Nanoscale Materials for Sustainable Energy

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One vision for a sustainable energy future

by Zhebo Chen

http://cneec.stanford.edu
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

![Diagram of p-type and n-type semiconductors showing separation and recombination of charge carriers](image-url)
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

\[
\begin{align*}
\text{Anode: } & \quad H_2 \rightarrow 2H^+ + 2 e^- \\
\text{Electrolyte: } & \quad 2H^+ + \frac{1}{2} O_2 + 2 e^- \rightarrow H_2O \\
\text{Cathode: } & \quad e^- \rightarrow
\end{align*}
\]
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)
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Figure by Zhebo Chen

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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.
The CNEEC Team of PIs

Co-Directors

Stacey Bent (ChE)
Fritz Prinz (ME)
Turgut Gür (MSE)

DOE-EFRC Center on Nanostructuring for Efficient Energy Conversion
Examples of Nanomaterials

Examples of nanostructures fabricated in CNEEC. Clockwise from top left: Atomic layer deposited CdS, size-controlled MnO$_x$ nanoparticles, porous Si nanowires and ZnO nanorods, CZTS in a photovoltaic device structure, and tungsten oxide nanostructures.

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  ![p n](image1)

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![p n](image2)
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

Dye sensitized solar cell
3D Nanojunction Designs to Enhance Efficiency of Solar Cells Using Low-Cost Materials


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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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

- Solution processable

CdS Quantum Dots by ALD

Increasing size of the quantum dots (ALD cycles)

Photo credit: L.A. Cicero
How can we improve this process?

Answer: **Make things smaller**

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  - ![Diagram showing p and n types of semiconductor materials](image)

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

\[ \text{H}_2\text{O} \rightarrow \text{H}_2 + \frac{1}{2} \text{O}_2 \]

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

Minimum applied potential needed:
\[ E = -\Delta G / nF \]

Current (mA/cm\(^2\) geom)

E (V vs. RHE)

With Yelena Gorlin and Tom Jaramillo
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Website: http://cneec.stanford.edu