Energy Tutorial:
Solar Energy 101

GCEP RESEARCH SYMPOSIUM 2010 | STANFORD, CA

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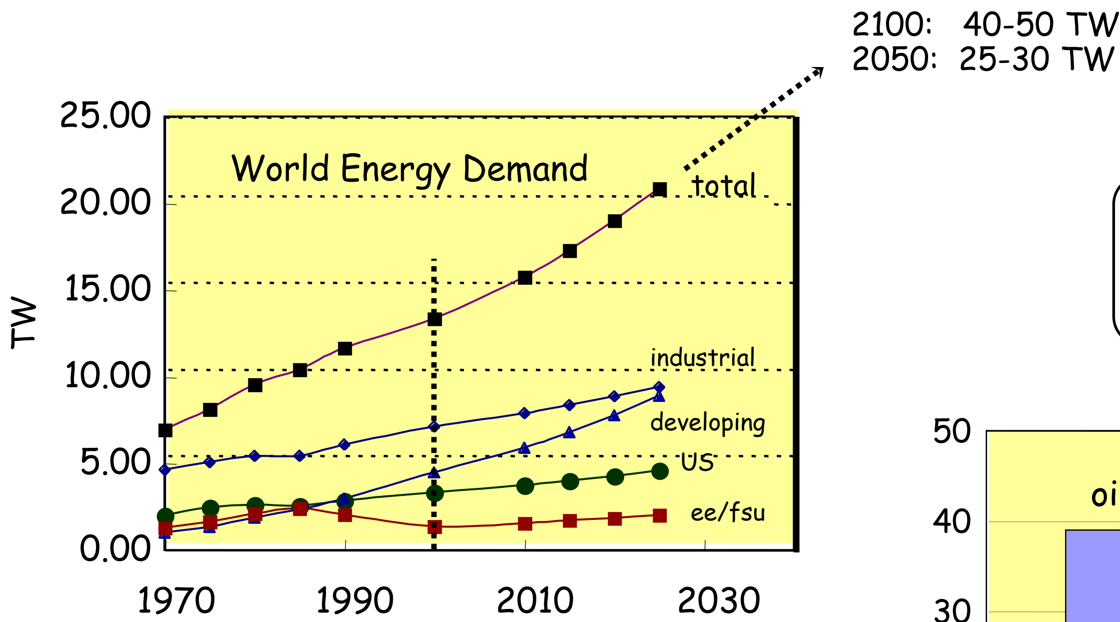
Basic Research Needs for Solar Energy

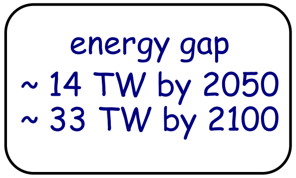
- ***The Sun is a singular solution to our future energy needs***
  - capacity dwarfs fossil, nuclear, wind . . .
  - sunlight delivers more energy in one hour than the earth uses in one year
  - free of greenhouse gases and pollutants
  - secure from geo-political constraints

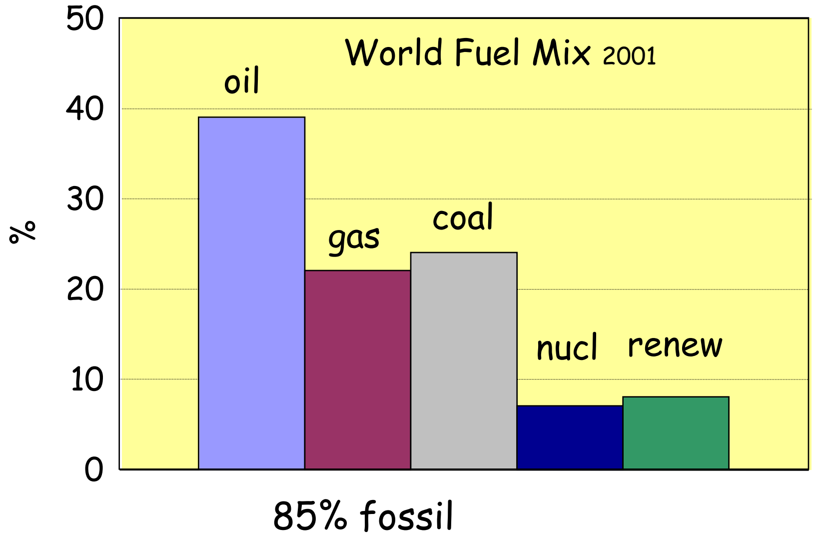
- ***Enormous gap between our tiny use of solar energy and its immense potential***
  - Incremental advances in today's technology will not bridge the gap
  - Conceptual breakthroughs are needed that come only from high risk-high payoff basic research

- ***Interdisciplinary research is required***
  physics, chemistry, biology, materials, nanoscience
- ***Basic and applied science should couple seamlessly***

World Energy Demand







EIA Intl Energy Outlook 2004
http://www.eia.doe.gov/oiaf/ieo/index.html

Hoffert et al Nature 395, 883,1998

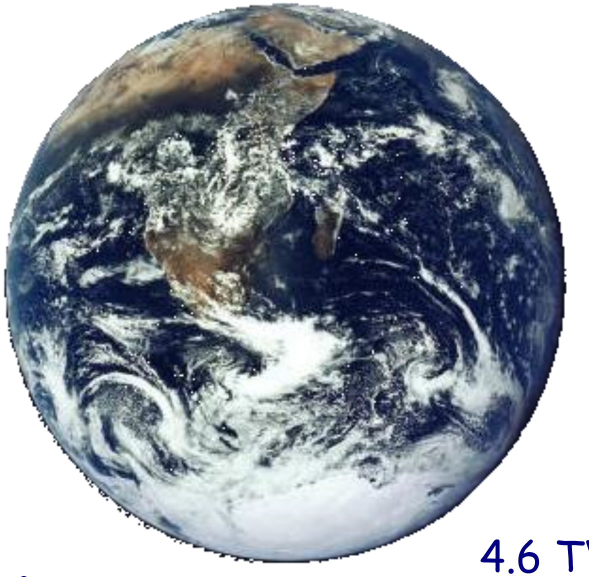
Renewable Energy

Solar
1.2×10^5 TW at Earth surface
600 TW practical

energy gap
~ 14 TW by 2050
~ 33 TW by 2100

Wind
2-4 TW extractable

Biomass
5-7 TW gross
all cultivatable
land not used
for food



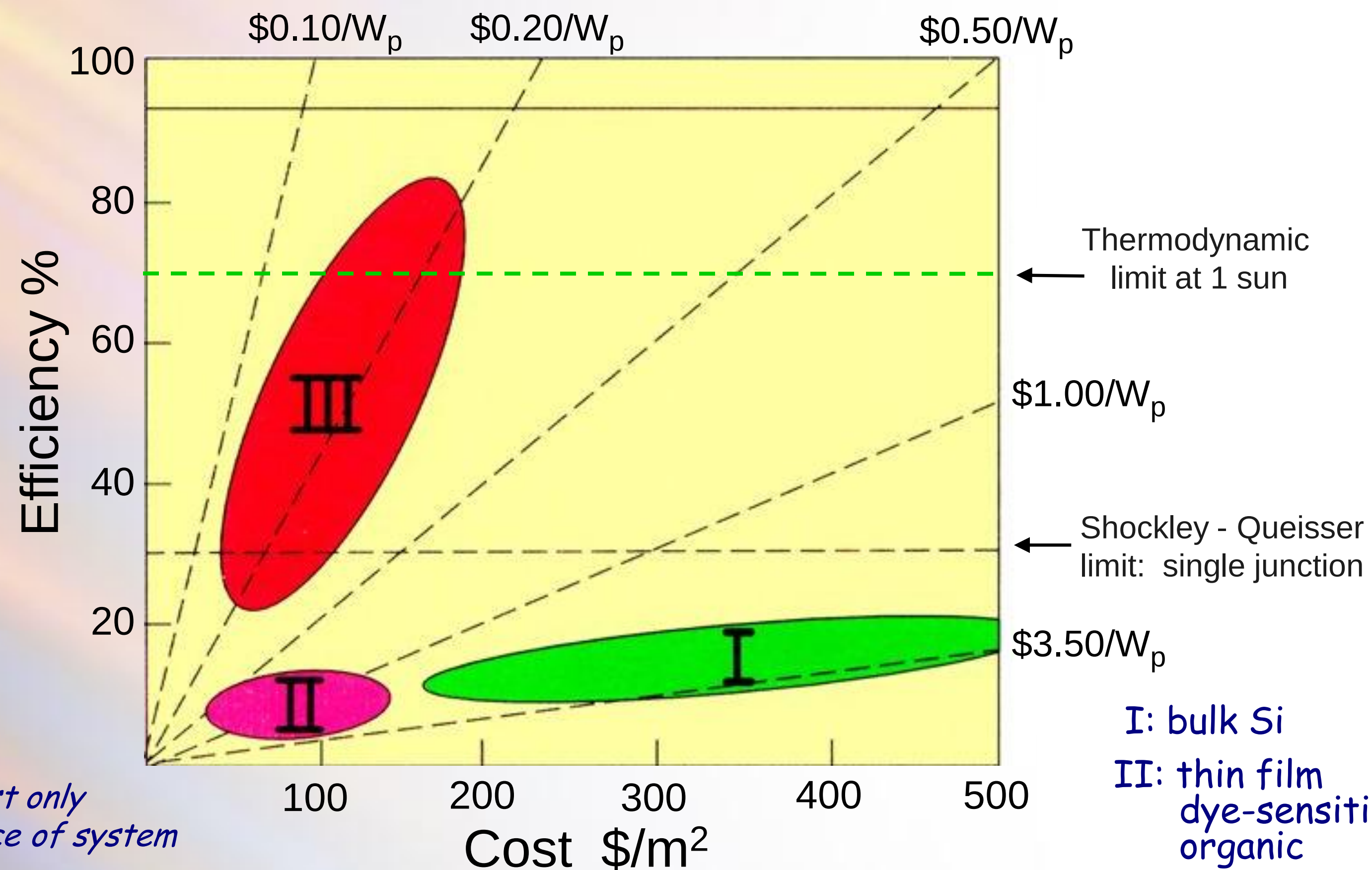
Tide/Ocean Currents
2 TW gross

Hydroelectric
4.6 TW gross
1.6 TW technically feasible
0.9 TW economically feasible
0.6 TW installed capacity

Geothermal
12 TW gross over land
small fraction recoverable

Solar Land Area Requirements

Cost of Solar Electric Power

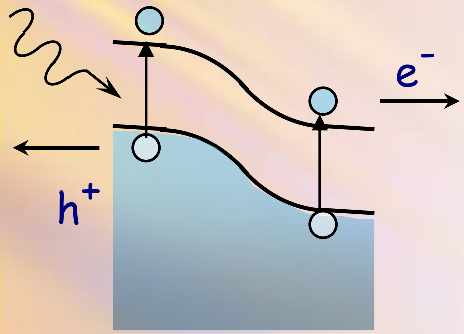


module cost only
double for balance of system

I: bulk Si
II: thin film
dye-sensitized
organic
III: next generation

competitive electric power: \$0.40/W$_p$ = \$0.02/kWh
competitive primary power: \$0.20/W$_p$ = \$0.01/kWh
assuming no cost for storage

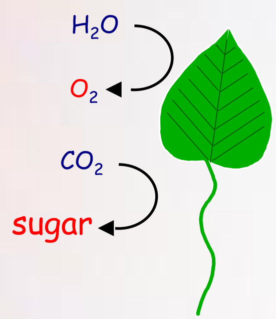
Solar Energy Utilization



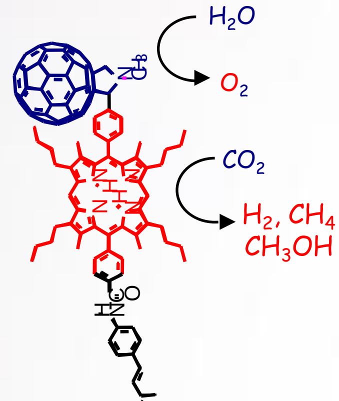
Solar Electric

.001 TW PV
\$0.20/kWh w/o storage

1.5 TW electricity
\$0.03-\$0.06/kWh (fossil)



natural
photosynthesis



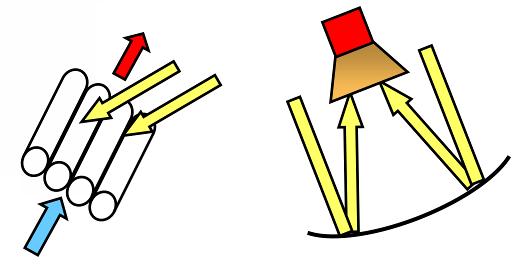
artificial
photosynthesis

Solar Fuel

1.4 TW solar fuel (biomass)

11 TW fossil fuel
(present use)

~ 14 TW additional energy by 2050



50 - 200 °C
space, water
heating

500 - 3000 °C
heat engines
electricity generation
process heat

Solar Thermal

0.002 TW

2 TW
space and water
heating

Report of the Basic Energy Sciences Workshop on Solar Energy Utilization

Solar Energy Challenges

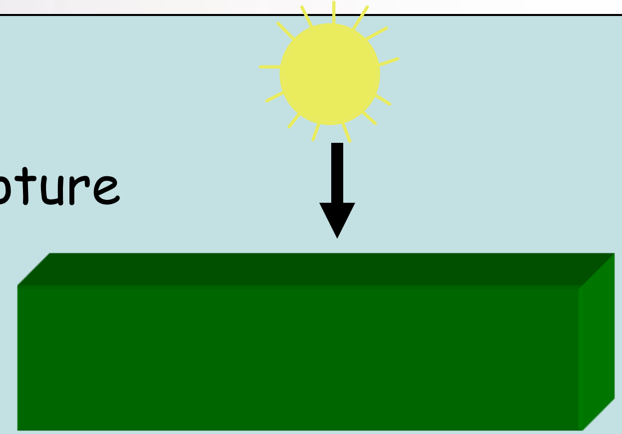
- Solar electric
- Solar fuels
- Solar thermal
- Cross-cutting research

Solar Electric

- Despite 30-40% growth rate in installation, photovoltaics generate
  - *less* than 0.1% of our electricity
  - *less* than 0.01% of total energy
- Decrease *cost*/watt by a factor 10 - 25 to be competitive with fossil electricity (without storage)
- Find effective method for *storage* of photovoltaic-generated electricity

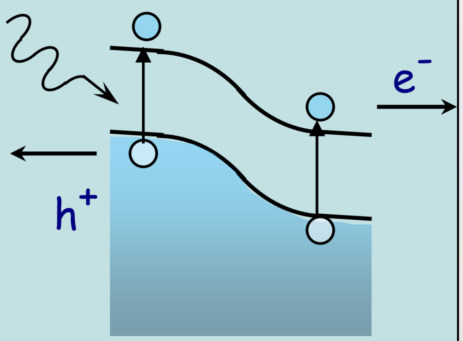
Solar Energy Conversion

Capture

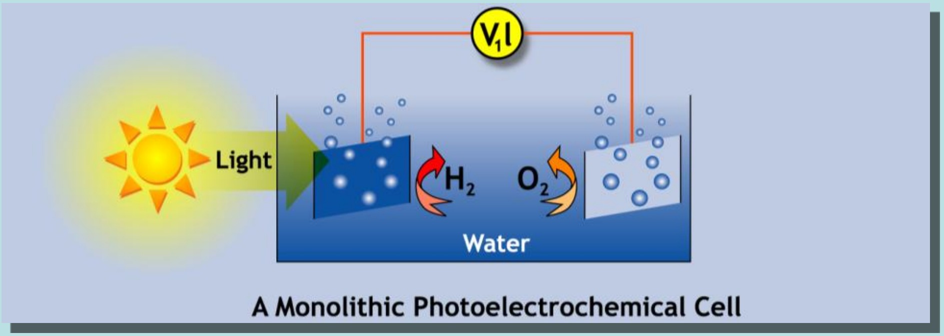


100 nm-100 μm

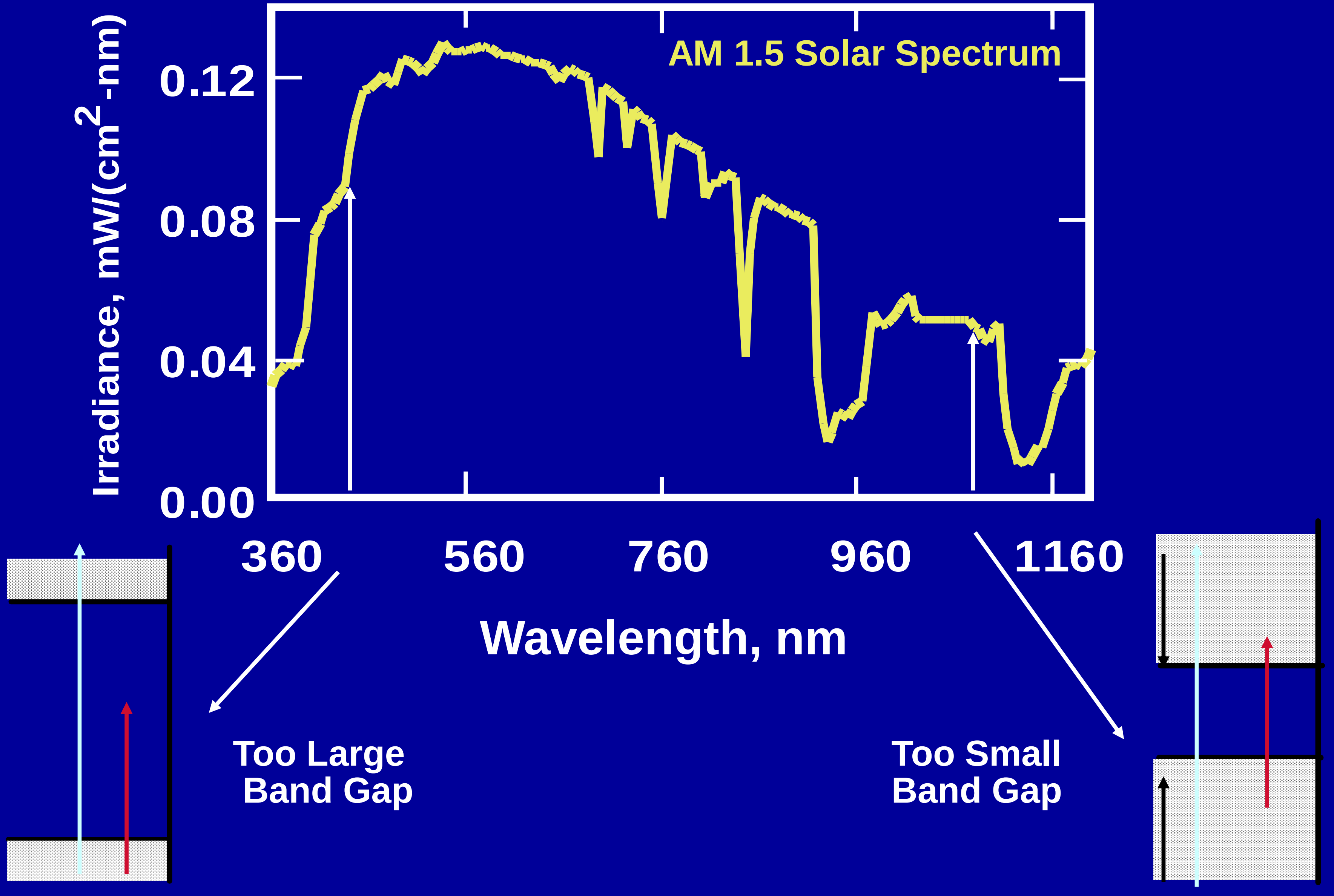
Conversion



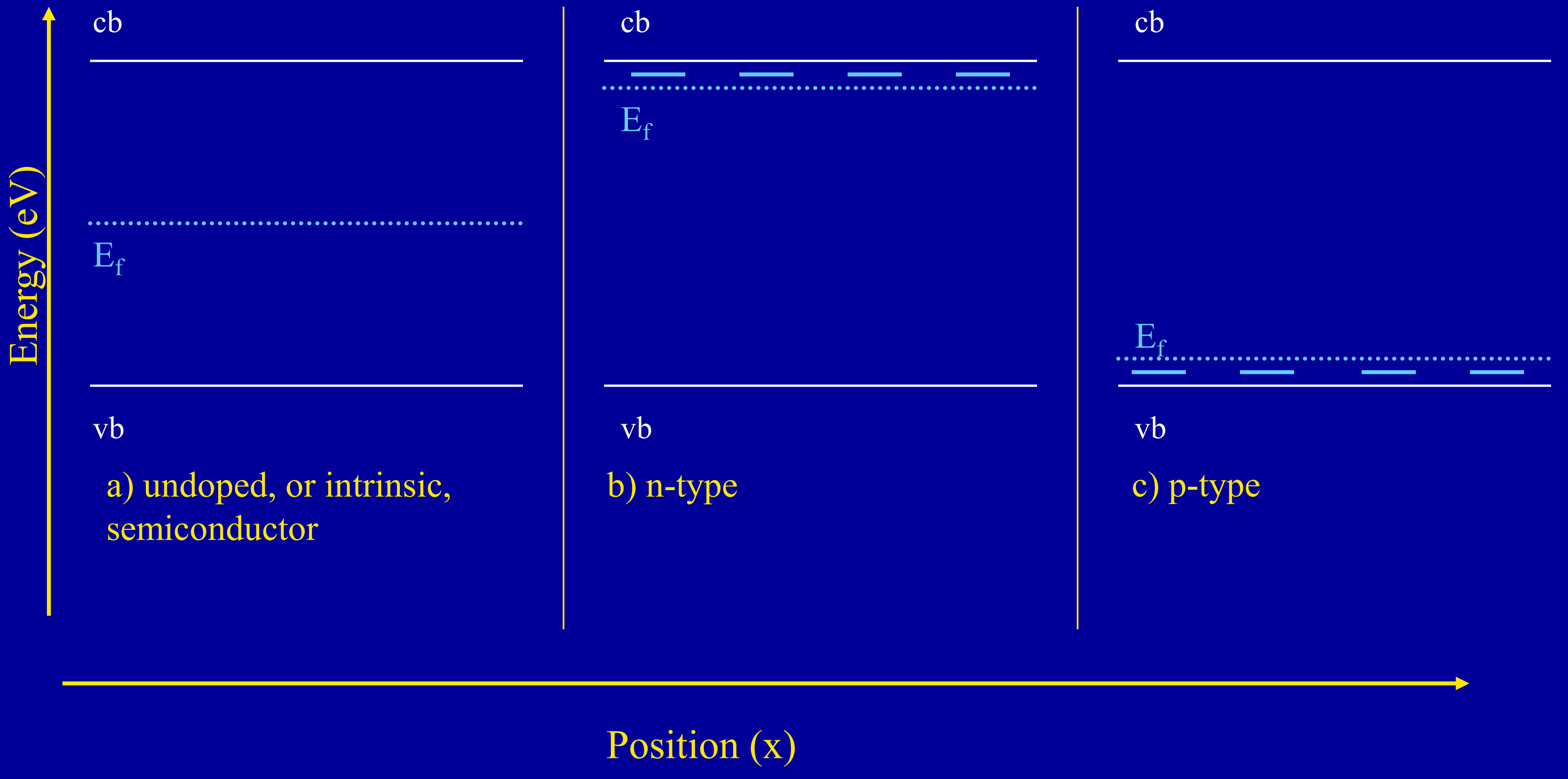
Storage



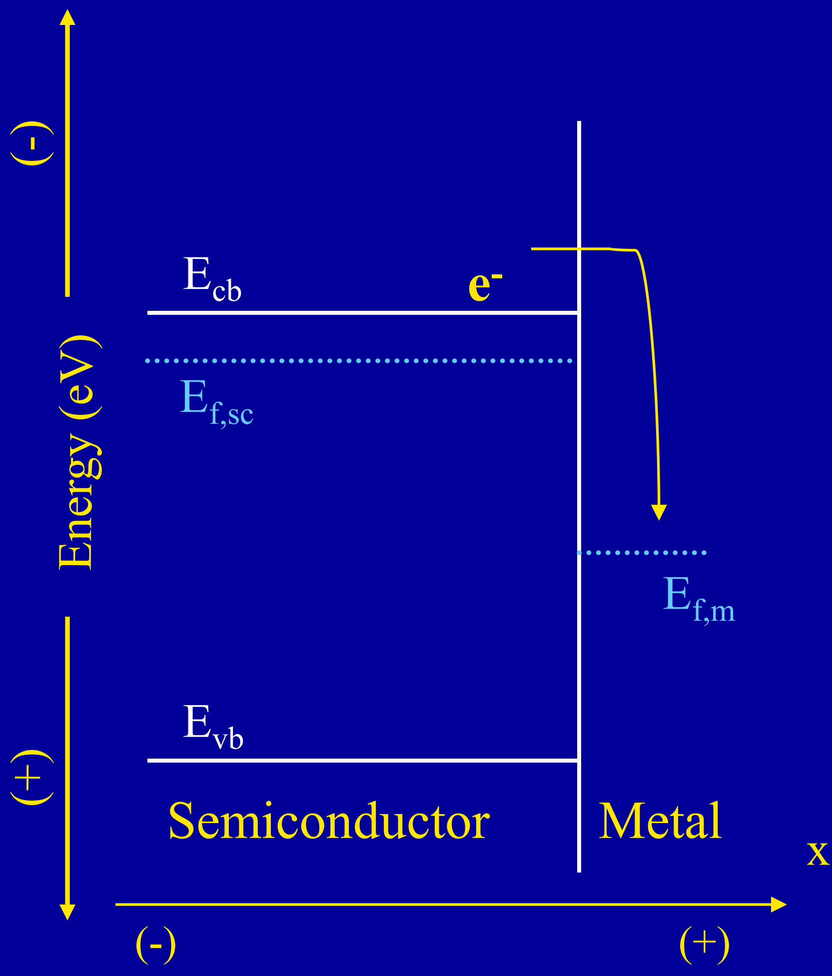
Optimum Absorption Threshold

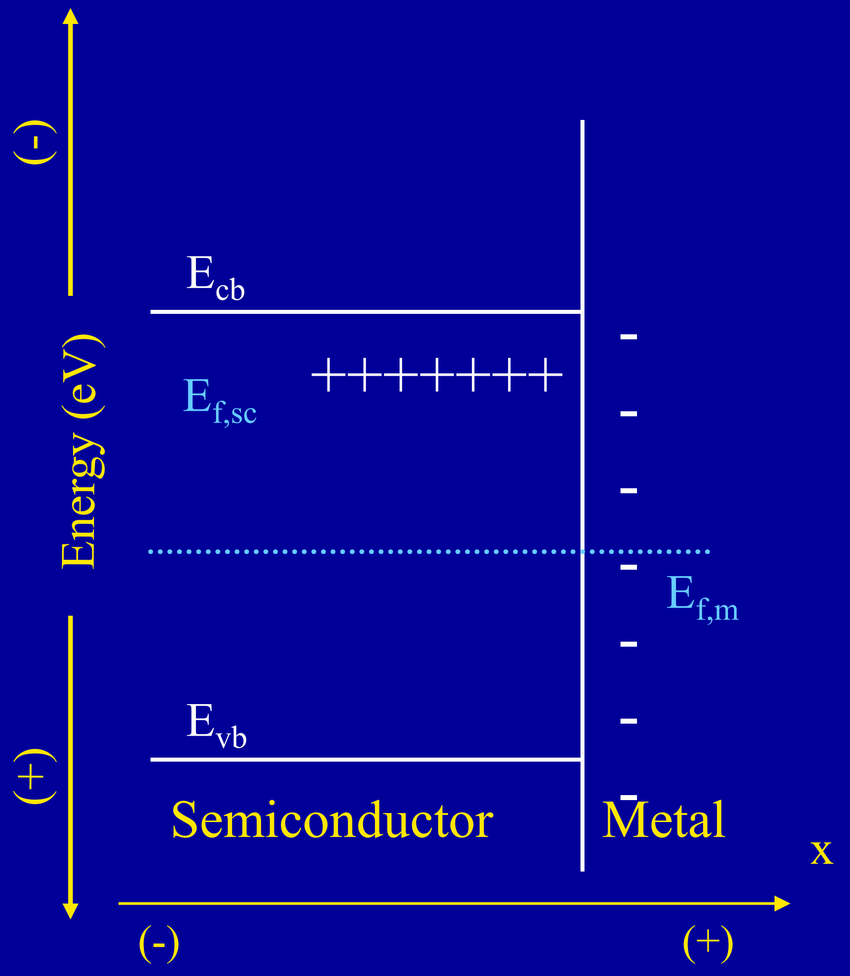


Semiconductor Doping

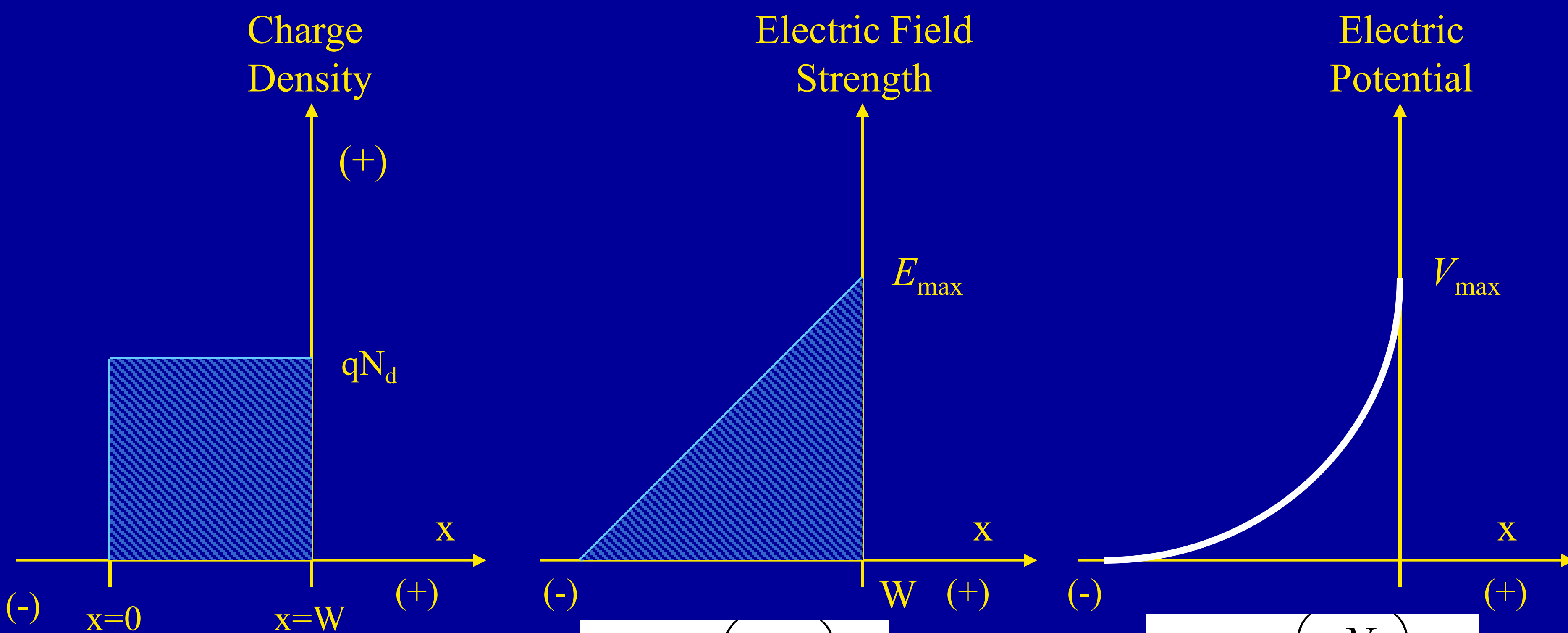


Band Bending at SC/Metal Junctions





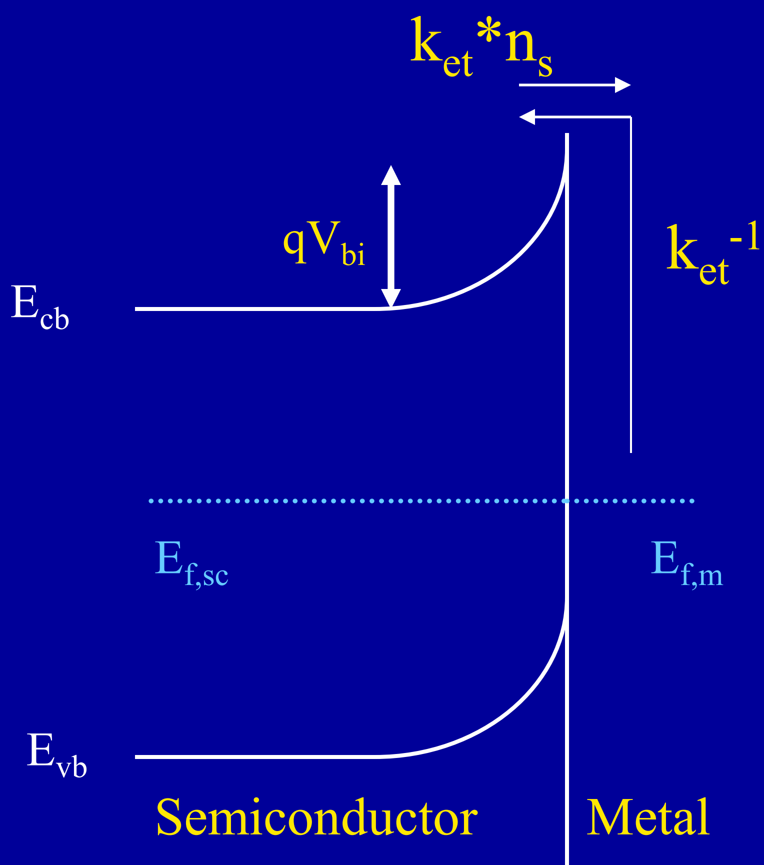
The Depletion Region



$$E_{max} = \left(\frac{qN_d}{\varepsilon_s}\right)W$$

$$\left|V_{max}\right| = \left(\frac{qN_d}{2\varepsilon_s}\right)W^2$$

Thermionic Emission



Thus, always

$$-dn/dt = k_{et}*n_s - k_{et}^{-1}$$

Rewrite it as:

$$-dn/dt = k_{et}(n_s - n_{so})$$

Now relate flux to current density:

$$J = -q(-dn/dt) = -q\, k_{et}(n_s - n_{so}) =$$
$$-qk_e n_{so}\,(n_s/n_{so} - 1)$$

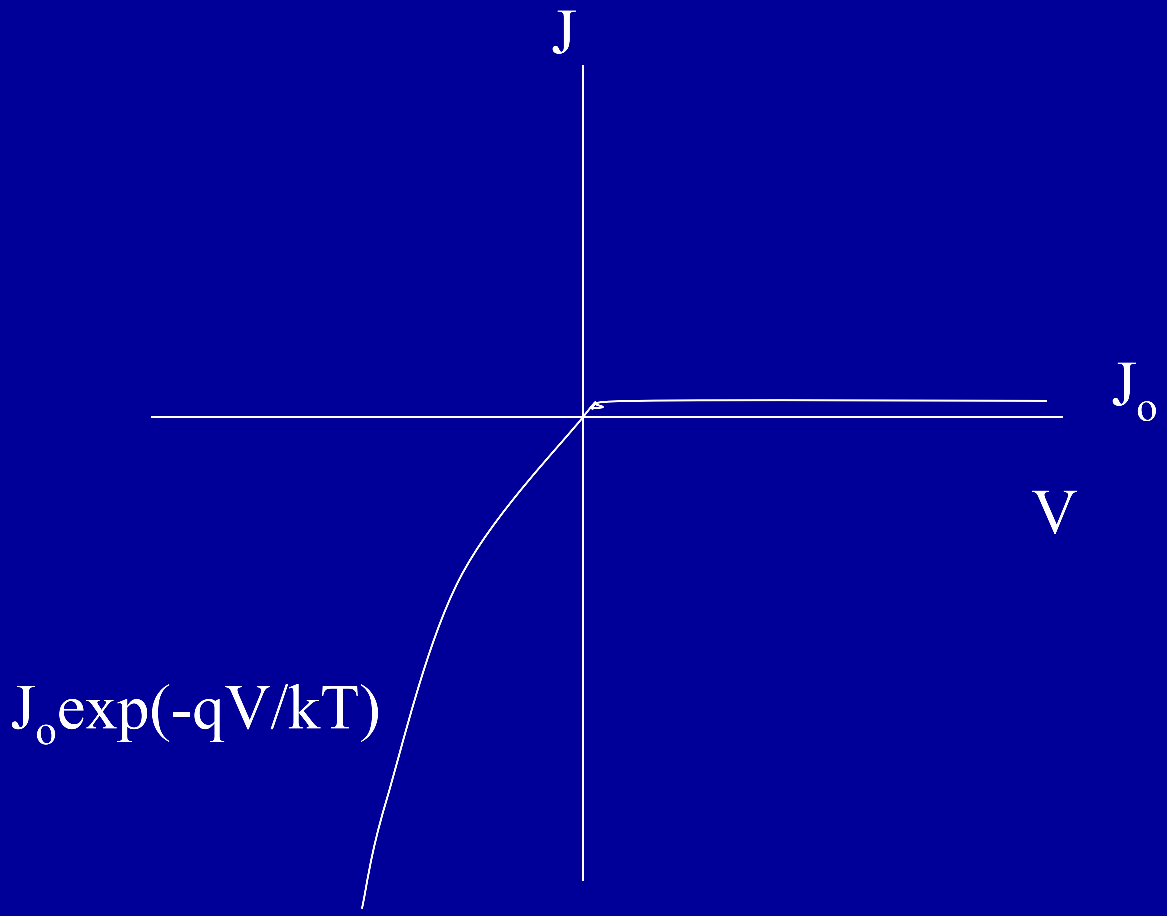
By substituting for n_s/n_{so}, we obtain:

$$J = -qk_{et}n_{so}[\exp\left(\frac{-qV}{kT}\right) - 1] = -J_o[\exp\left(\frac{-qV}{kT}\right) - 1]$$

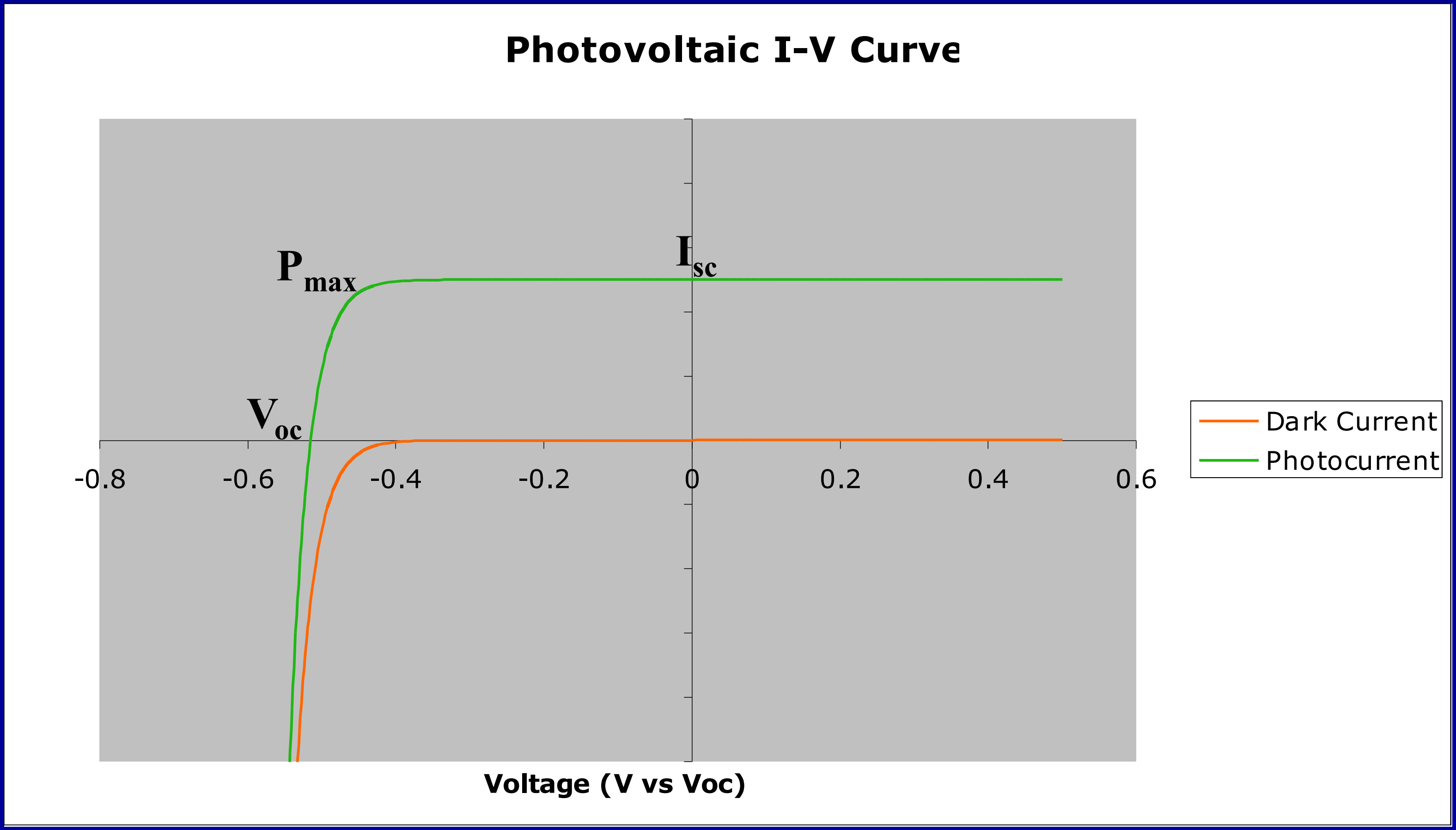
The Dark Current

The current given by the equation:

$$J = -J_o[\exp\left(\frac{-qV}{kT}\right) - 1]$$



I-V Curves



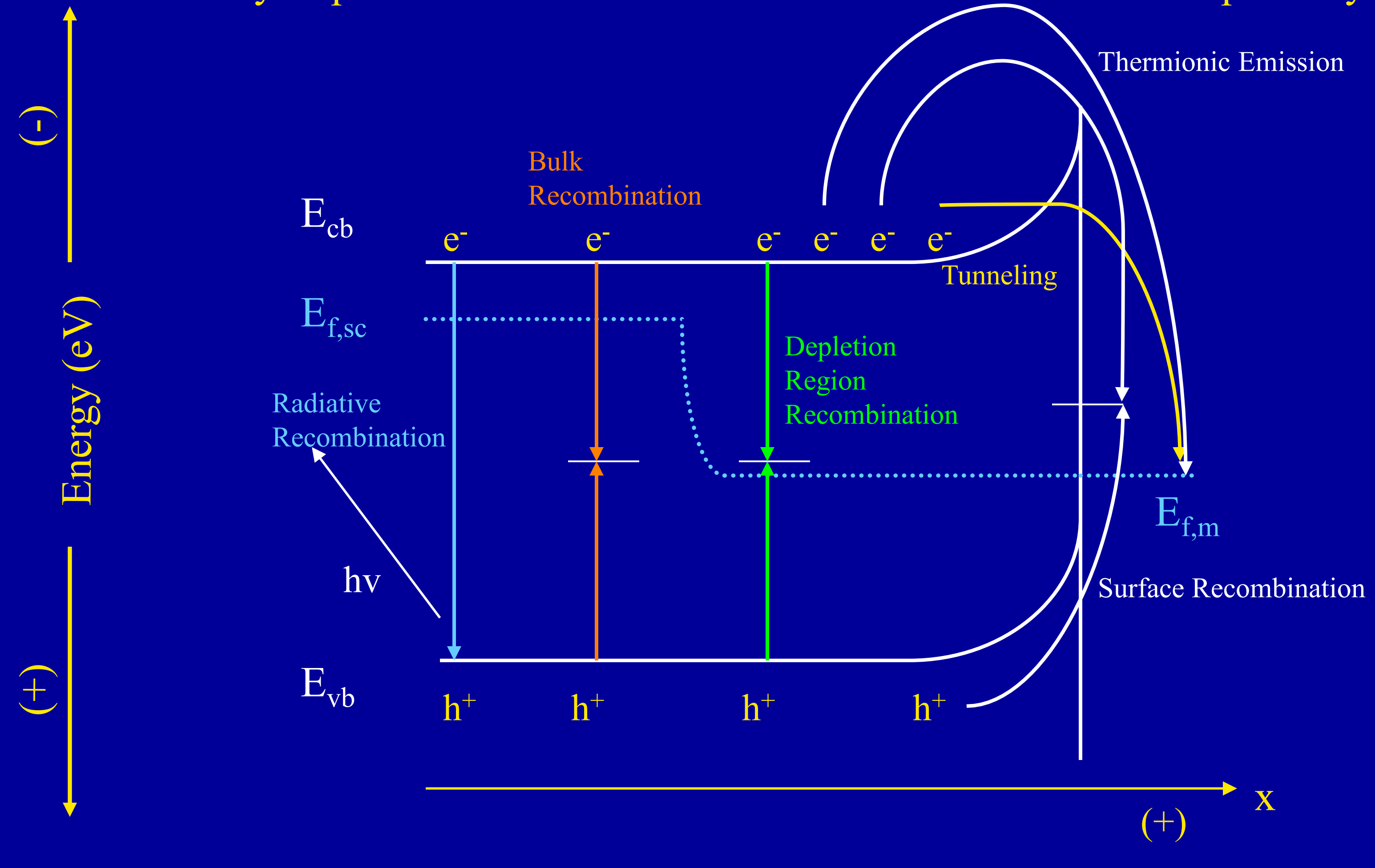
V_{oc}: Open circuit voltage, the voltage when no current flows. $J_{ph} = -J_0$

I_{sc}: Short circuit current, current where V = 0

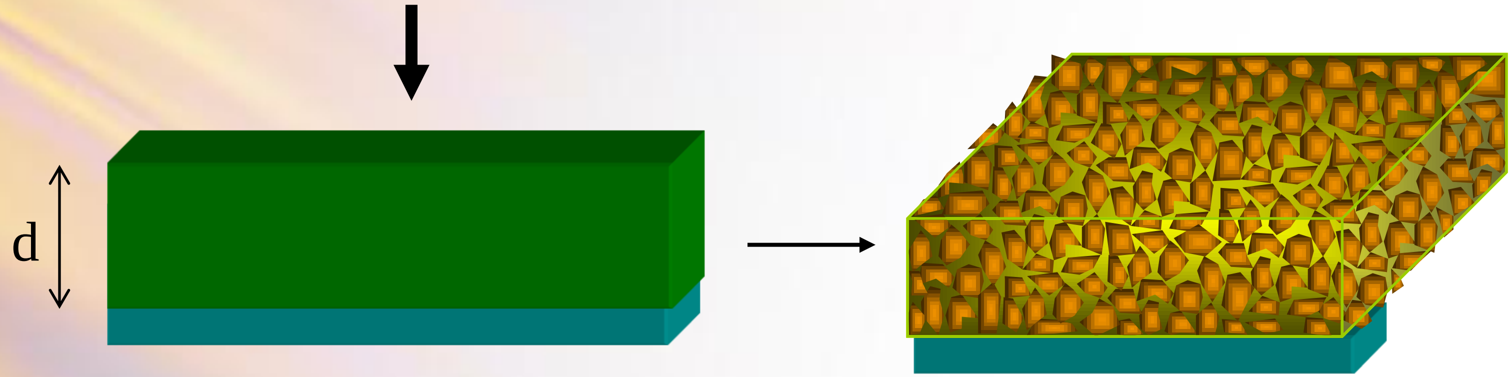
P_{max}: Maximum power point, greatest value of I * V

Carrier Recombination

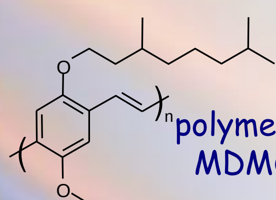
In an ideal system, electrons and holes will only recombine at the back face of the semiconductor after they have performed work. In a real system, alternative pathways for recombination will shorten the effective carrier lifetime of the sample and lower the efficiency of photovoltaic devices. The dominant recombination pathways are:



“Solar Paint”

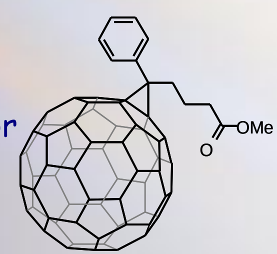


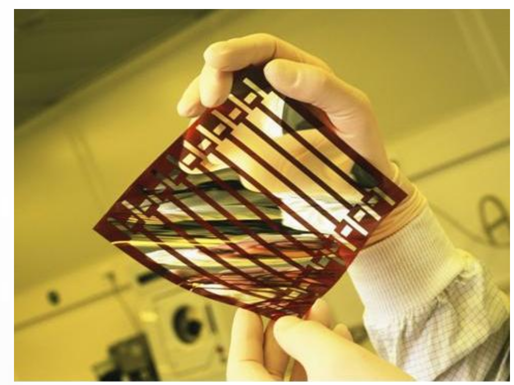
“Fooling “inexpensive particles into behaving as single crystals



polymer donor
MDMO-PPV

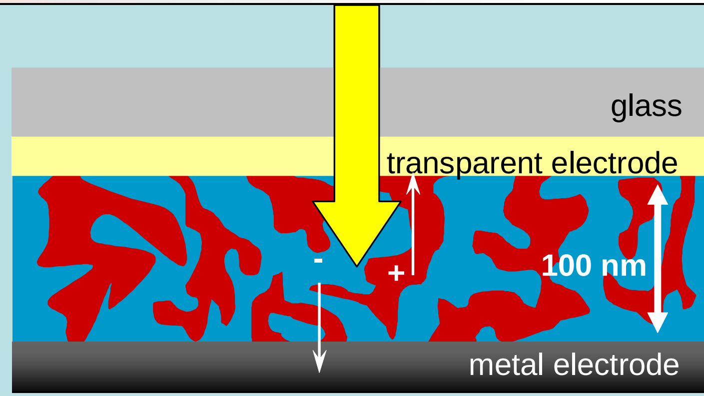
fullerene acceptor
PCBM

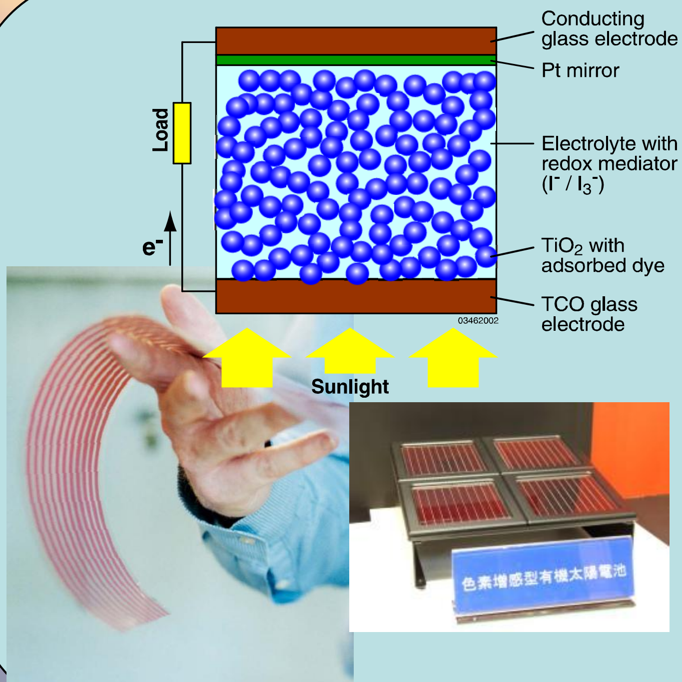


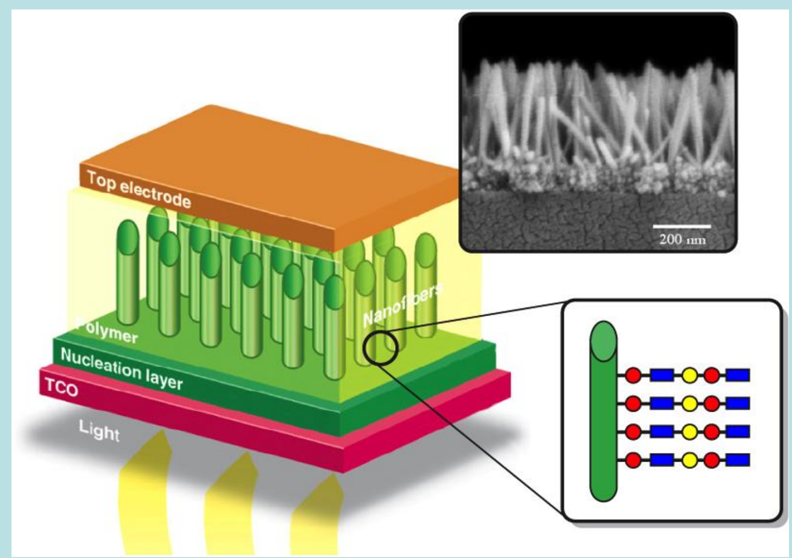


inexpensive processing, conformal layers

Interpenetrating Nanostructured Networks



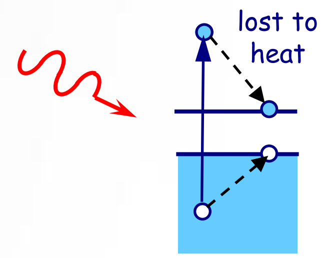


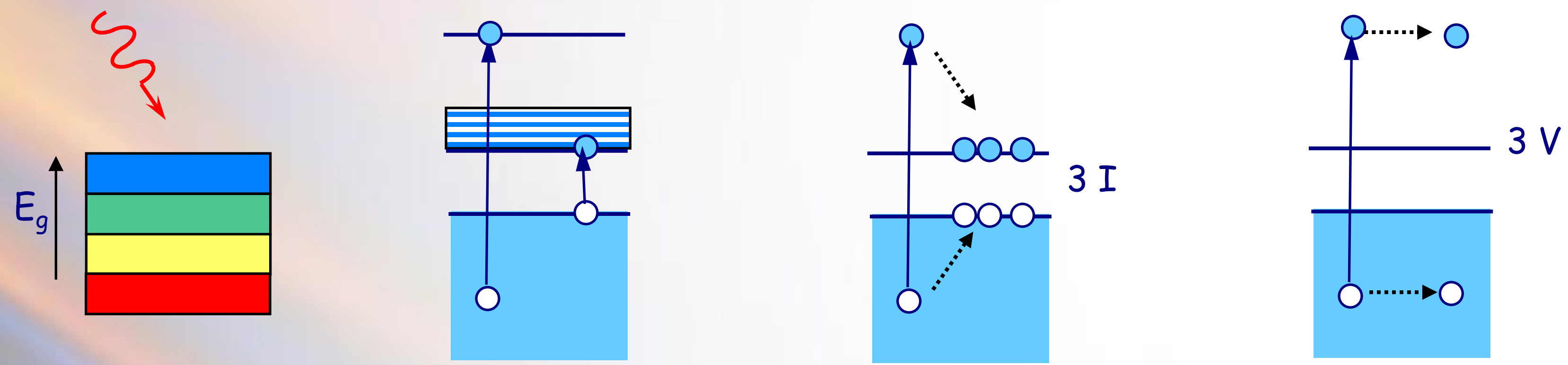


Revolutionary Photovoltaics: 50% Efficient Solar Cells

present technology: 32% limit for

- single junction
- one exciton per photon
- relaxation to band edge



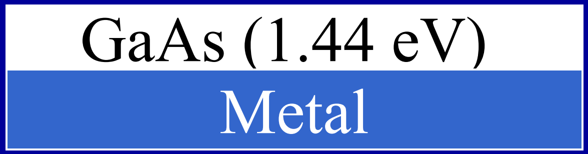


multiple junctions | multiple gaps | multiple excitons per photon | hot carriers

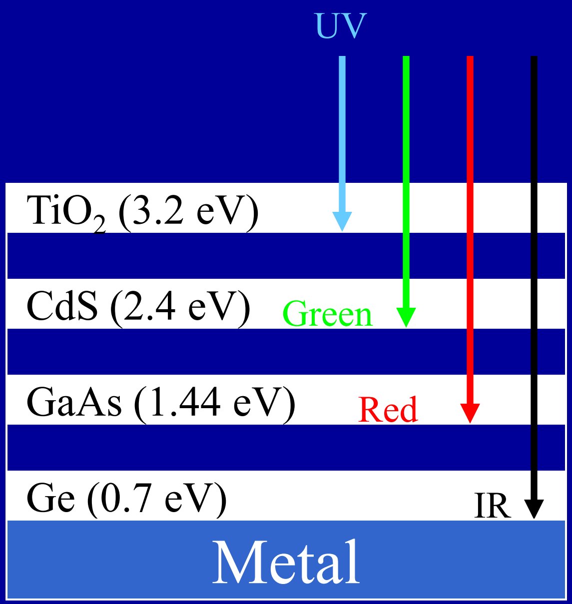
rich variety of new physical phenomena
understand and implement

Concentrator vs. Flat Plate Arrays

Why not stack several semiconductors to get better energy conversion ? A large band gap semiconductor can get higher voltage out of the more energetic photons, then smaller band gap semiconductors underneath can extract additional energy from the remaining photons.

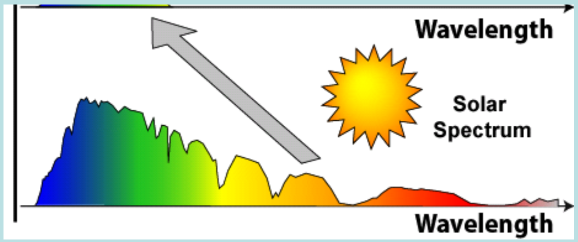


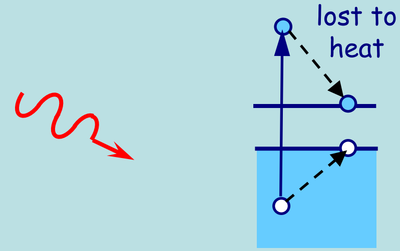
Flat Plate Array

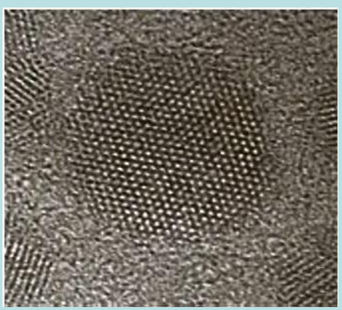


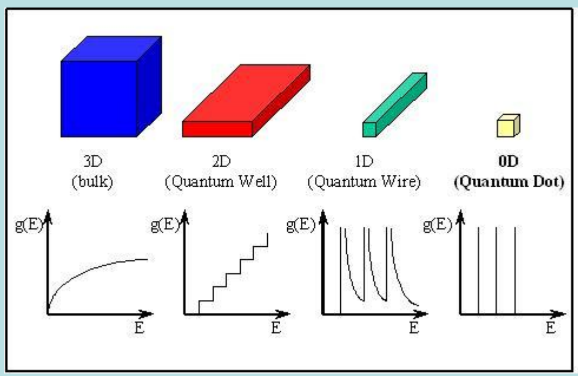
Concentrator Array

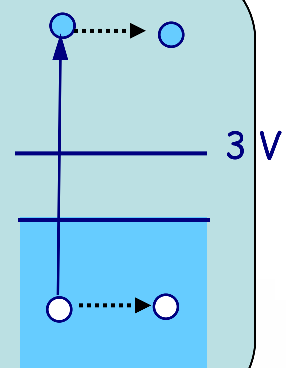
Ultra-high Efficiency Solar Cells



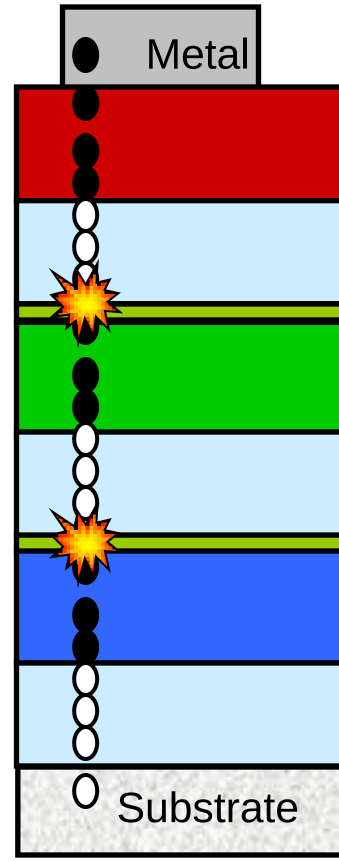








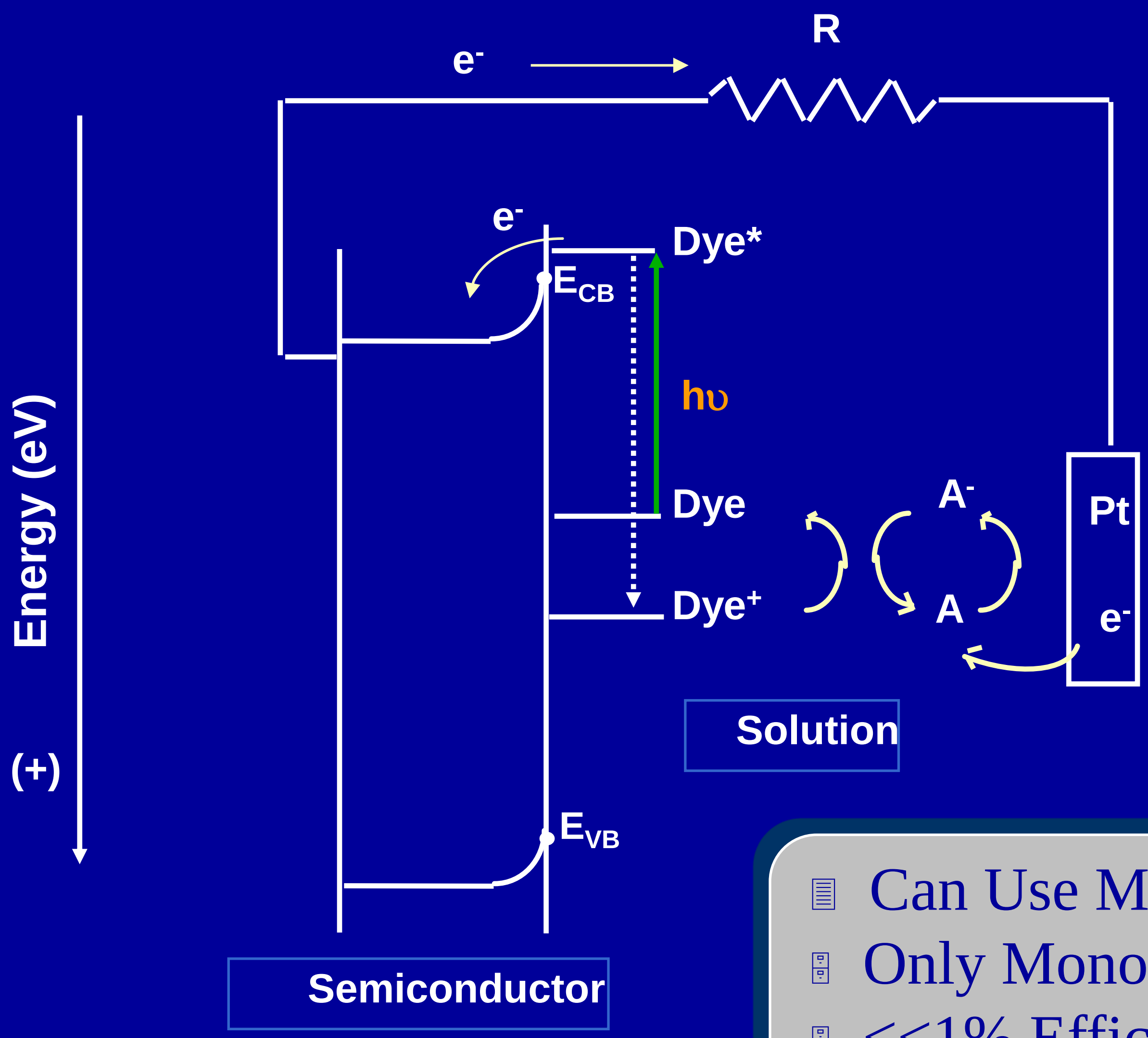
hot carriers



multiple junctions

rich variety of new physical phenomena
understand and implement

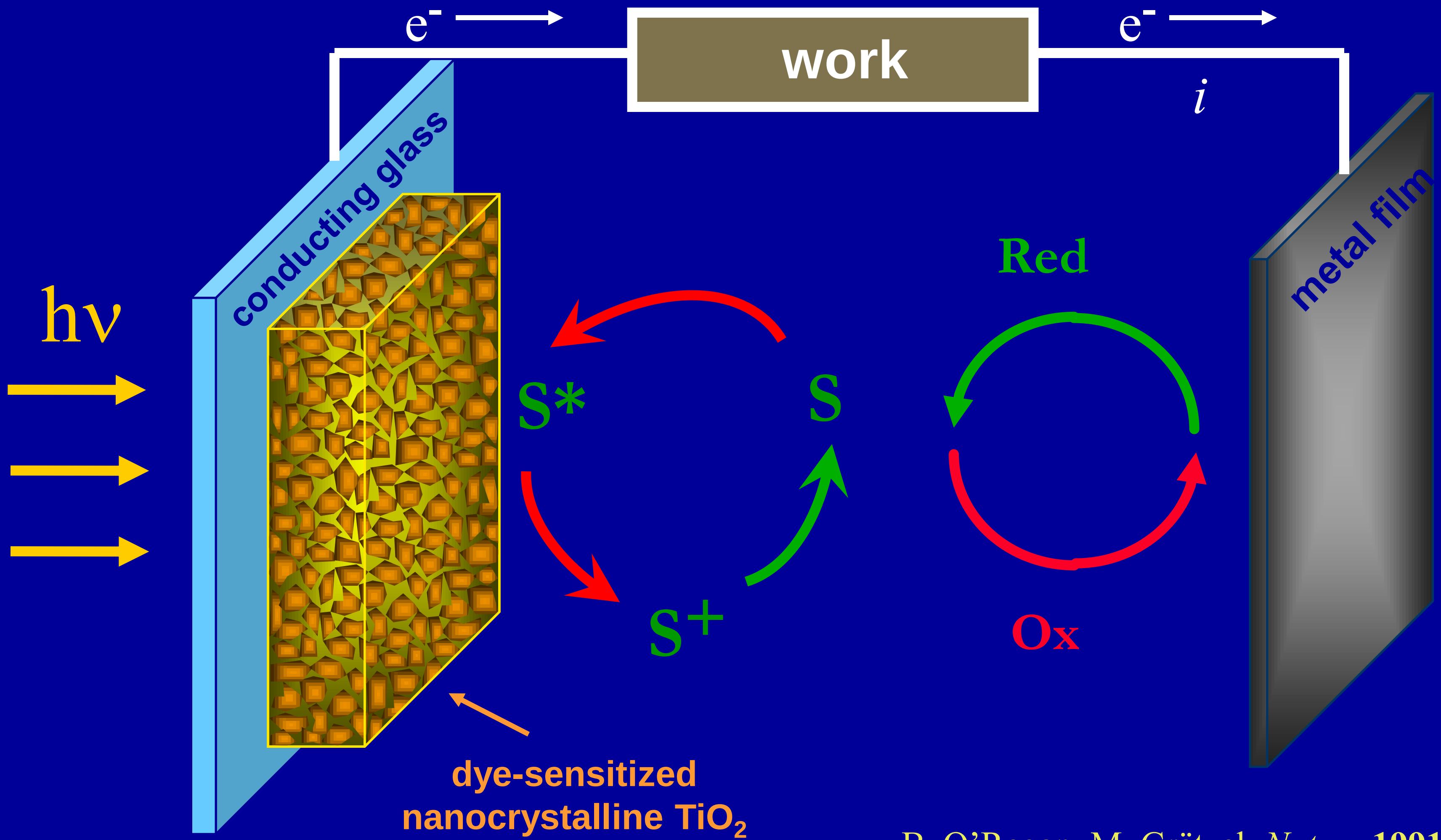
Dye Sensitization



- Can Use Metal Oxides
- Only Monolayer of Dye
- <<1% Efficiency

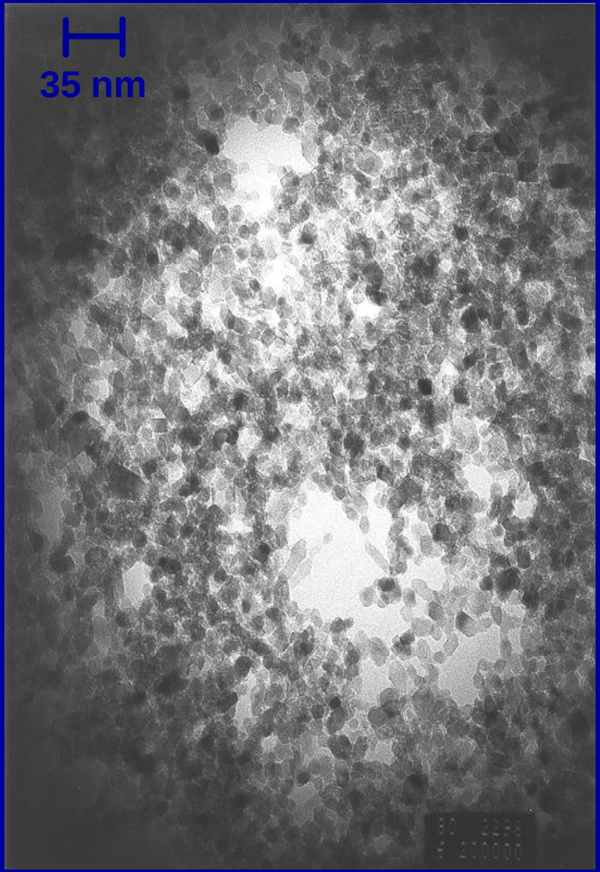
Semiconductor Photoelectrochemistry

nanocrystalline solar cell



B. O'Regan, M. Grätzel *Nature* **1991**, *353,* 737

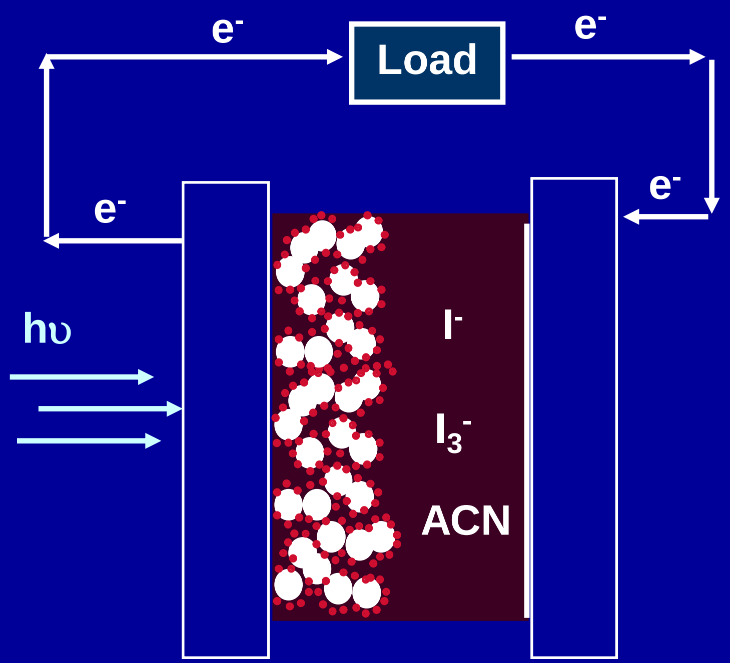
Nanocrystalline Titanium Dioxide

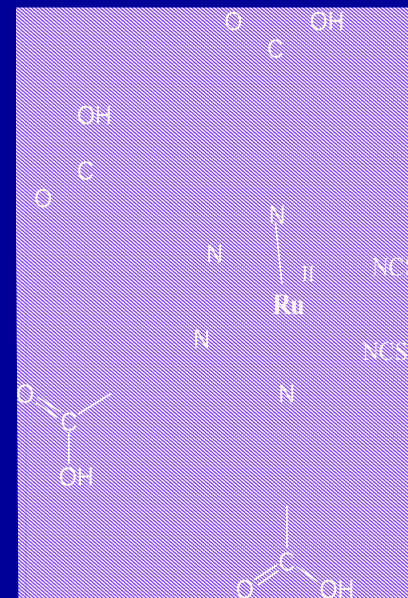


TEM of nanostructured TiO_2

- Particle Size ~ 15nm
- Surface Area
  is larger than single crystal ~1000 times
- No Quantum Size Effects
  (large electron effective mass)
- Different Electrochemistry
  from single crystal semiconductors

Dye Sensitized Solar Cells

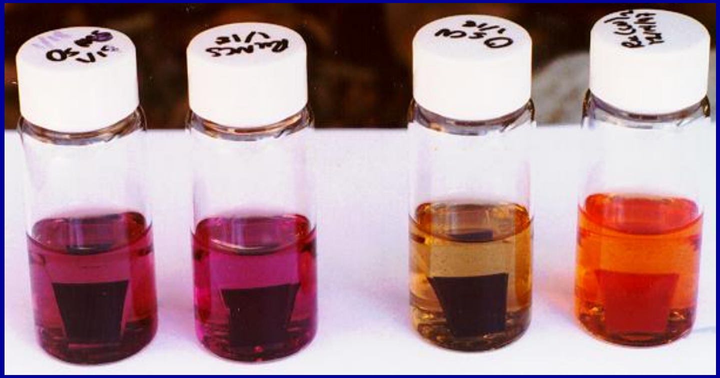




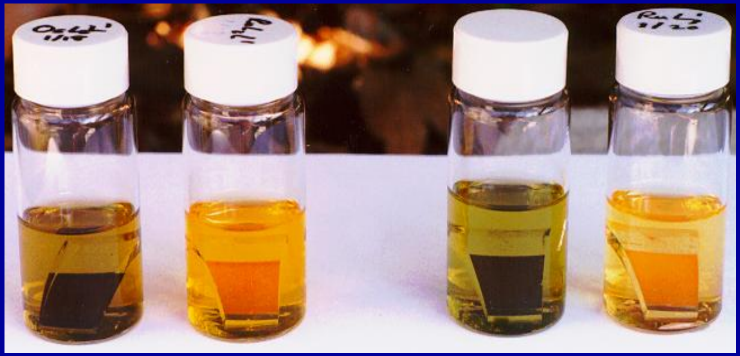
$RuL'_2(NCS)_2$

- 8-10% Efficient
- >15% Efficiency Possible
- Stability

Dye-Coated TiO_2 Electrodes



$OsL'_2(NCS)_2$ $RuL'_2(NCS)_2$ $OsL'_2(CN)_2$ $RuL'_2(CN)_2$

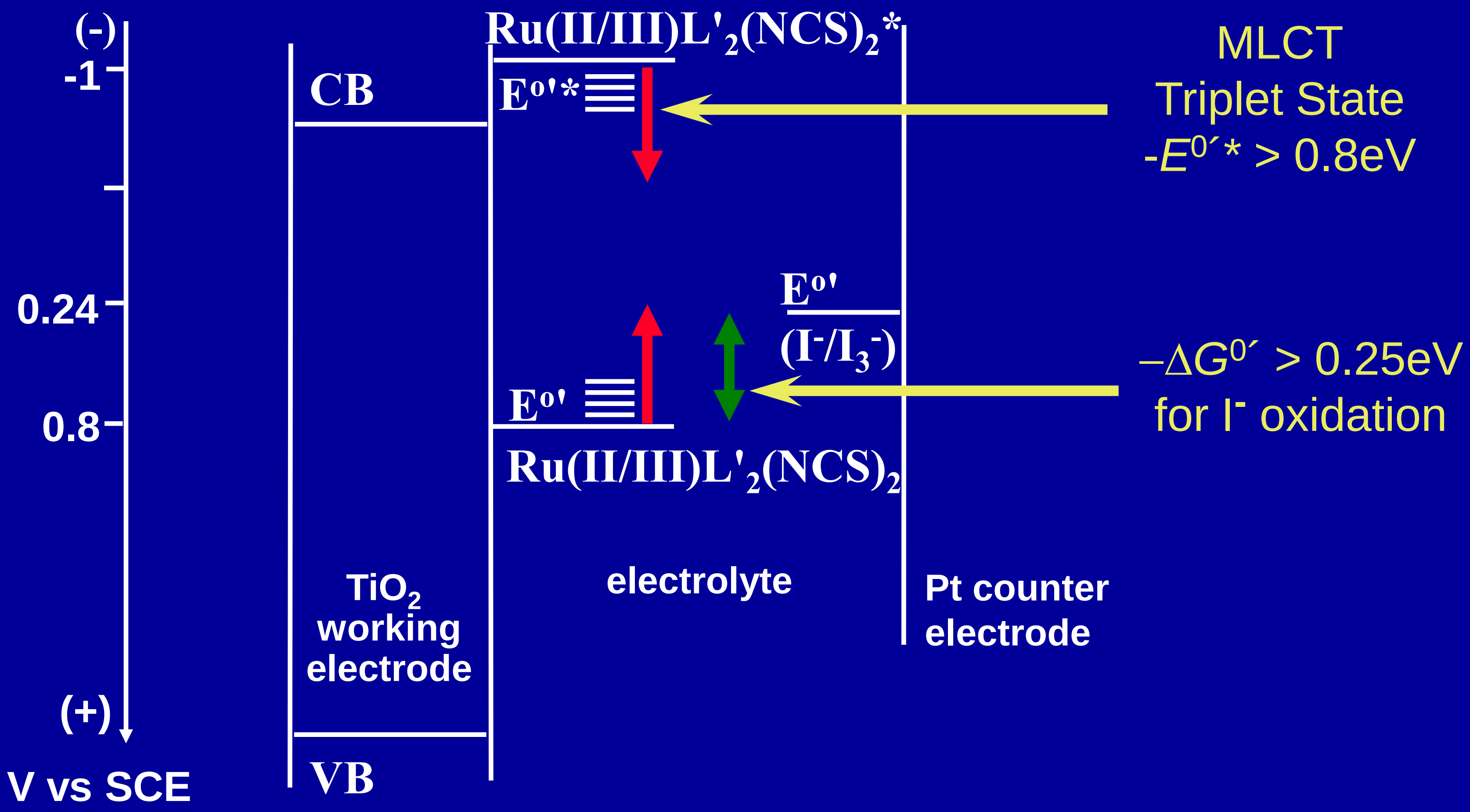


OsL_2L' RuL_2L' OsL'_3 RuL'_3

TIO_2 coated on conducting glass (INAP), deposited $TiCl_4$ overnight, heated 450 °C for 30 min, cooled to 120 °C, immersed in ethanolic dye solution for 15-24 h

Energetics of Sensitized TiO_2 Solar Cell

To red-shift the absorption spectra, require:
More positive excited state potential, or more negative ground state potential



Solar Energy Challenges

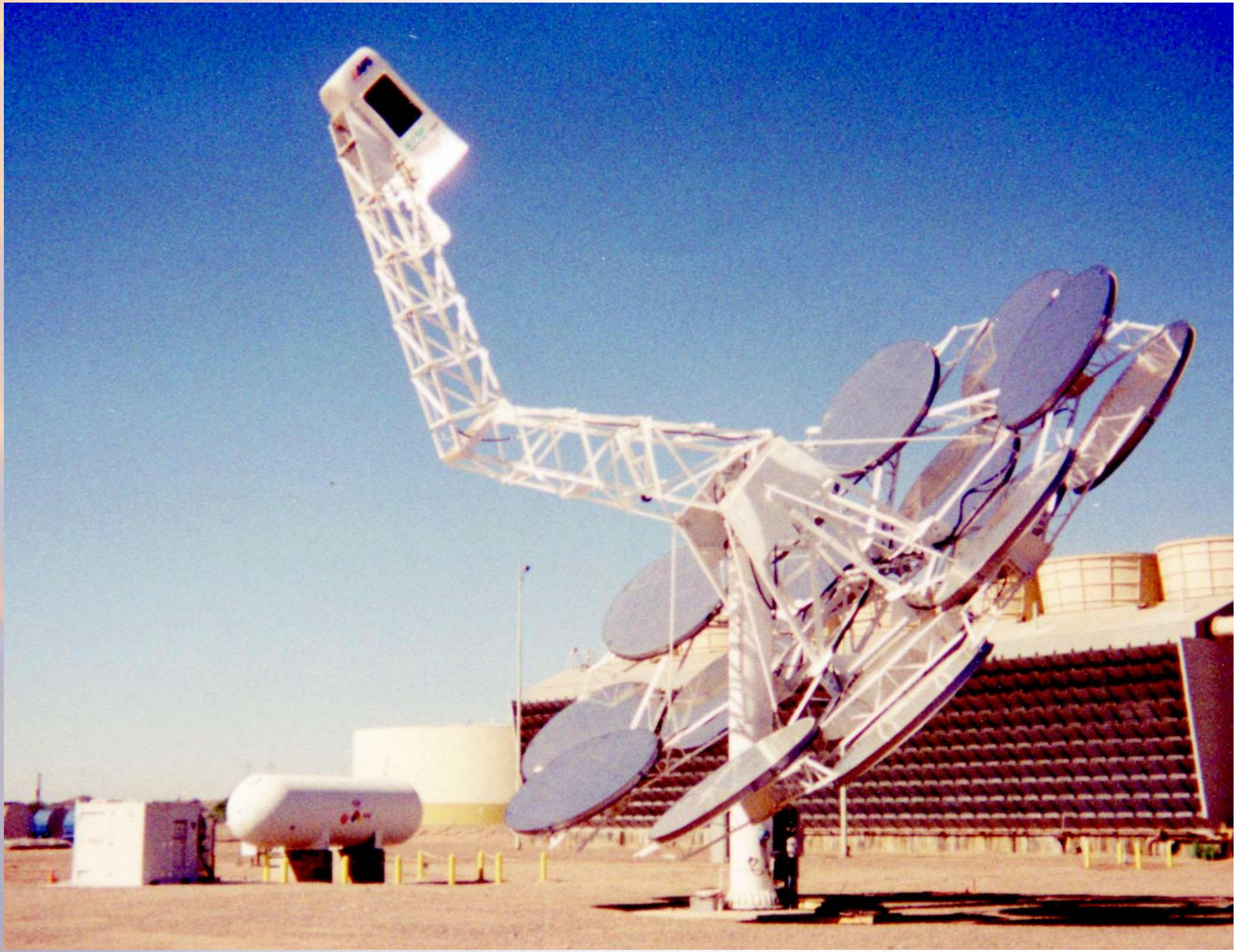
Solar electric

Solar fuels

Solar thermal

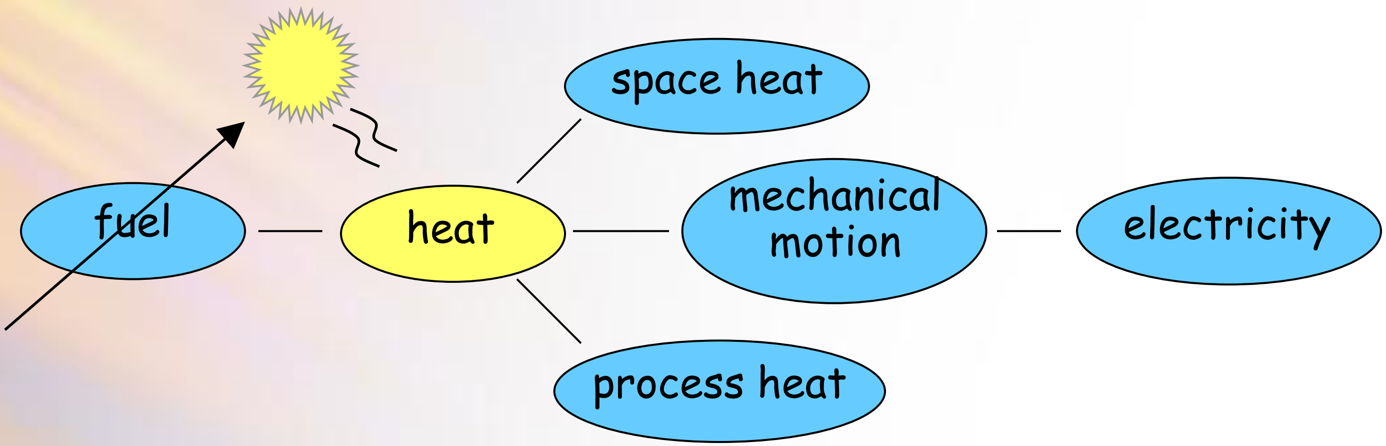
Cross-cutting research

Solar Thermal + Electrolyzer System



Report of the Basic Energy Sciences Workshop on Solar Energy Utilization

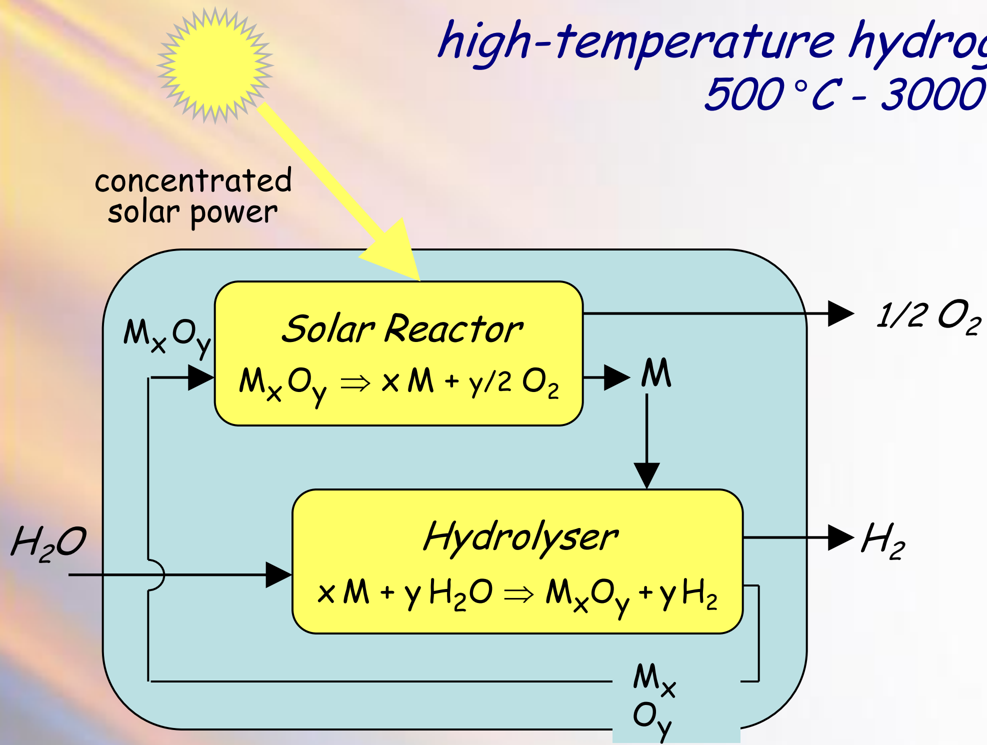
Solar Thermal

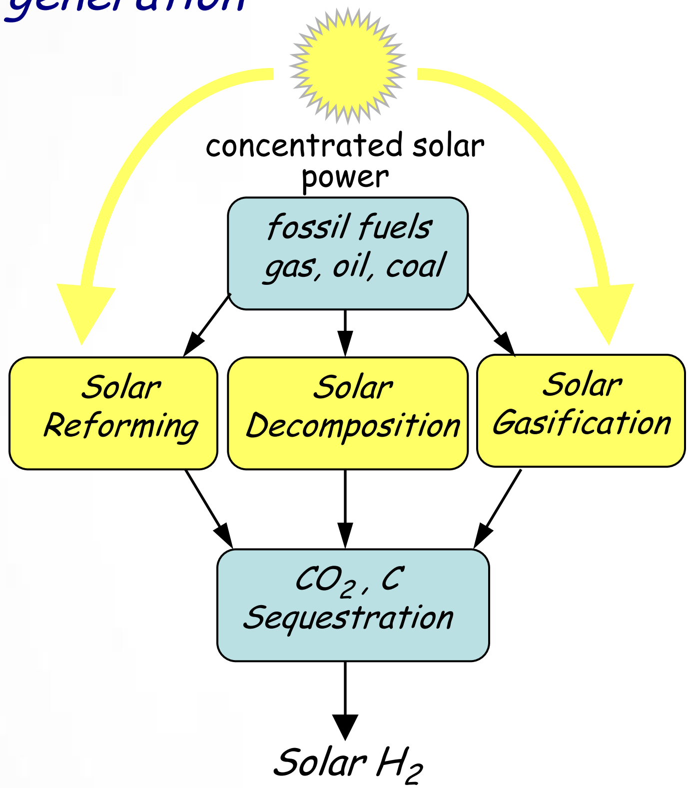


- heat is the first link in our existing energy networks
- solar heat replaces combustion heat from fossil fuels
- solar steam turbines currently produce the lowest cost solar electricity
- challenges:
  - new uses for solar heat
  - store solar heat for later distribution

Solar Thermochemical Fuel Production

high-temperature hydrogen generation
500°C - 3000°C





Scientific Challenges

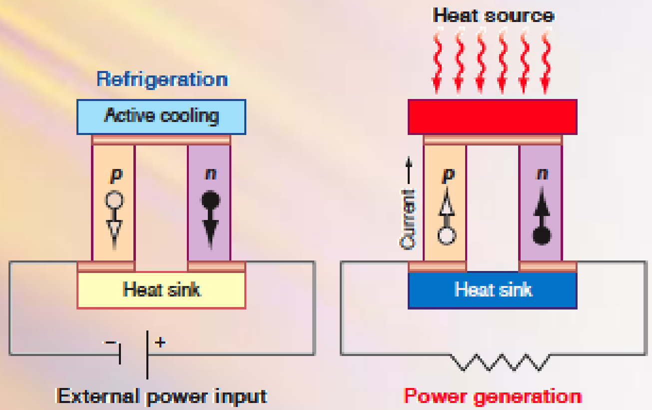
high temperature reaction kinetics of

- metal oxide decomposition
- fossil fuel chemistry

robust chemical reactor designs and materials

A. Streinfeld, Solar Energy, 78,603 (2005)

Thermoelectric Conversion



thermal gradient ⇔ electricity

figure of merit: ZT ~ (σ/κ) T

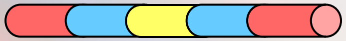
ZT ~ 3: efficiency ~ heat engines

no moving parts

Scientific Challenges

increase electrical conductivity

decrease thermal conductivity



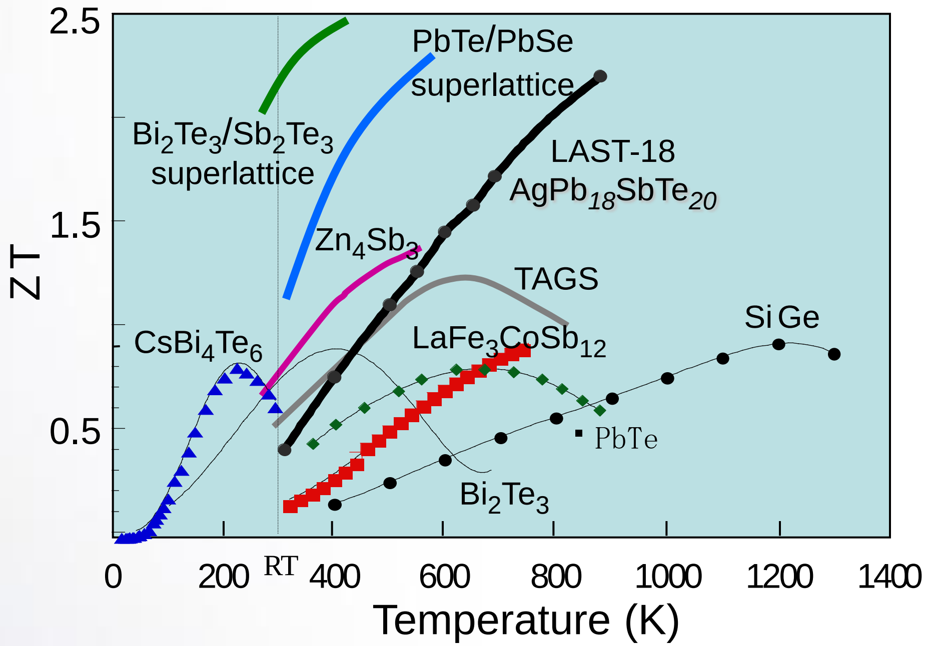
nanowire superlattice

nanoscale architectures

interfaces block heat transport

confinement tunes density of states

doping adjusts Fermi level



Solar Energy Challenges

Solar electric

Solar fuels

Solar thermal

Cross-cutting research

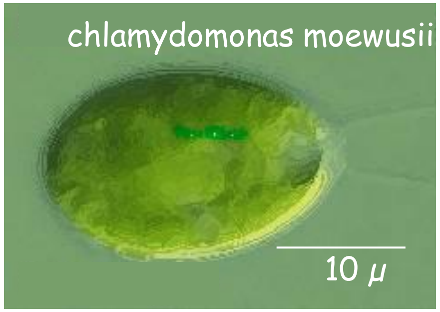
Leveraging Photosynthesis for Efficient Energy Production

- photosynthesis converts ~ 100 TW of sunlight to sugars: nature's fuel
- low efficiency (< 1%) requires too much land area

switchgrass

Modify the biochemistry of plants and bacteria

- improve efficiency by a factor of 5–10
- produce a convenient fuel methanol, ethanol, H_2, CH_4



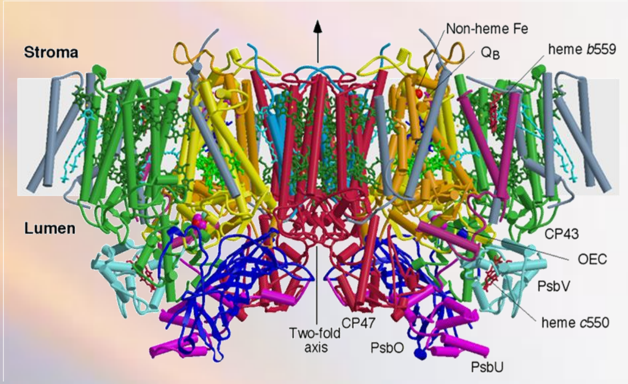
hydrogenase
$2H^+ + 2e^- \Leftrightarrow H_2$

Scientific Challenges

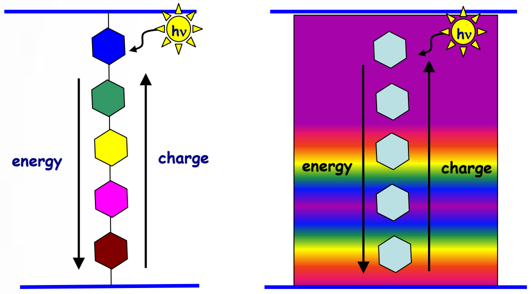
- understand and modify genetically controlled biochemistry that limits growth
- elucidate plant cell wall structure and its efficient conversion to ethanol or other fuels
- capture high efficiency early steps of photosynthesis to produce fuels like ethanol and H_2
- modify bacteria to more efficiently produce fuels
- improved catalysts for biofuels production

Smart Matrices for Solar Fuel Production

- Biology: protein structures dynamically control energy and charge flow
- Smart matrices: adapt biological paradigm to artificial systems



photosystem II

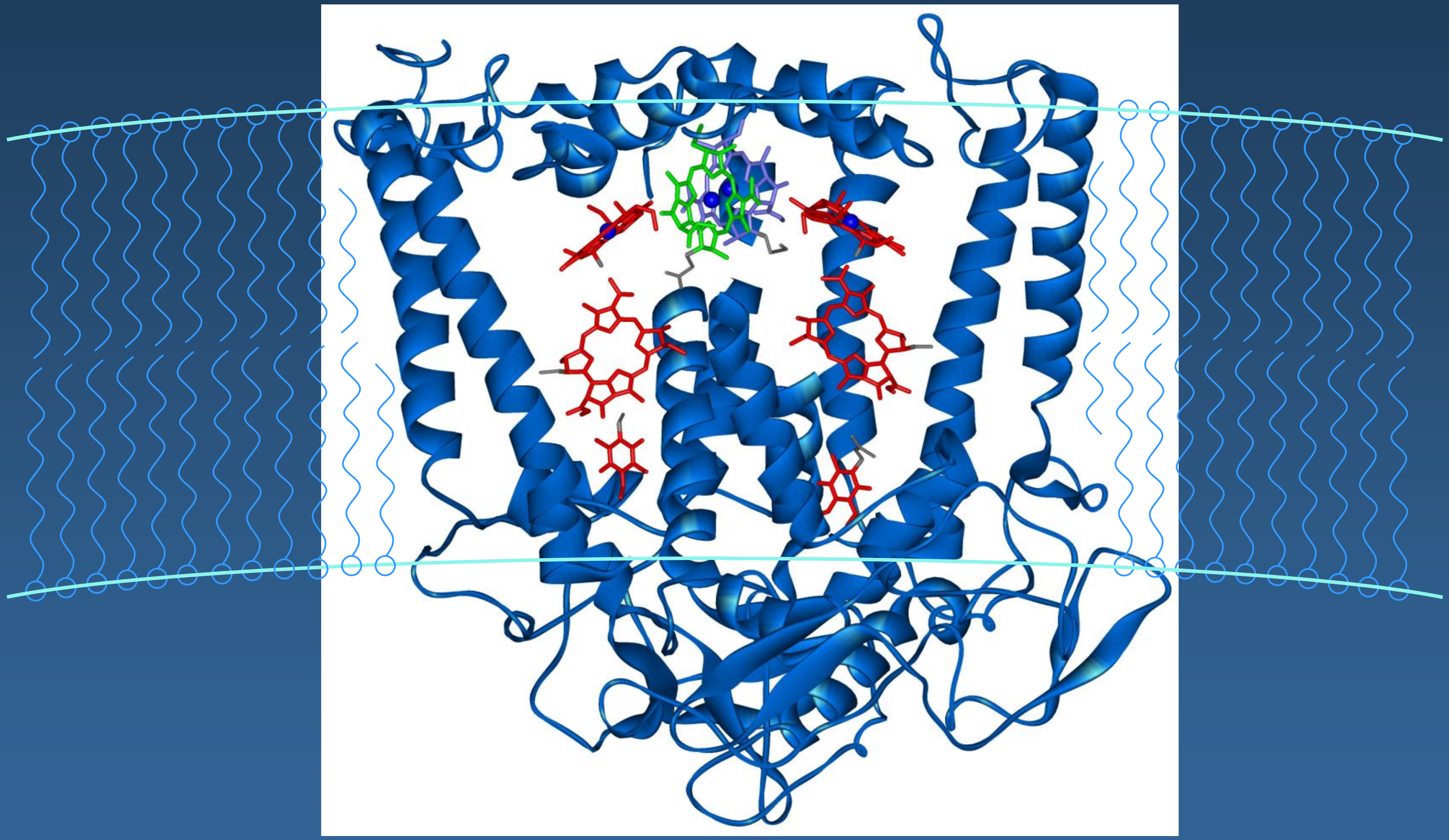


smart matrices carry energy and charge

Scientific Challenges

- engineer tailored active environments with bio-inspired components
- novel experiments to characterize the coupling among matrix, charge, and energy
- multi-scale theory of charge and energy transfer by molecular assemblies
- design electronic and structural pathways for efficient formation of solar fuels

Bacterial Photosynthetic Reaction Center



rhodobacter sphaeroides

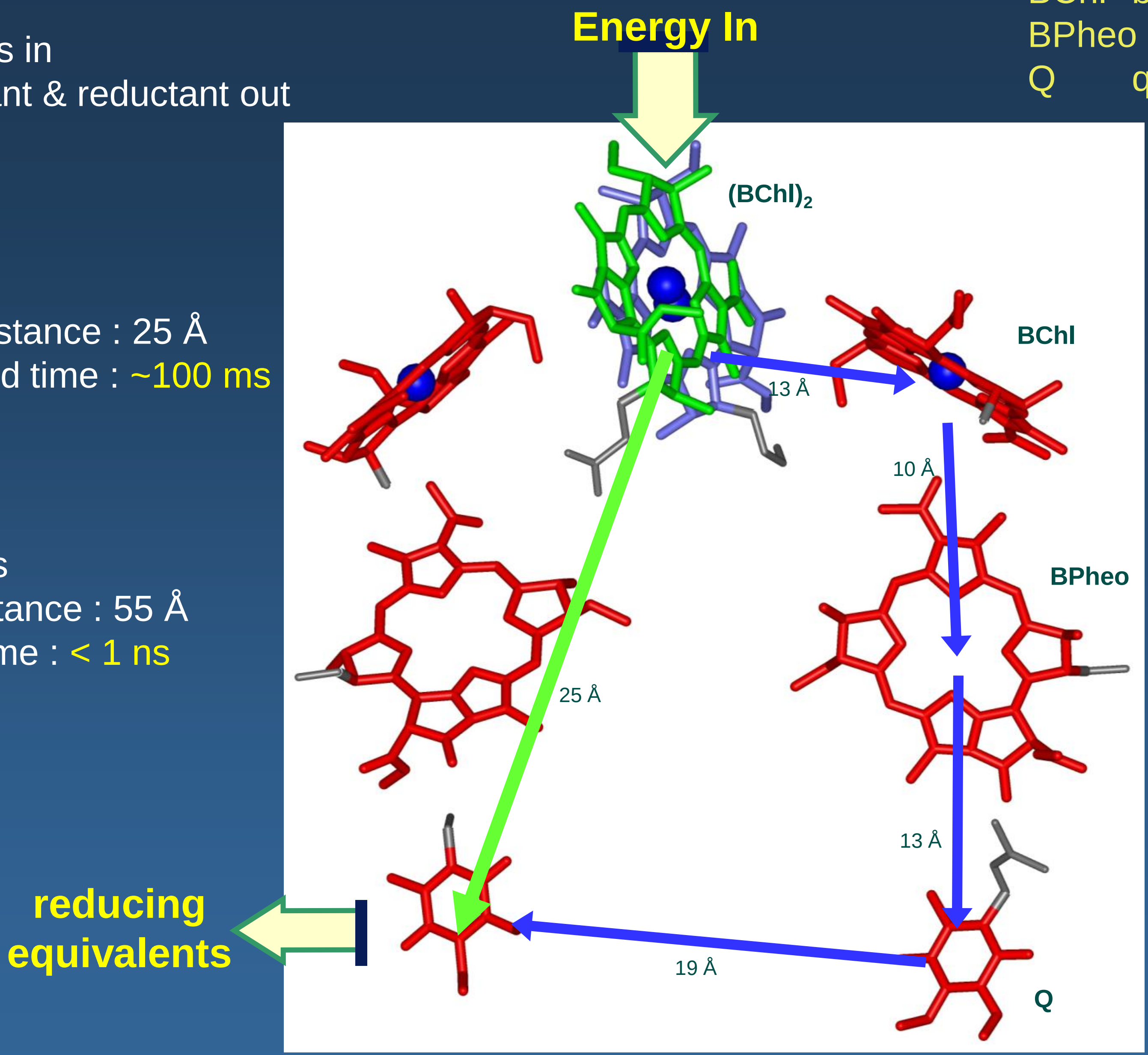
Stowell, M.H.B.; Rees, D.C.; *et. al. Science* **1997**, *276*, 882.

photons in
1 oxidant & reductant out

BChl bacteriochlorophyll
BPheo bacteriopheophytin
Q quinone

1 step distance : 25 Å
calculated time : ~100 ms

4 steps
ET distance : 55 Å
total time : < 1 ns



Boxer, S.G. ***Annu. Rev. Biophys. Biophys. Chem.*** **1990, *19*, 267.**

Nature uses two photosystems to span the redox space from O_2/H_2O to $NAD^+/NADH$

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.

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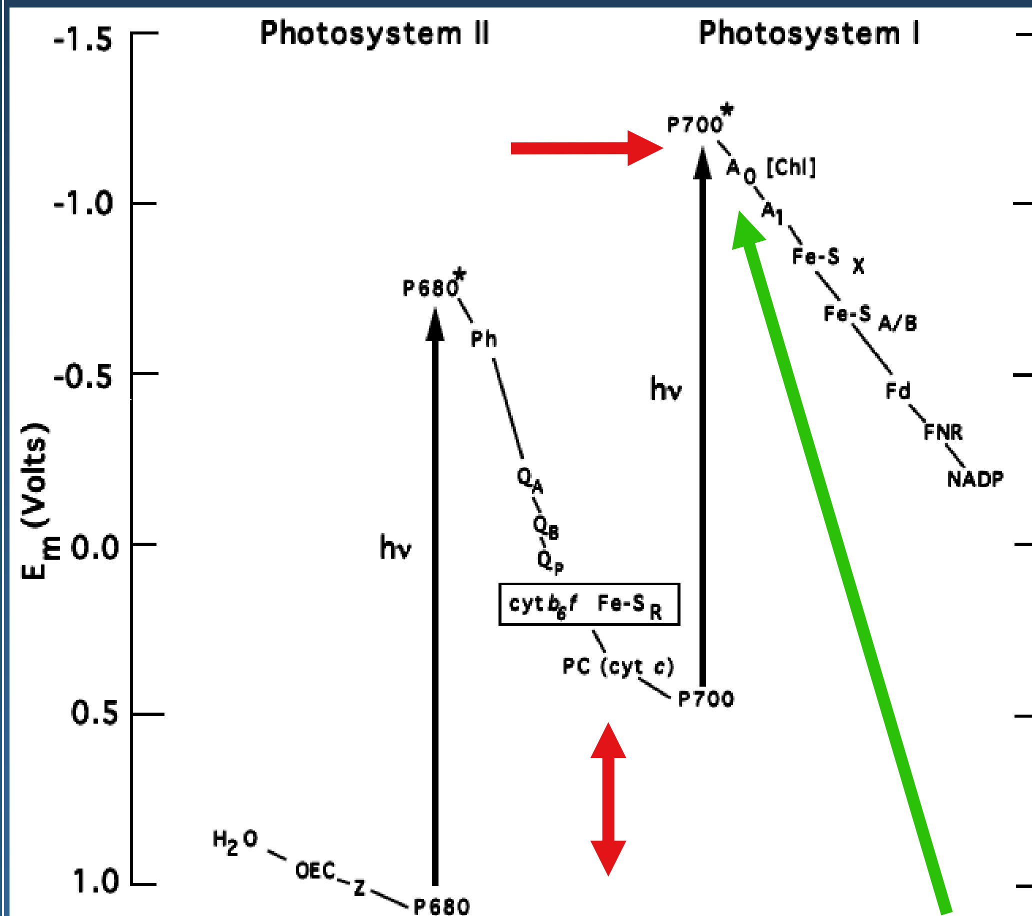


QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.

N.B.

Giving more thermodynamic push to synthesis

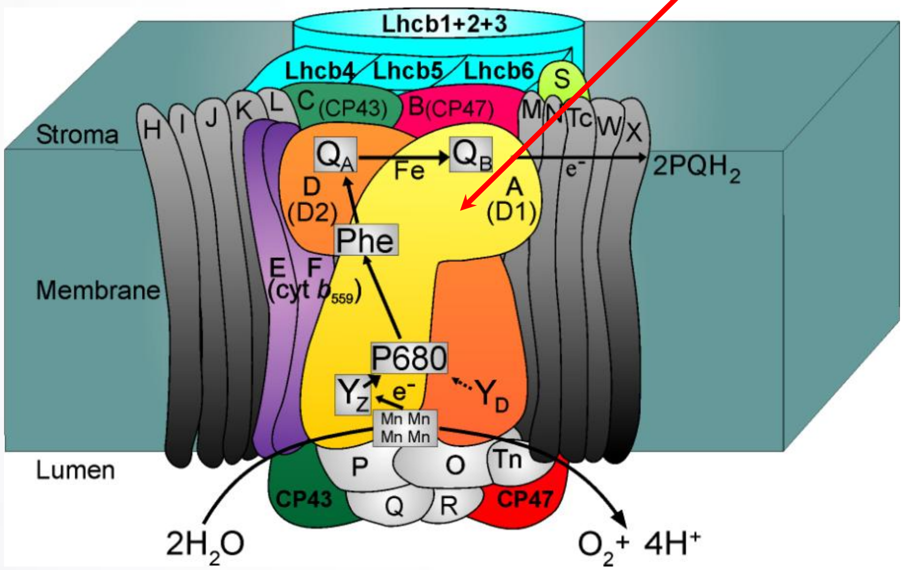
B Blankenship

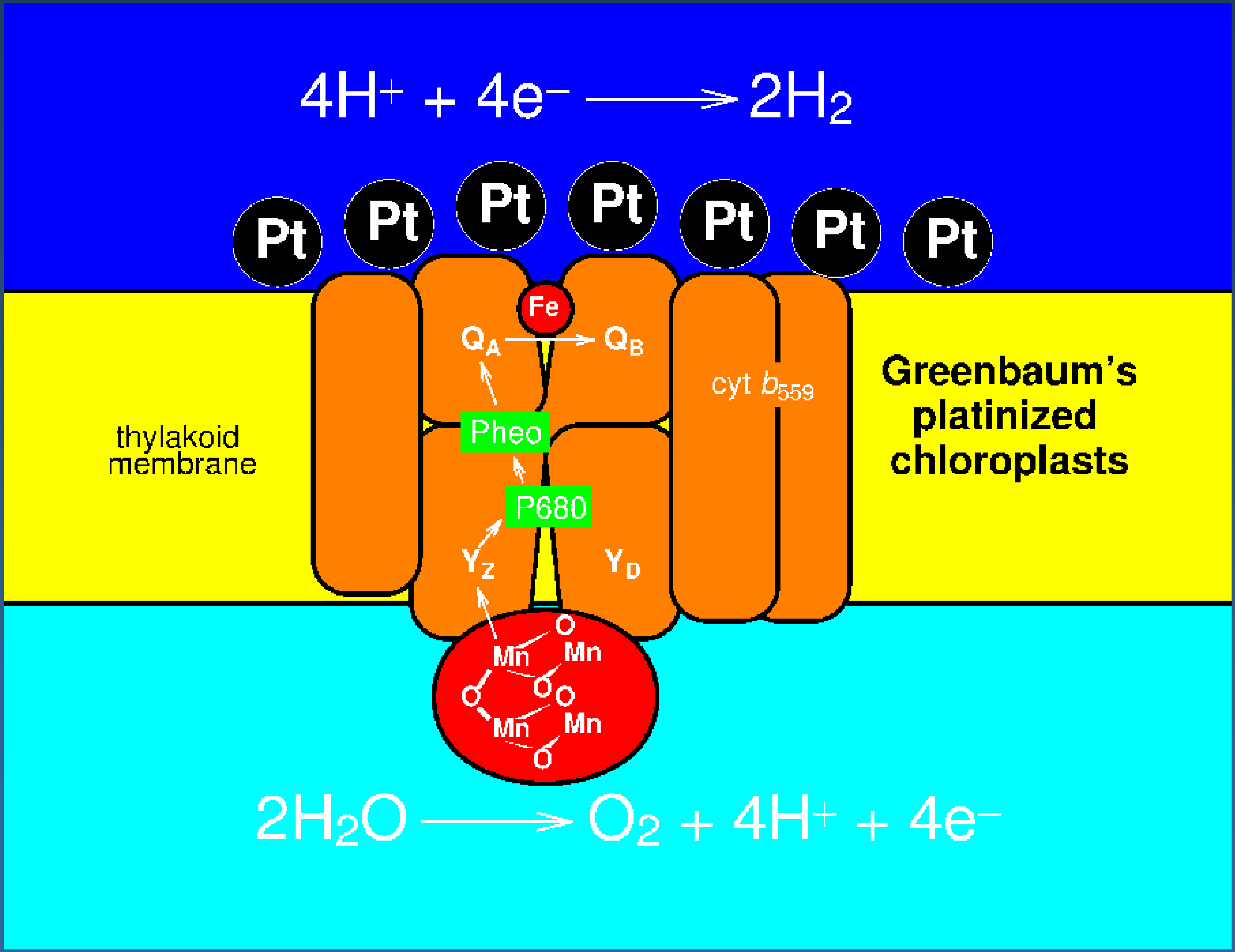
Defect Tolerance and Self-repair

- Understand defect formation in photovoltaic materials and self-repair mechanisms in photosynthesis

- Achieve defect tolerance and active self-repair in solar energy conversion devices, enabling 20–30 year operation

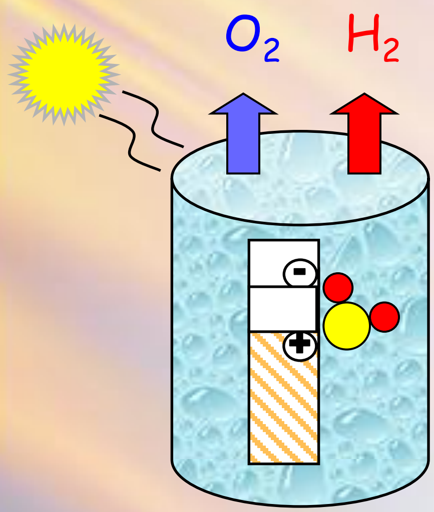
the water splitting protein in Photosystem II is replaced every hour!

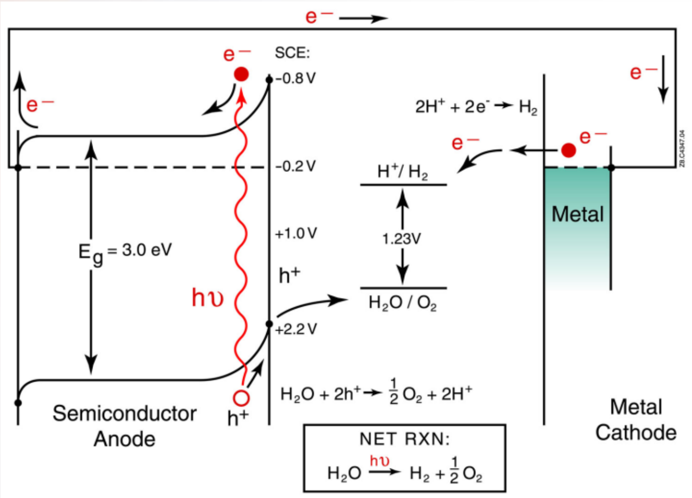


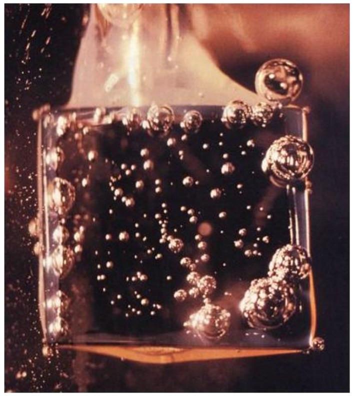


4H+ + 4e− → 2H2
Pt
Fe
QA
QB
cyt b559
Greenbaum's platinized chloroplasts
thylakoid membrane
Pheo
P680
YZ
YD
Mn
O
2H2O → O2 + 4H+ + 4e−

Efficient Solar Water Splitting







demonstrated efficiencies 10-18% in laboratory

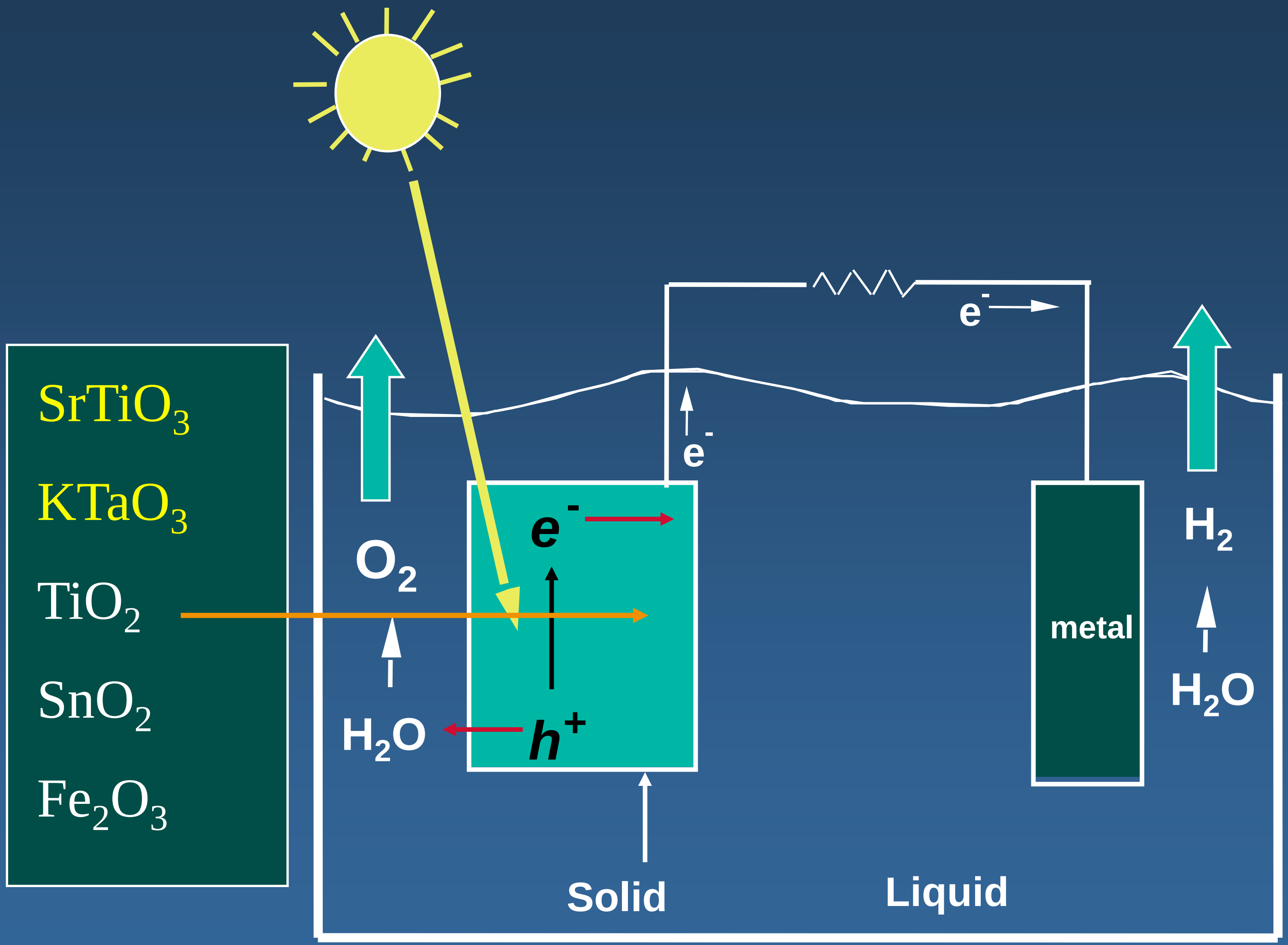
Scientific Challenges

- cheap materials that are robust in water
- catalysts for the redox reactions at each electrode
- nanoscale architecture for electron excitation ⇒ transfer ⇒ reaction

Fuel from Sunlight

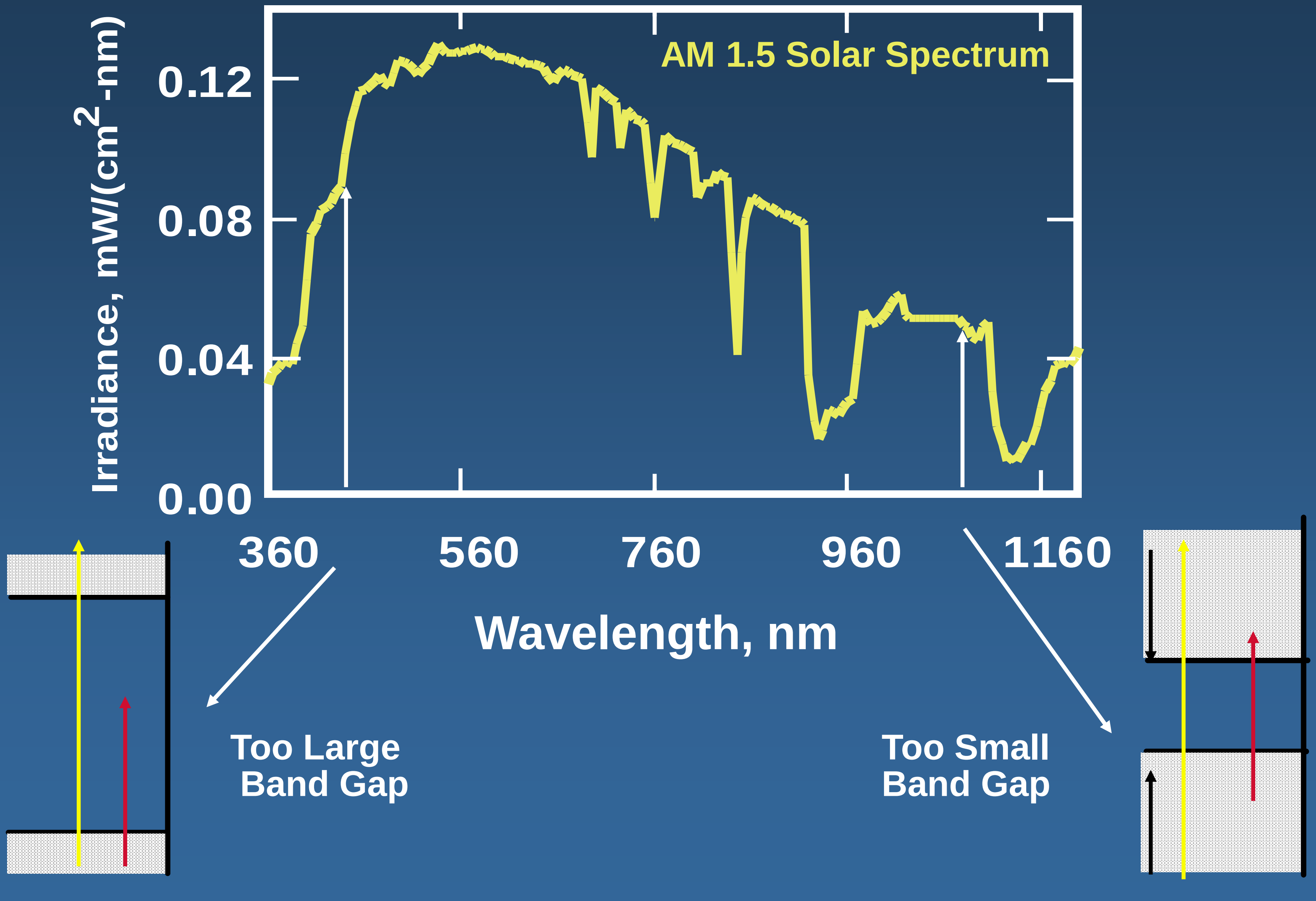
QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Photoelectrochemical Cell



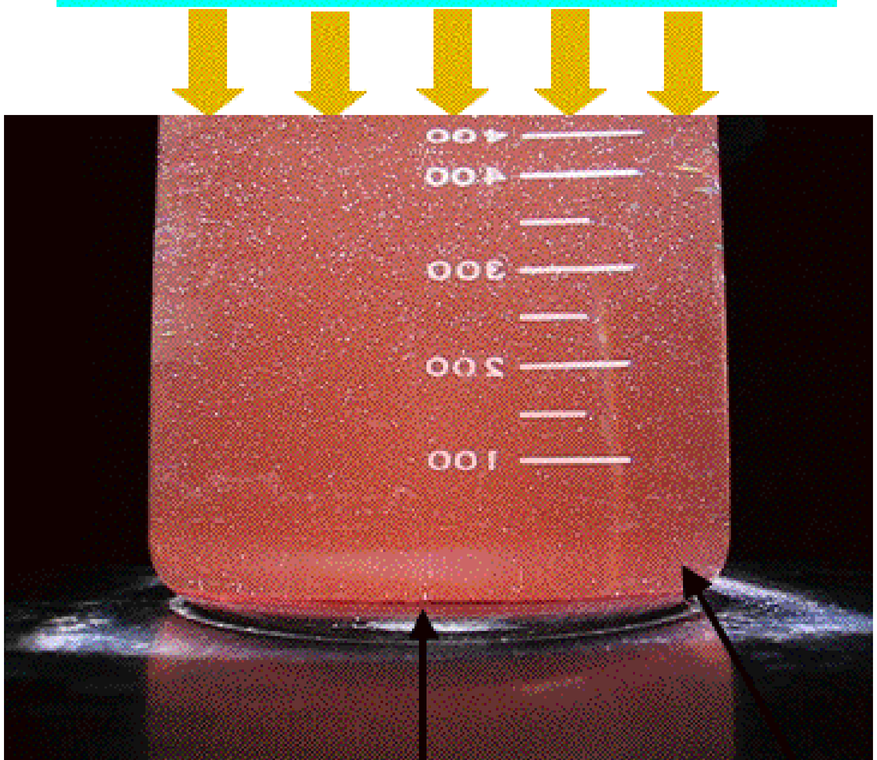
Light is Converted to Electrical+Chemical Energy

Optimum Absorption Threshold



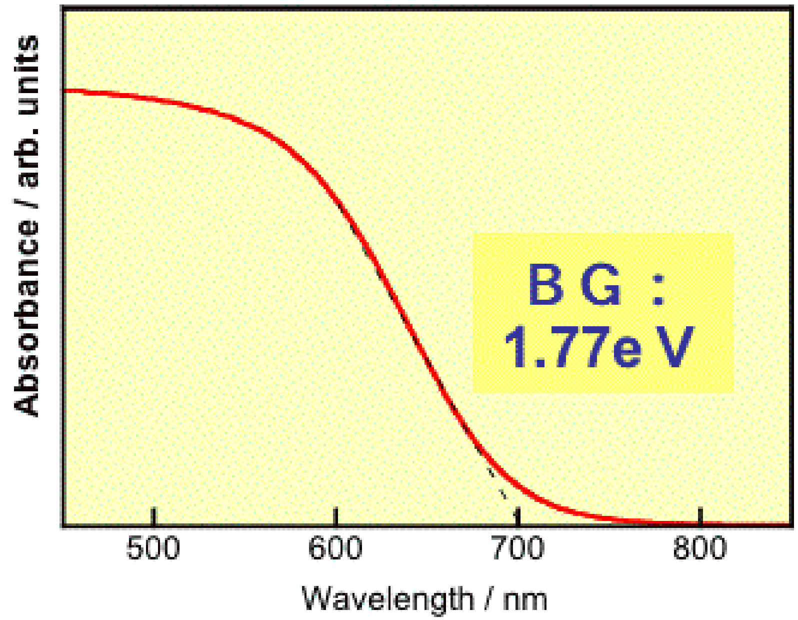
Solar H_2 production on Ru/$CuInS_2$-$AgInS_2$-ZnS solid solution photocatalyst

Solar simulator(AM-1.5)



Photocatalyst   Reactant: K_2SO_3 + Na_2S

Rate of H_2 evolution
8L/h•m²



I. Tsuji, H. Kato, and A. Kudo,
Angew. Chem., Int. Ed., 44, 3565 (2005), *Chem. Mater., 18, 1969* (2006).

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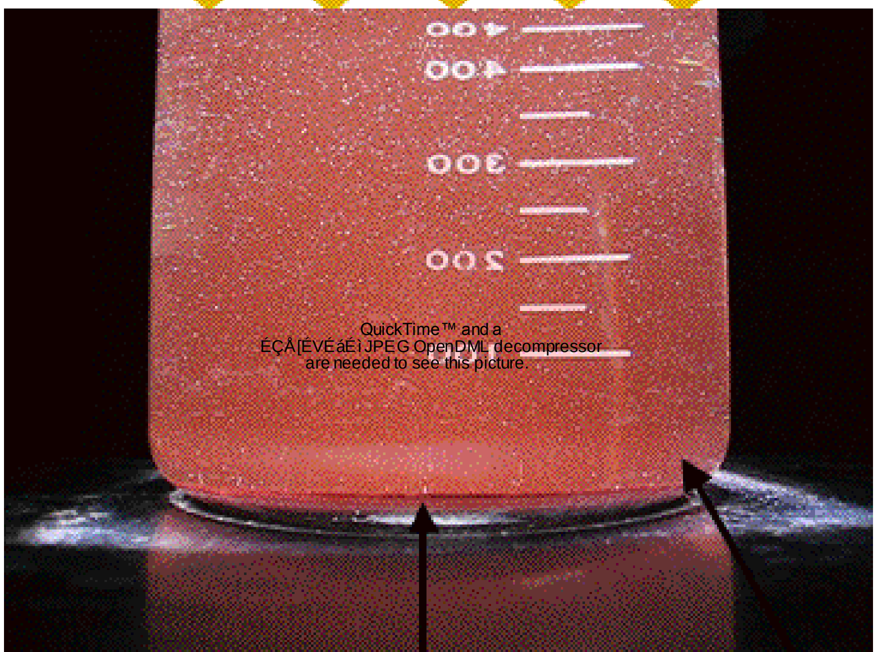

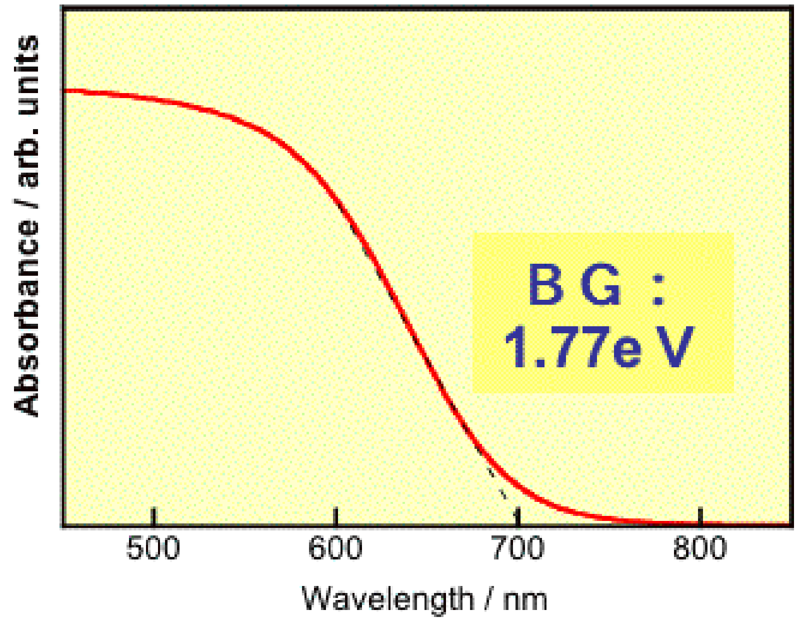

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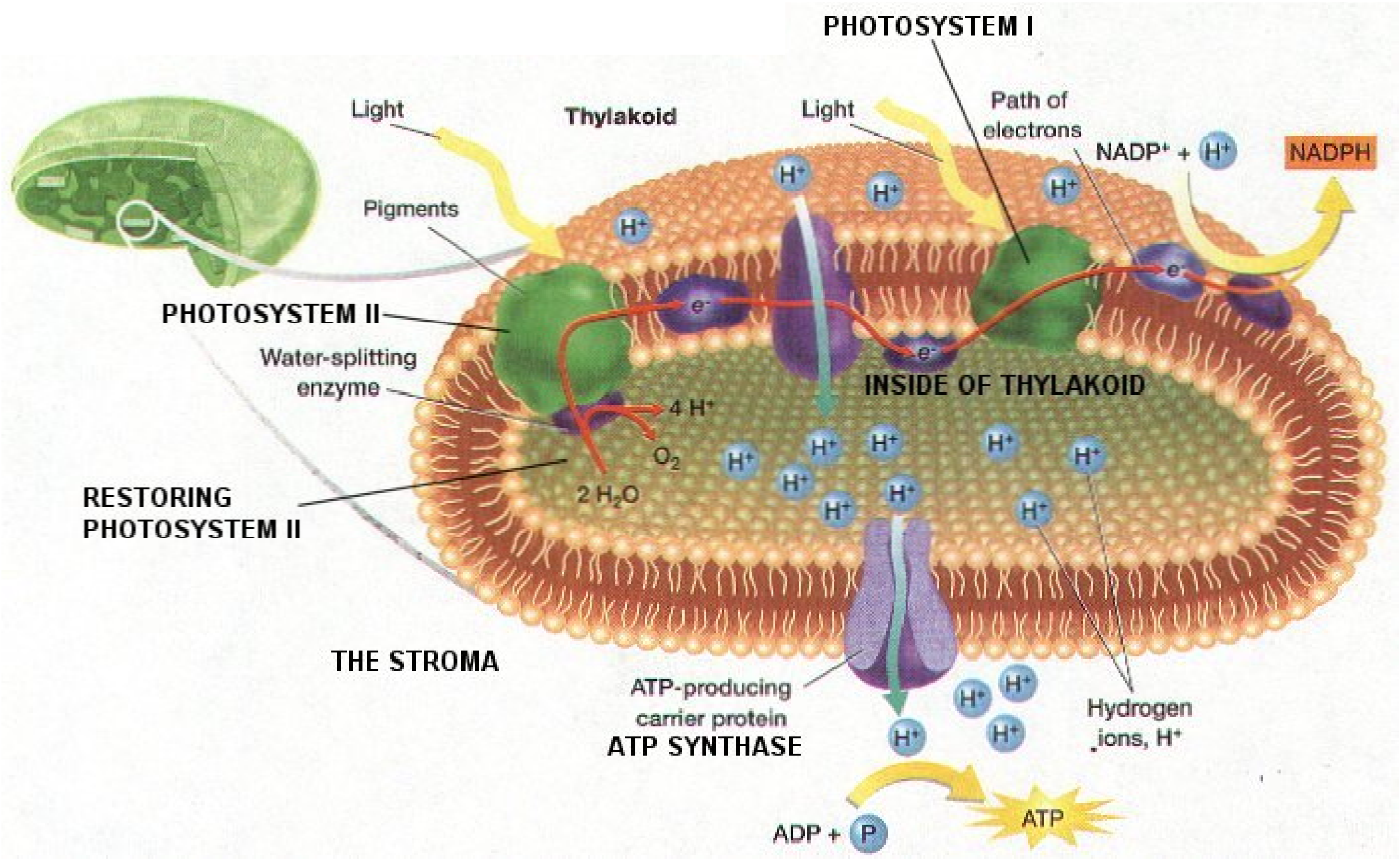
I. Tsuji, H. Kato, and A. Kudo,
Angew. Chem., Int. Ed., 44, 3565 (2005), *Chem. Mater., 18, 1969* (2006).

Lessons from Photosynthesis

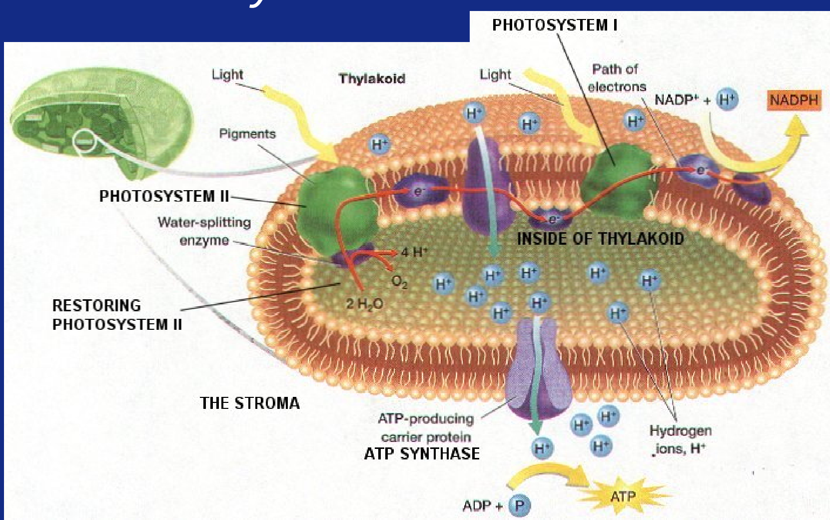


April 18-21, 2005

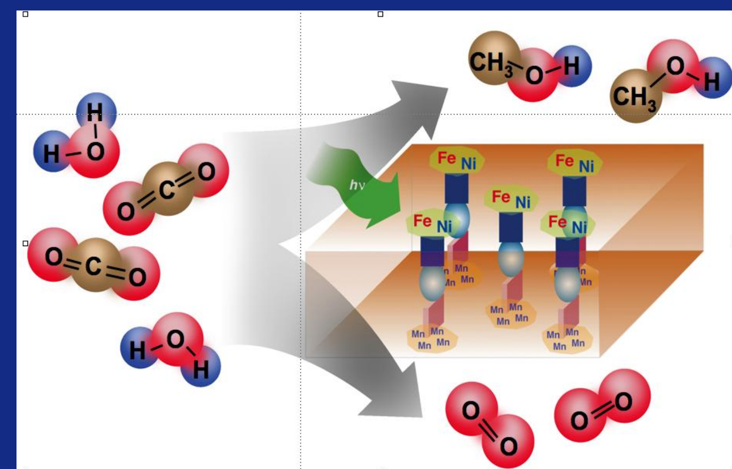
Mission of JCAP

- **Melvin Calvin, 1982**: It is time to build an actual artificial photosynthetic system, to learn what works and what doesn't work, and thereby set the stage for making it work better
- **10-year JCAP Goal, 2010**: To demonstrate a manufacturably scalable solar fuel generator, using earth-abundant elements, that, with no wires, robustly produces fuel from the sun, 10 times more efficiently than (current) crops

Photosynthesis

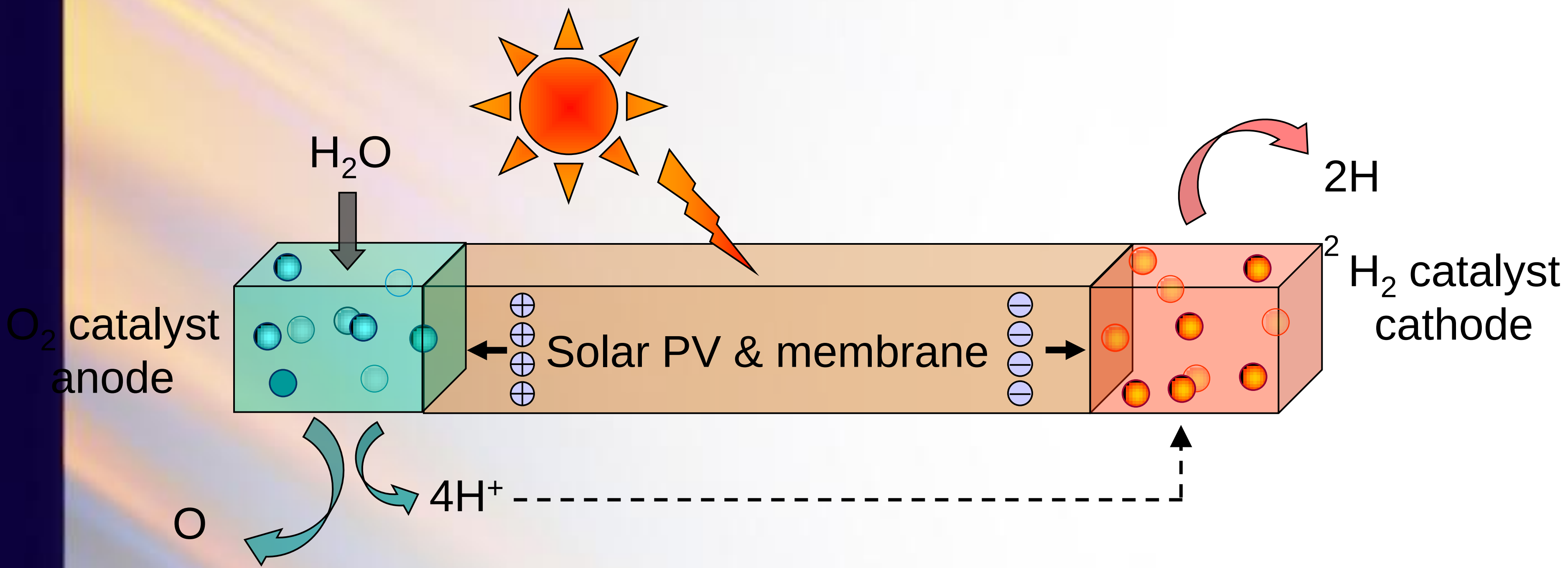


Artificial Photosynthesis



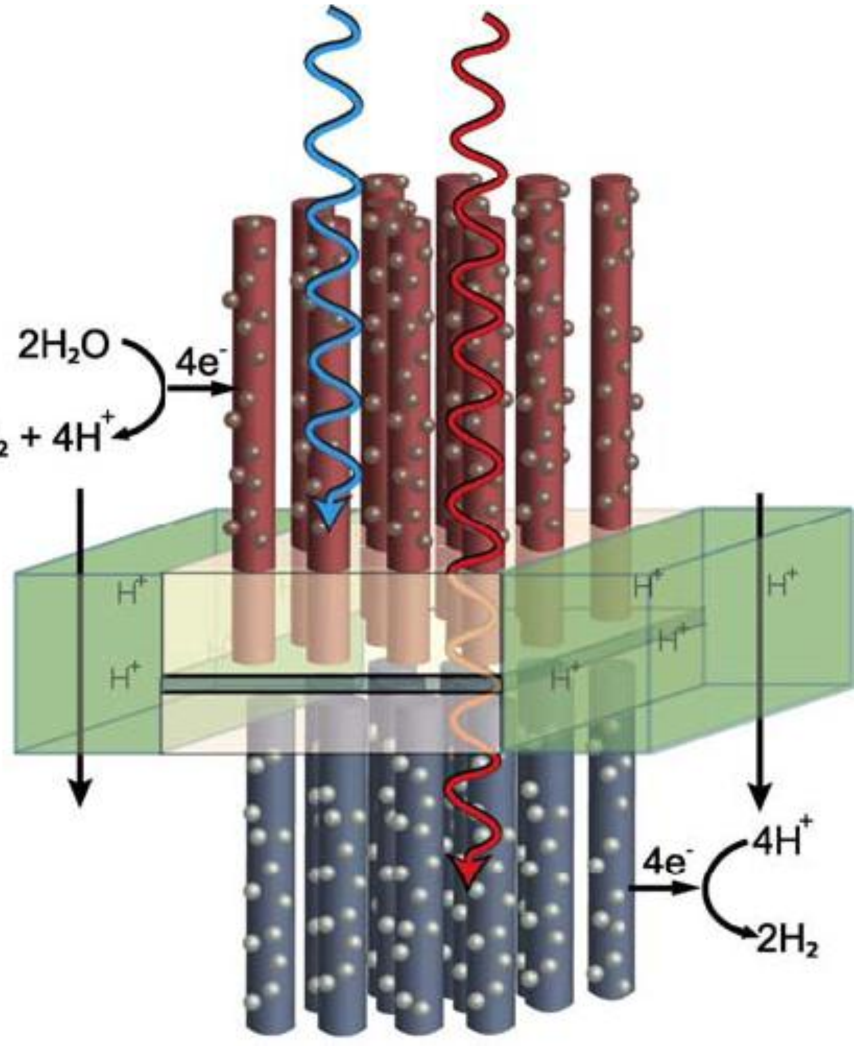
JCAP JOINT CENTER FOR ARTIFICIAL PHOTOSYNTHESIS
BERKELEY LAB

System Concept

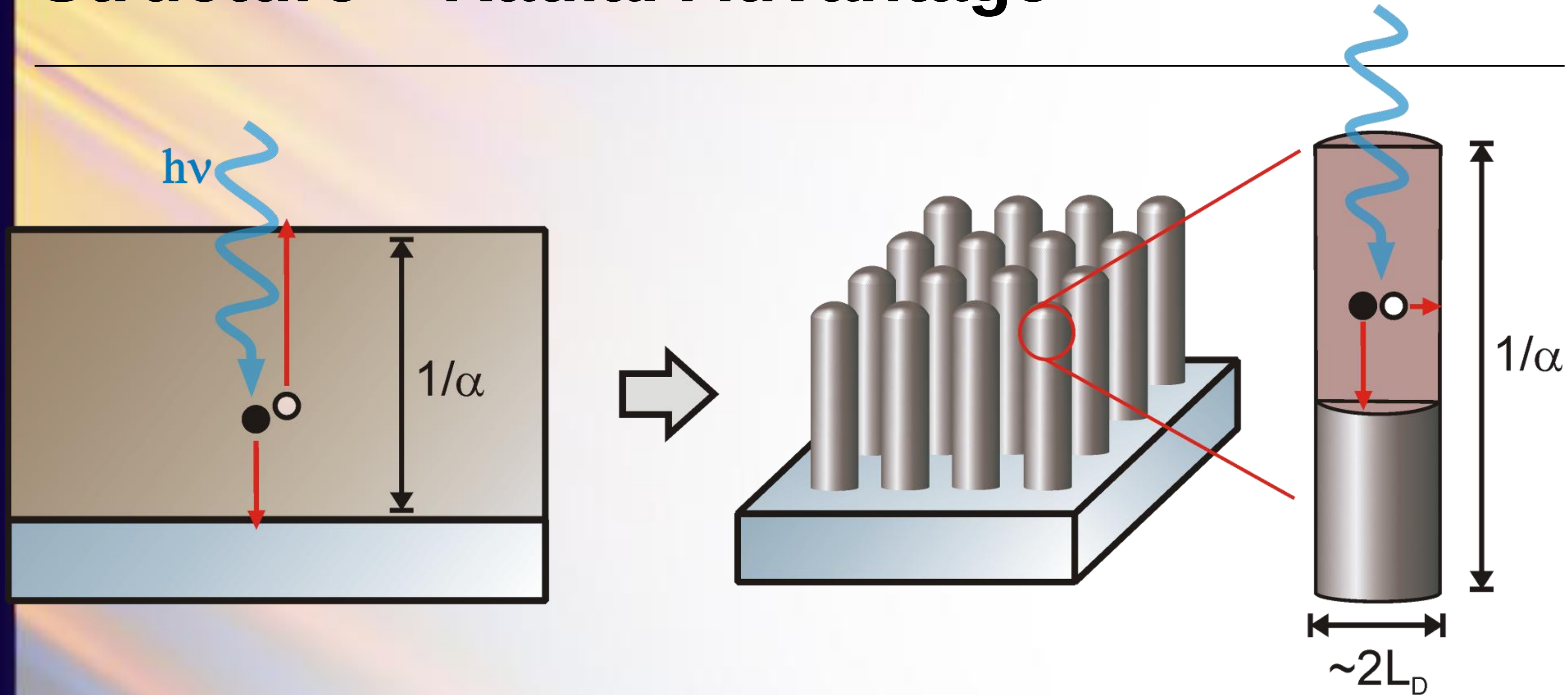


$$2\,H_2O \xrightarrow{\text{Light}} 2\,H_2 + O_2$$

Constructing the Pieces of a Solar (H_2) Fuel Generator



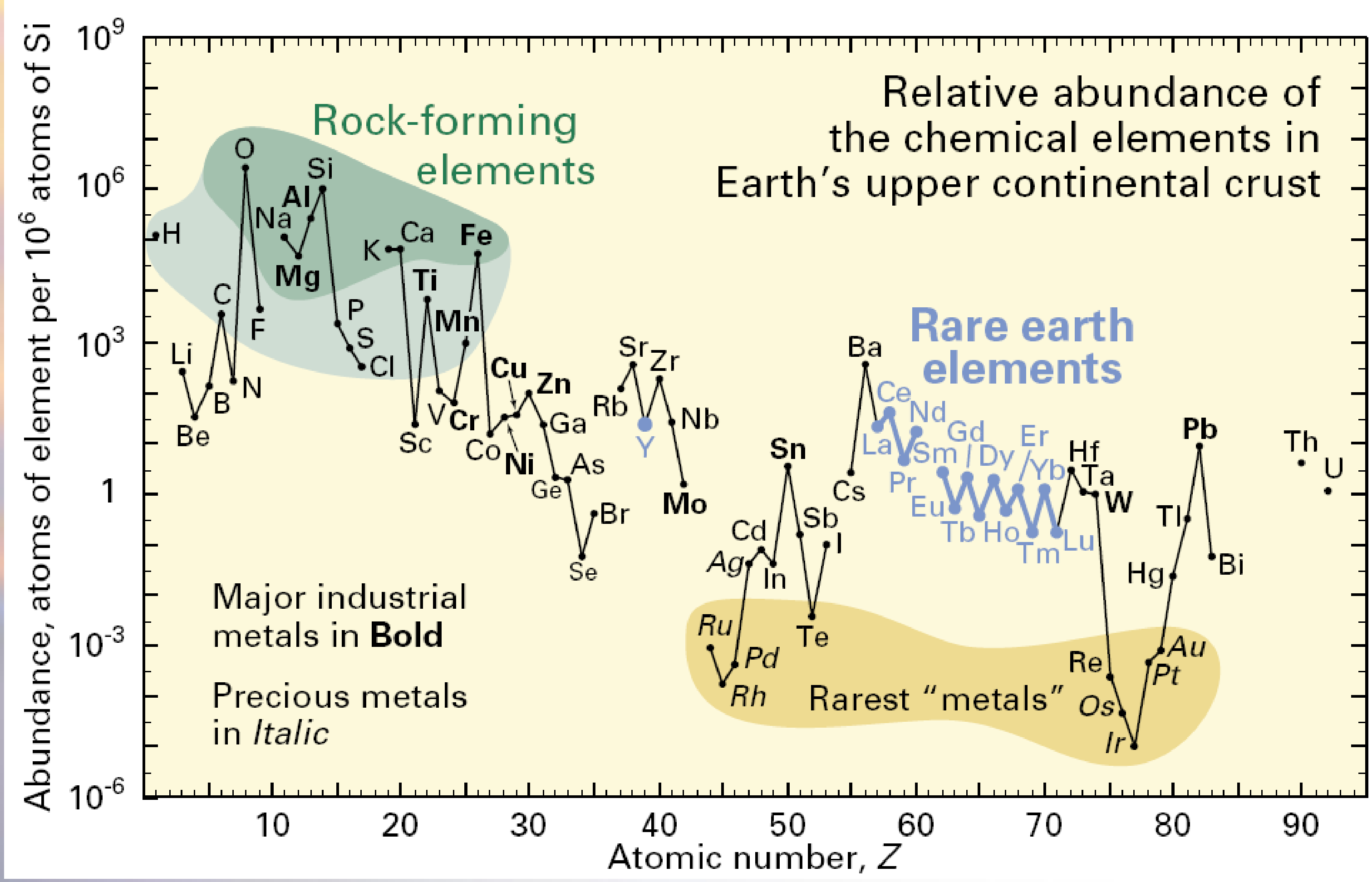
Structure – Radial Advantage



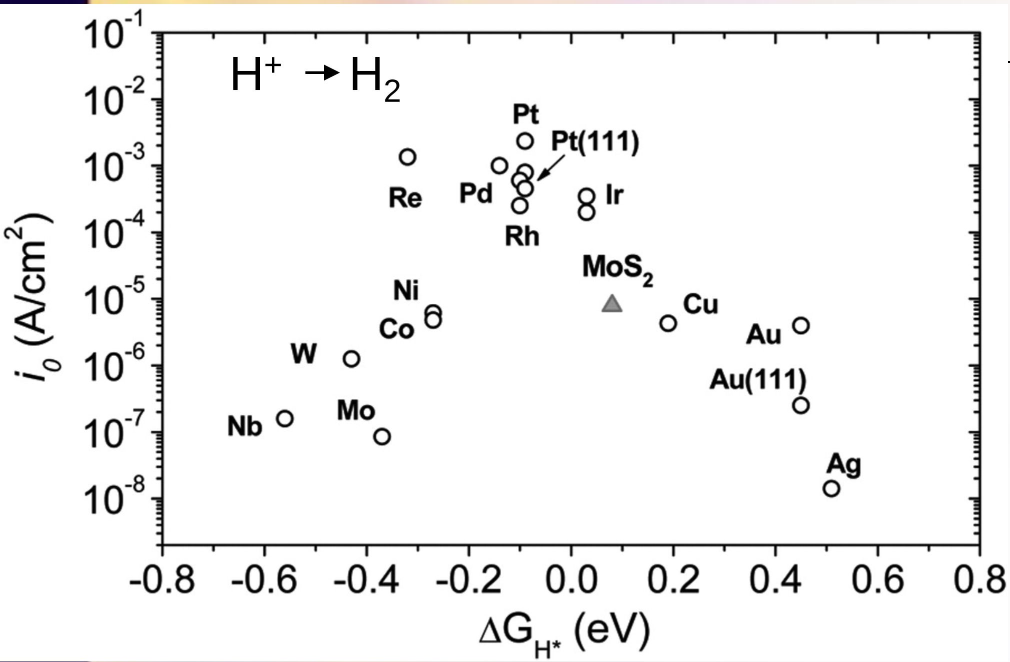
L_D ✪ purity ✪ materials cost

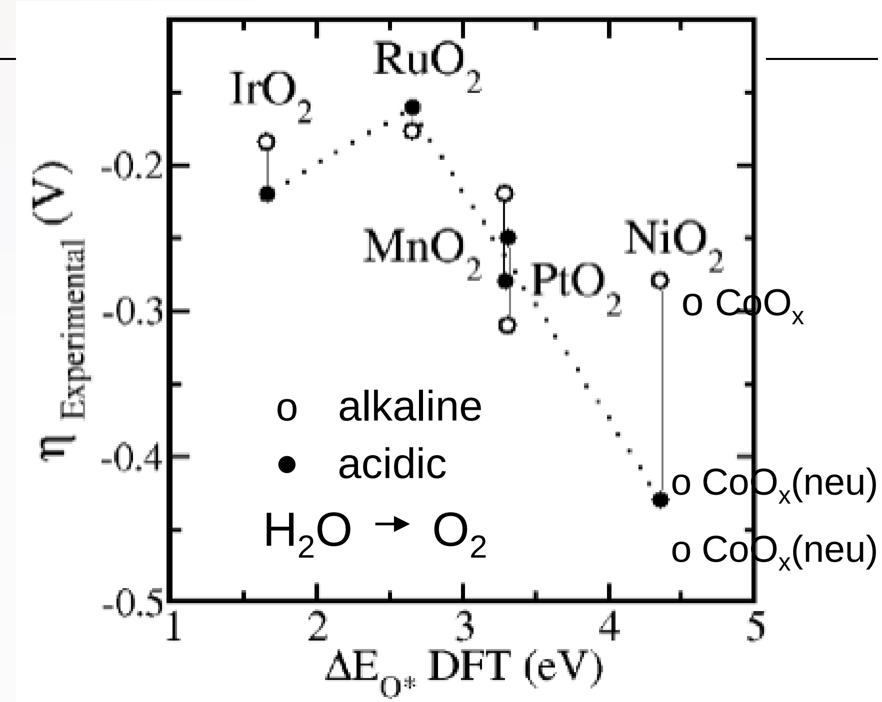
Impure material but high performance

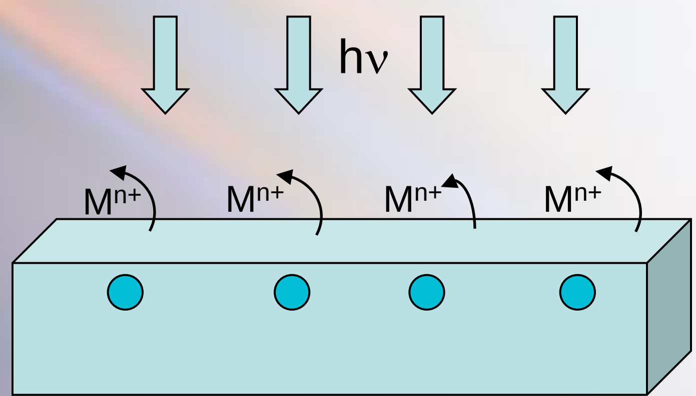
Enables Application of New Materials

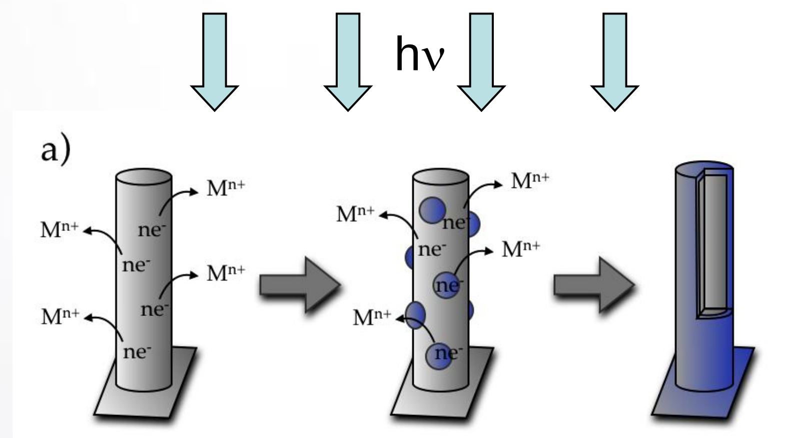


Relaxes Catalyst Activity Requirements



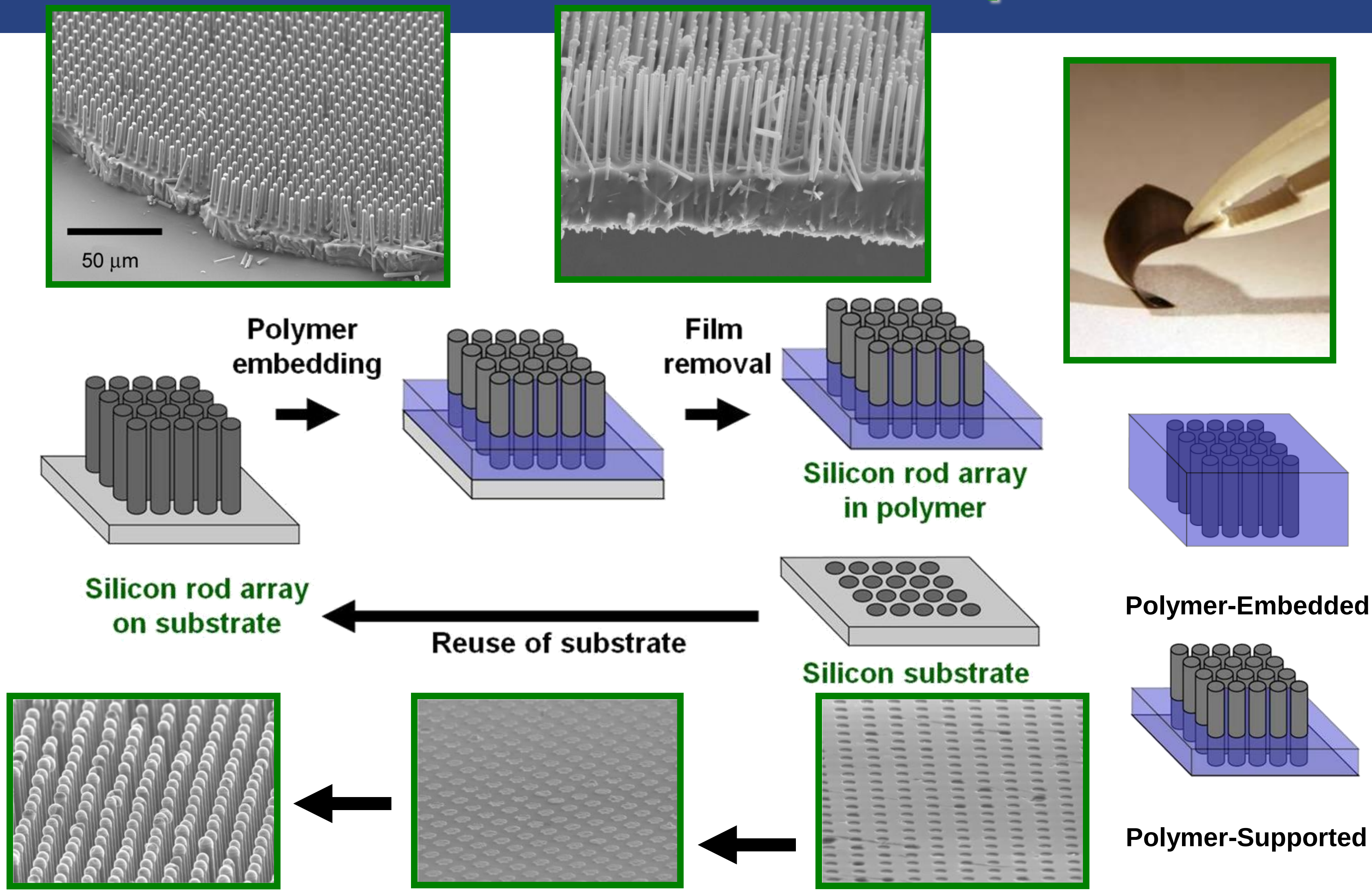






Report of the Basic Energy Sciences Workshop on Solar Energy Utilization

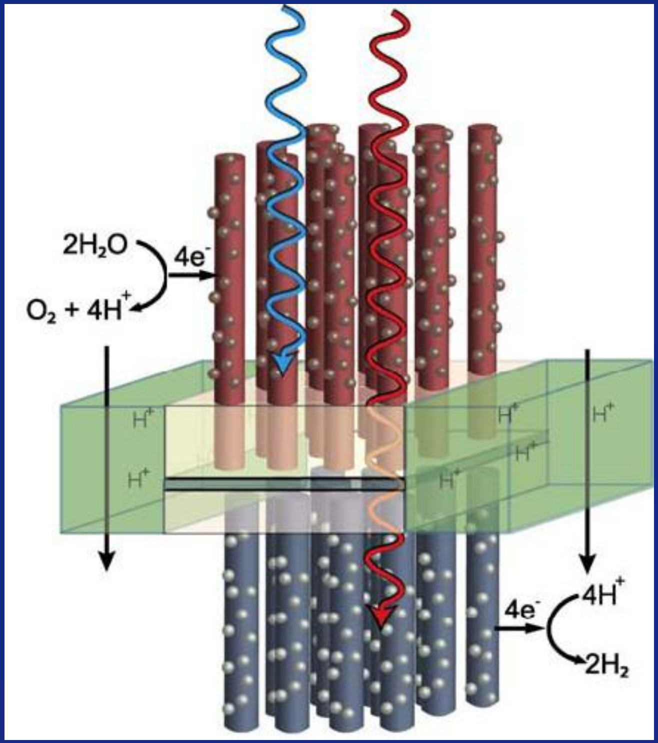
Flexible PDMS-Si Wire Composites

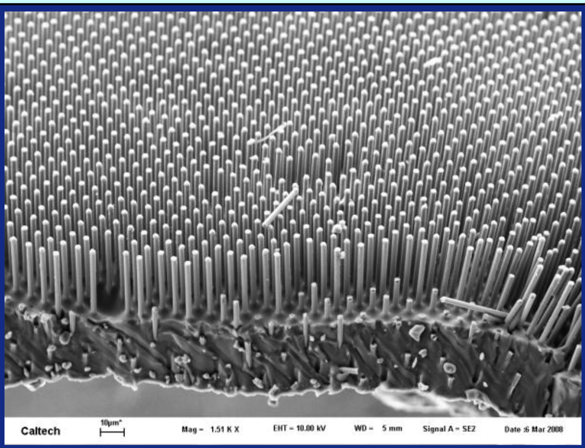


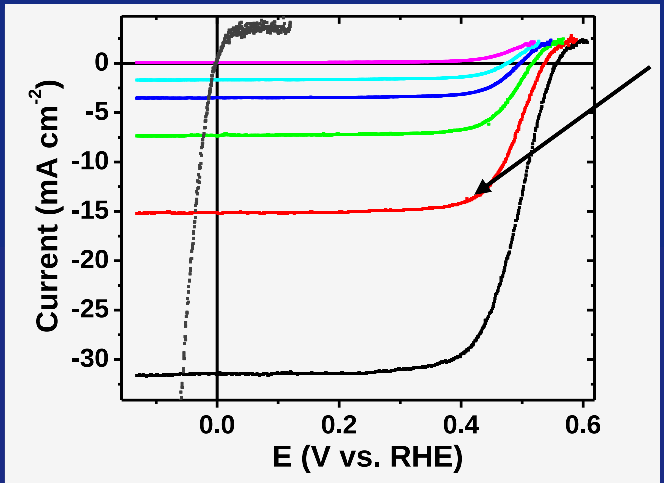
Spurgeon, et al., *Appl Phys. Lett.* 93 (3) (2008).
Plass, et al., *Adv. Mater.* **21** (325) (2009).

Fundamental Design Principles and Progress

- Require >1.23 V of photovoltage
- Require membrane to neutralize pH gradient and separate products
- Require catalytic sites to transform individual e^--h^+ pairs into multi-electron transfer reactions



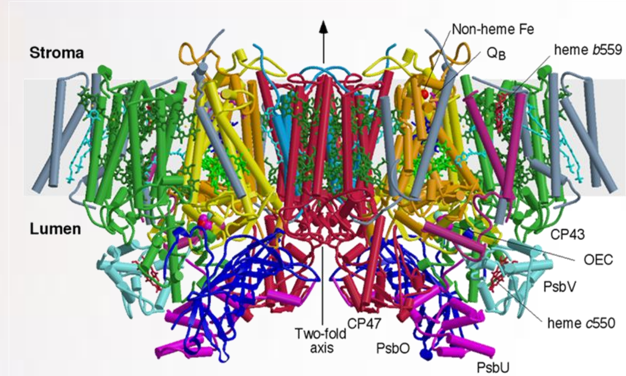




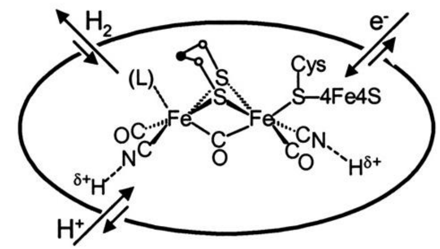
7% to H_2

(w only 60% absorption)

Solar-Powered Catalysts for Fuel Formation



photosystem II

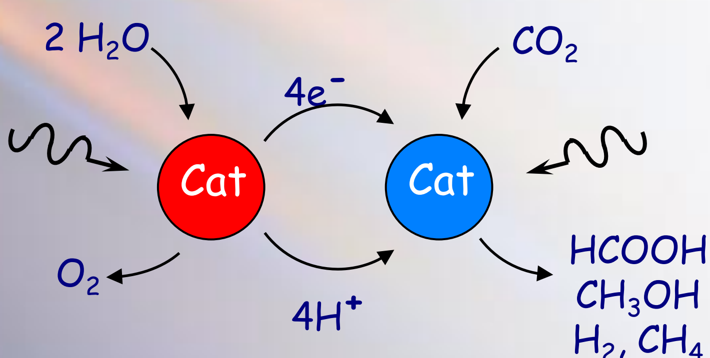


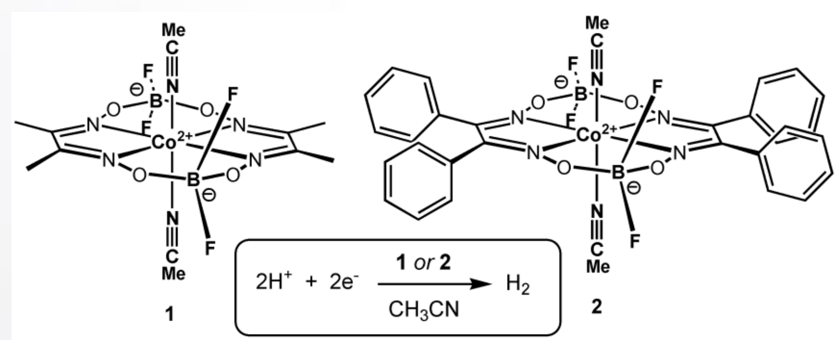
Active site of Fe-H_2ase

hydrogenase

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

oxidation *reduction*

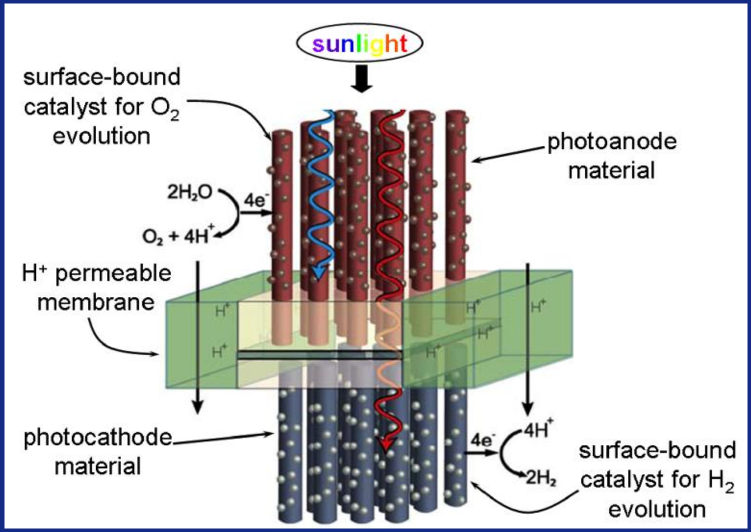




Molecular-Nanoscale Interface

Gaps: How to combine components into working system; functionality of components individually vs collectively

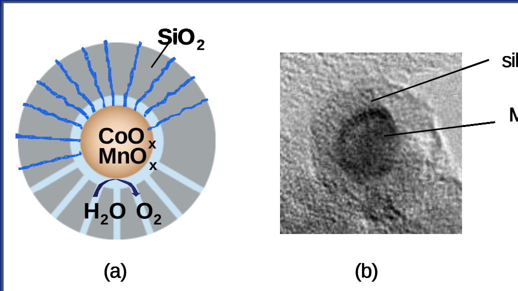
-



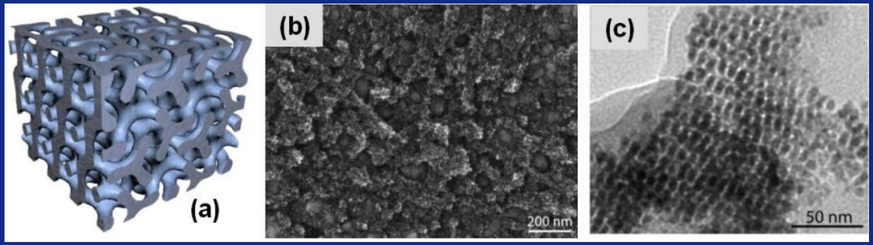
Starting Points: MnO_x; CoO_x Ni-Mo

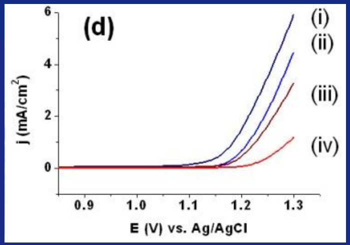
Approach: Control functionality of integrated components

Exploit 3-D to achieve desired activity and/or functionality



CoO_x/MnO_x core shell catalyst



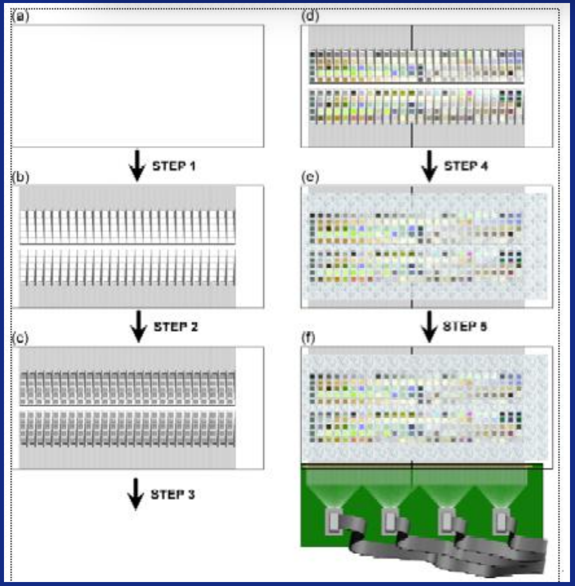


Synthesis and catalytic activity of Ru double gyroid vs planar Ru for O_2 evolution

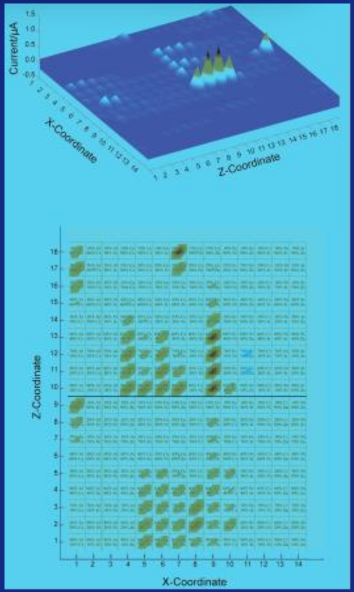
Heterogeneous Catalyst Discovery

Gaps: Complement with Ultra-high Throughput Experimentation

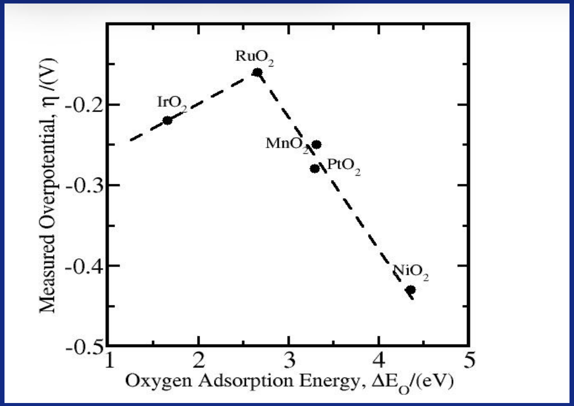
Outputs: Tie together theory, surface science, electro-chemistry, X-ray spectroscopy, high-throughput experimentation



Schematic of the process of preparing the substrate and making electrical contact to 130 individual materials on a single piece of FTO-coated glass.



False color images of the photocurrent of a slide that contained spots of binary mixed-metal oxides (top). Three-dimensional plot (bottom). Top-down view.



Measured OER overpotential vs calculated adsorption energy

Starting Points:

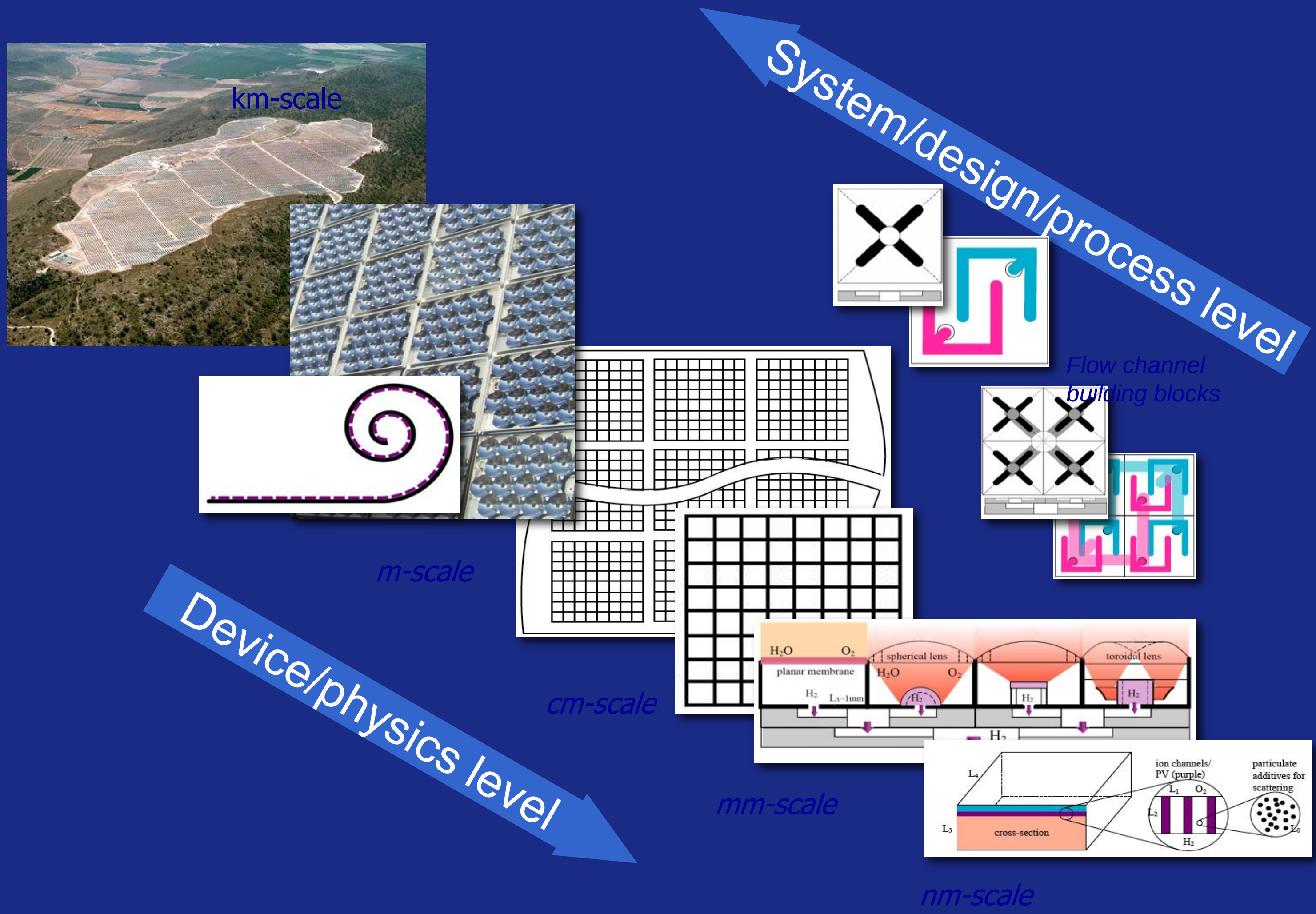
H_2/CO_2: MS_x; O_2: MO_x, MO_xN_y

Activity Metrics/Goals:

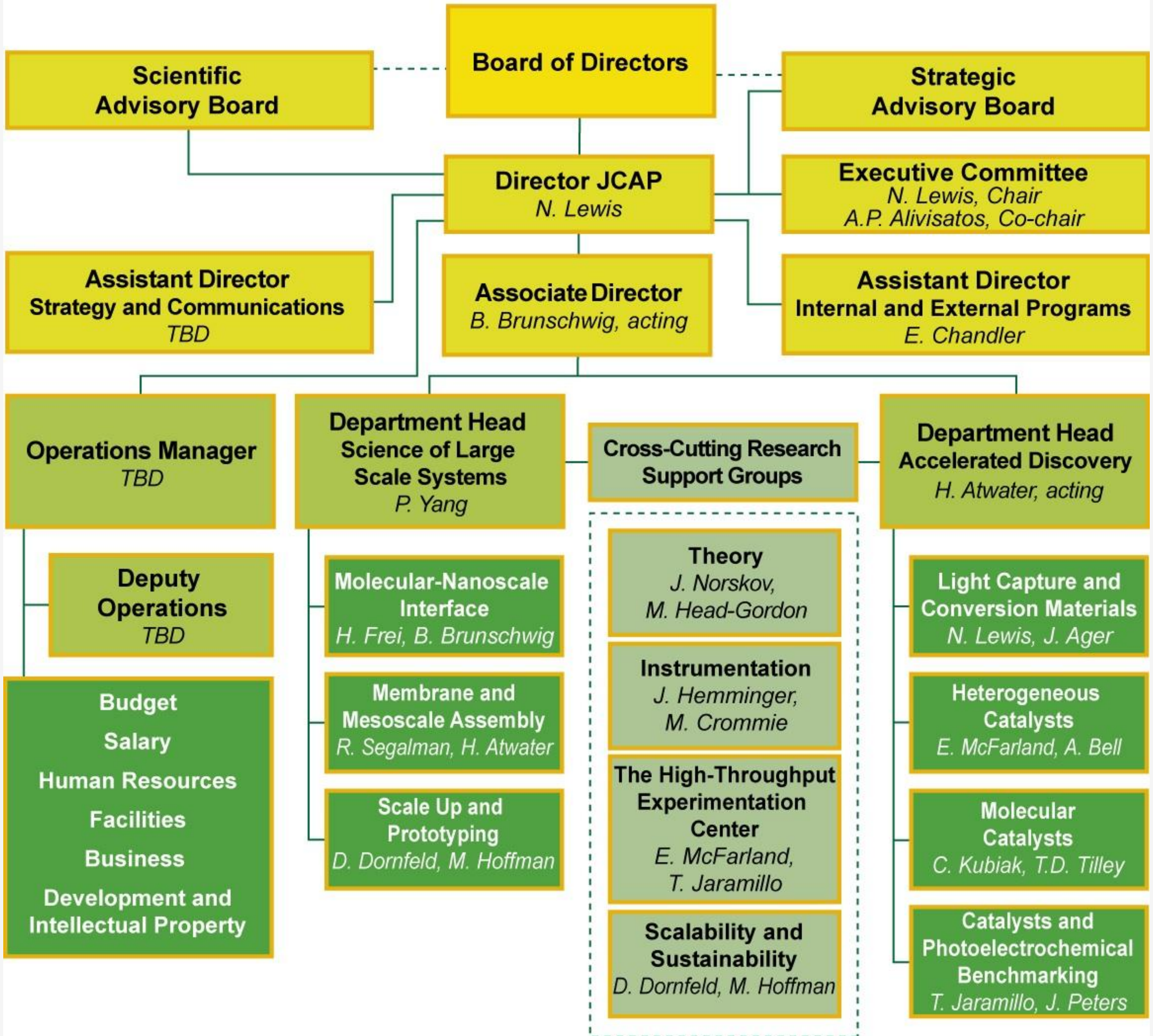
~x 10^2 for H_2; ~x 10^4 for O_2

>x 10^5 for CO_2

Envisioning JCAPs Products



JOINT CENTER FOR ARTIFICIAL PHOTOSYNTHESIS



Basic Research Needs for Solar Energy Utilization

Report of the Basic Energy Sciences Workshop on Solar Energy Utilization

Nathan S. Lewis
Caltech

with

George Crabtree, ANL
Arthur Nozik, NREL
Mike Wasielewski, NU
Paul Alivisatos, UC-Berkeley

April 18-21, 2005

Office of Science
U.S. DEPARTMENT OF ENERGY

CONCLUSIONS

- Without **massive** quantities (10-20 TW by 2050) of clean energy, CO_2 levels will continue to rise
- The only sufficient supply-side cards we have are "clean" coal, nuclear fission (with a closed fuel cycle), and/or cheap solar fuel
- We need to pursue globally scalable systems that can efficiently and cost-effectively capture, convert, and store sunlight in the form of chemical fuels
  - He that can not store, will not have power after four
- Semiconductor/liquid junctions offer the *only* proven method for achieving this goal, but we have a great deal of fundamental science to learn to enable the underpinnings of a cost-effective, deployable technology
  - Nanorods, randomly ordered junctions to generate the needed potential
  - Catalysts to convert the incipient electrons into fuels by rearranging the chemical bonds of water (and CO_2) into O_2 and a reduced fuel

BES Workshop on Basic Research Needs for Solar Energy Utilization

April 21-24, 2005

Workshop Chair: Nathan Lewis, Caltech
Co-chair: George Crabtree, Argonne

Panel Chairs
Arthur Nozik, NREL: Solar Electric
Mike Wasielewski, NU: Solar Fuel
Paul Alivisatos, UC-Berkeley: Solar Thermal

Topics
Photovoltaics
Photoelectrochemistry
Bio-inspired Photochemistry
Natural Photosynthetic Systems
Photocatalytic Reactions
Bio Fuels
Heat Conversion & Utilization
Elementary Processes
Materials Synthesis
New Tools

Plenary Speakers
Pat Dehmer, DOE/BES
Nathan Lewis, Caltech
Jeff Mazer, DOE/EERE
Marty Hoffert, NYU
Tom Feist, GE

200 participants
universities, national labs, industry
US, Europe, Asia
EERE, SC, BES

Charge
To identify basic research needs and opportunities in solar electric, fuels, thermal and related areas, with a focus on new, emerging and scientifically challenging areas that have the potential for significant impact in science and technologies.