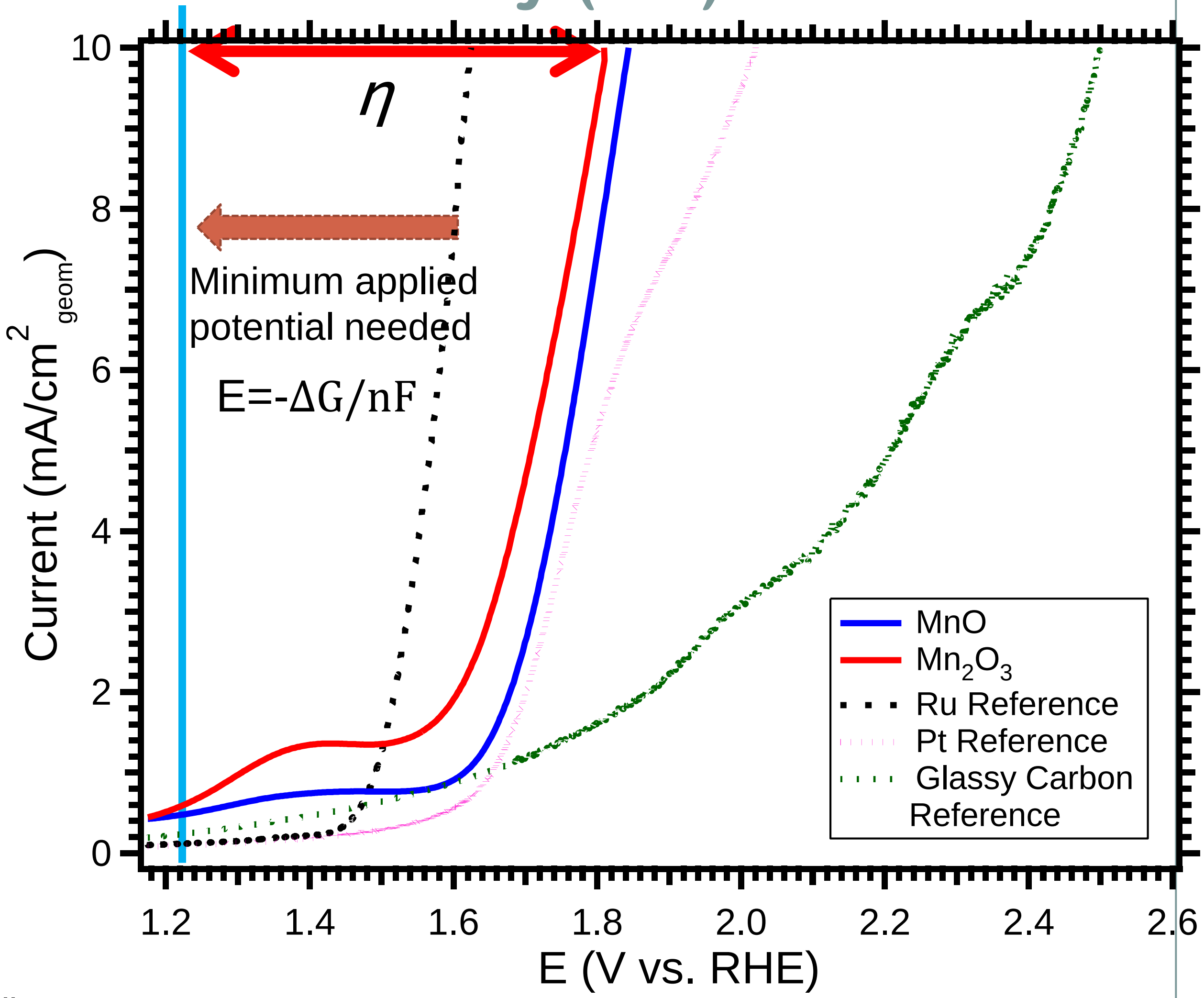
With Candace Chan and Yi Cui



Testing MnO_x as a OER Catalyst
Cyclic Voltammetry (CV)

Used a rotating disk electrode (RDE) configuration:

- Scan rate : 20 mV/s
- 0.1 M KOH electrolyte O_2 saturated
- Rotation Speed : 1600 rpm
- Room temperature
- Hg/HgO reference electrode
- Platinum wire counter-electrode



With Yelena Gorlin and Tom Jaramillo

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- Yesheng Yee
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- Dr. Han-Bo-Ram Lee
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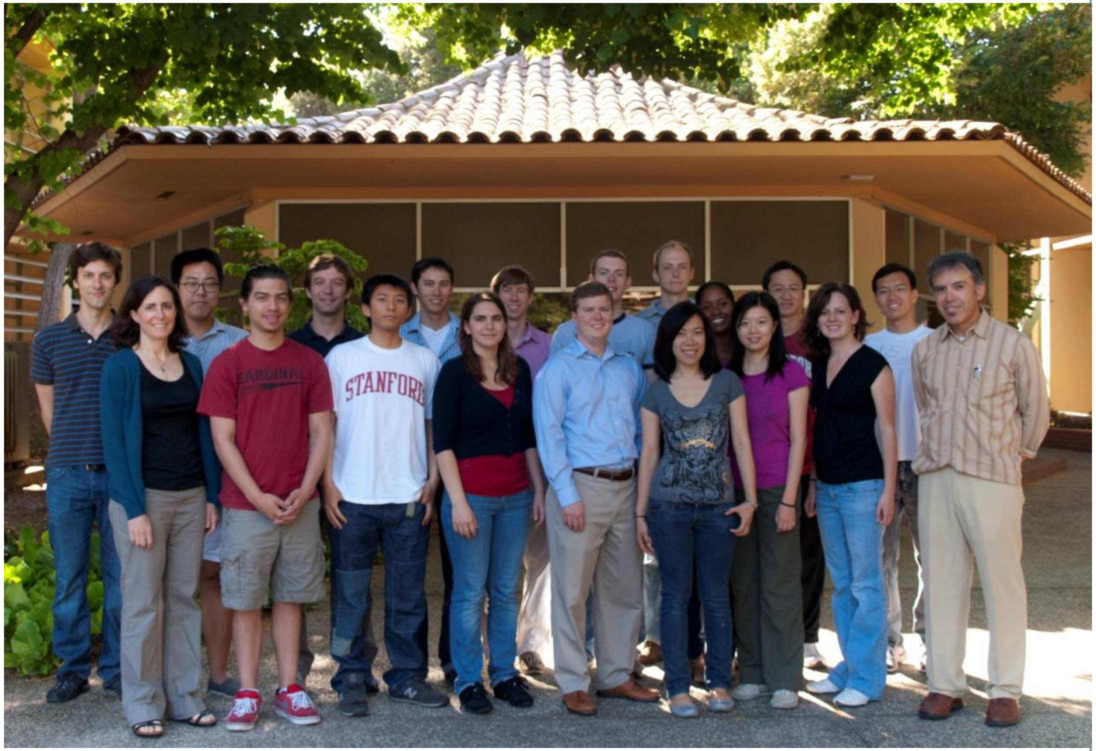
- Dr. Scott Geyer
- Dr. Jon Servaites
- Thomas Joseph
- Weikang Sun



- Center on Nanostructuring for Efficient Energy Conversion (CNEEC), an Energy Frontier Research Center, US Department of Energy, Office of Basic Energy Sciences

Website: http://cneec.stanford.edu