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Nanotechnology: Applications in Energy - Solar

NACK is an NSF-funded ATE Resource Center supporting faculty in Nanotechnology Education

Hosted by MATEC Networks

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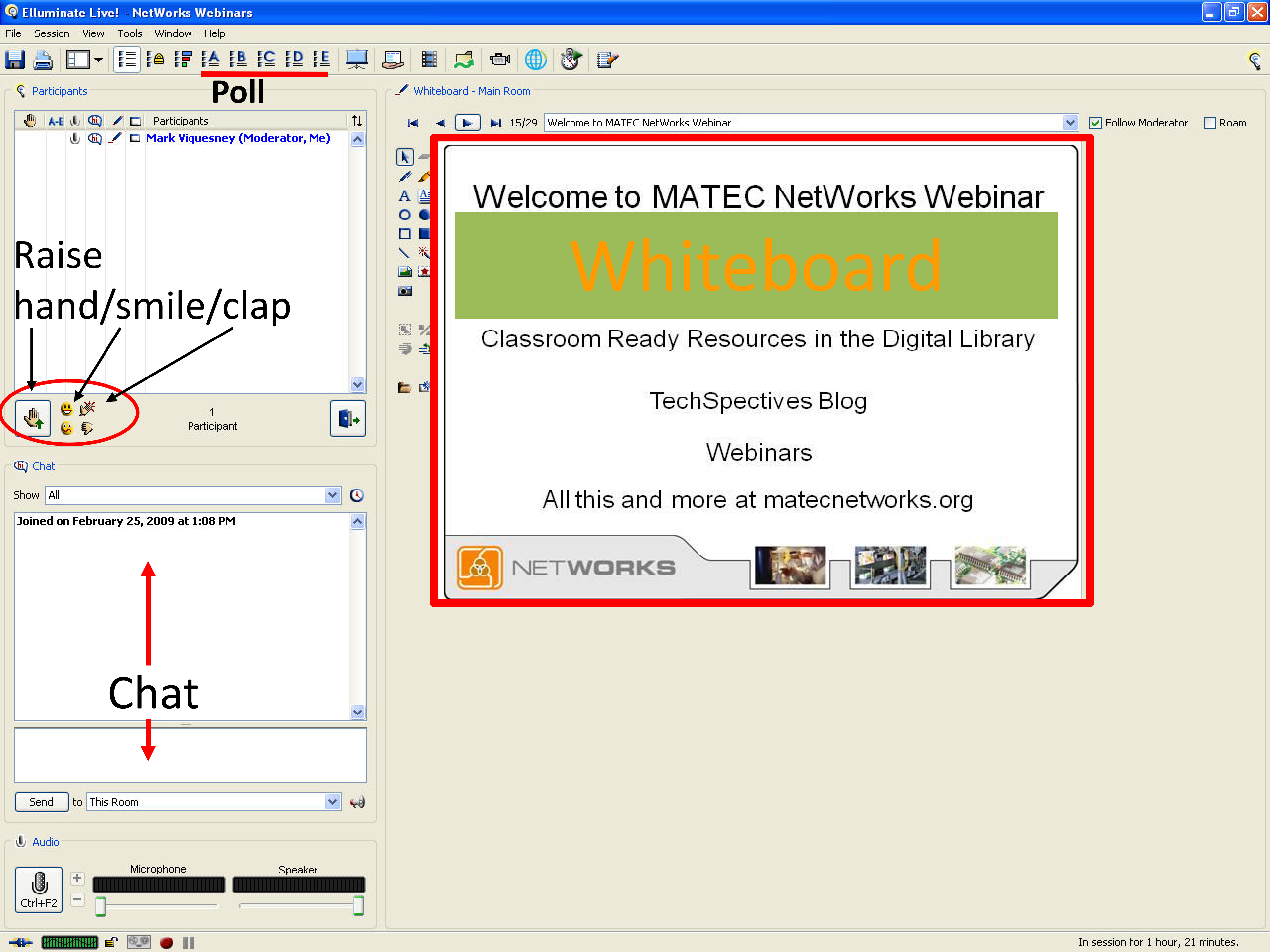
NACK CENTER

NACK is the NSF ATE National Center for Nanotechnology Applications and Career Knowledge

The NACK National Center is located at Penn State University

Funded, in part, by a grant from the National Science Foundation.
DUE-08020498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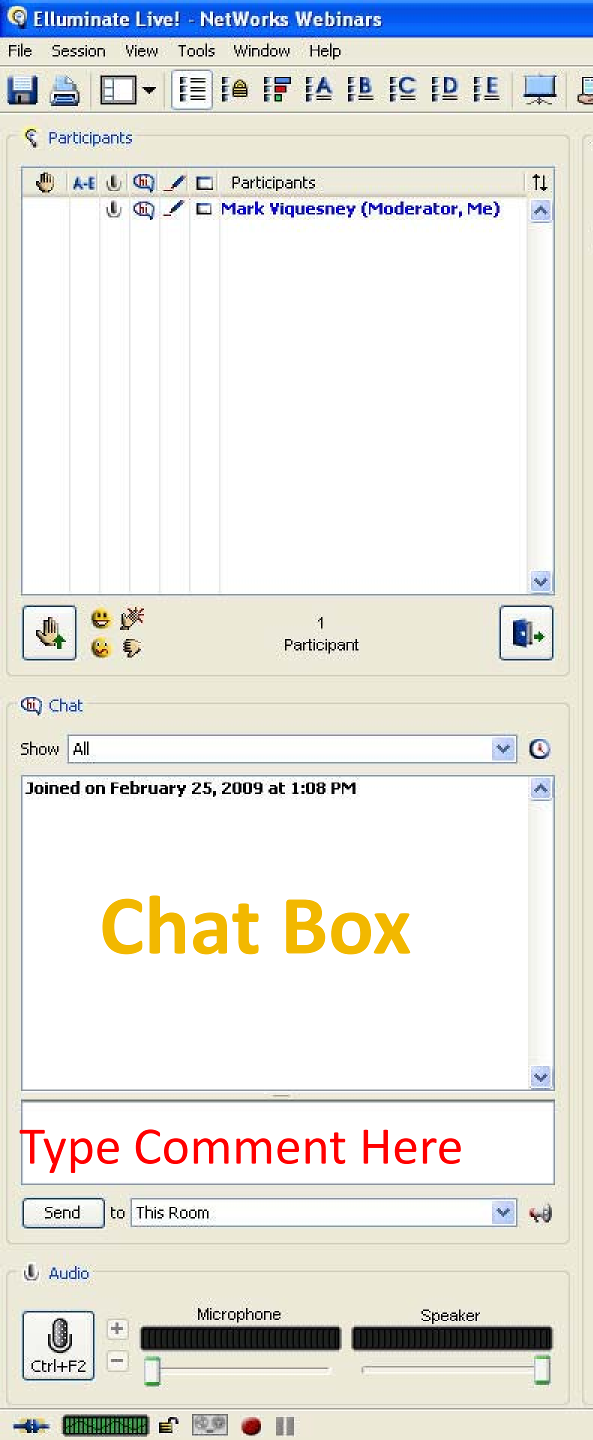

Chat Box

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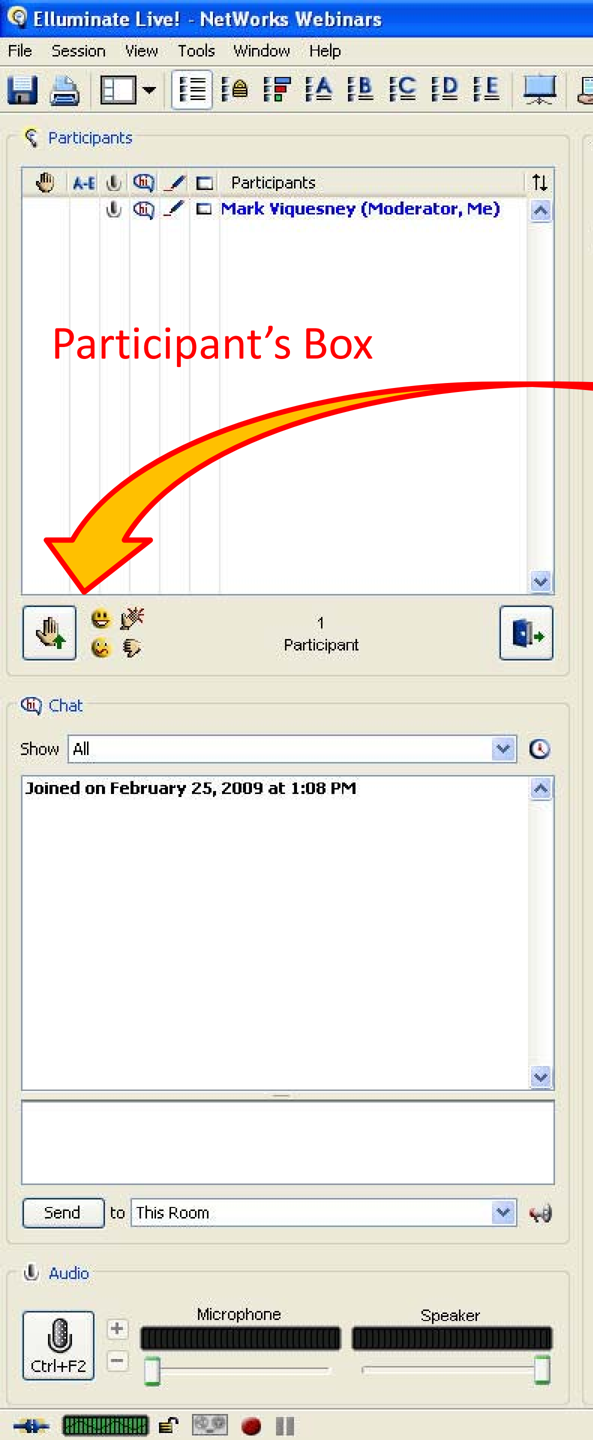
Allows you to non-verbally respond to the presenter's comments.

Participant’s Box



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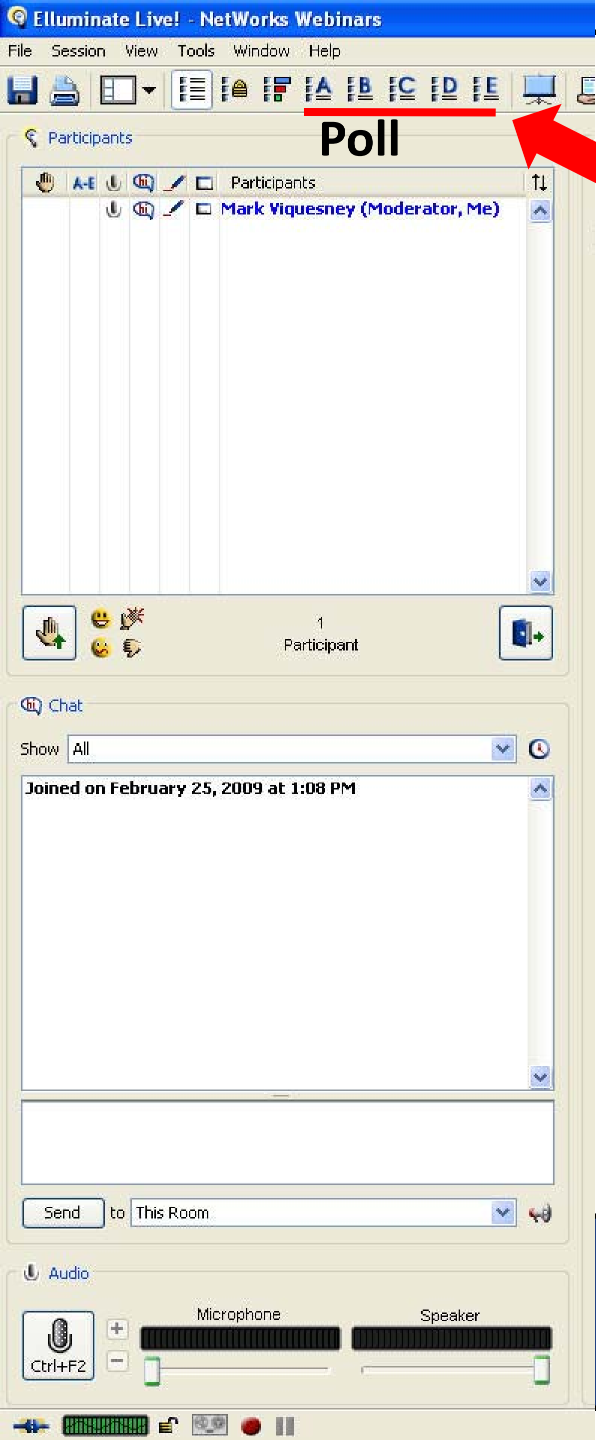

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NetWorks Webinar Presenter

Travis Benanti, Ph.D tbenanti@gmail.com

Research Associate

Center for Nanotechnology Education and Utilization (CNEU) Regional Center

Nanotechnology Applications and Career Knowledge (NACK) National Center

The Pennsylvania State University

MRS Bulletin **2005**, *30(6)*, 412.

MATERIAL MATTERS

Future Global Energy Prosperity: The Terawatt Challenge

Richard E. Smalley

Top 10 World Issues

1. Energy
2. Water
3. Food
4. Environment
5. Poverty
6. Terrorism and war
7. Disease
8. Education
9. Democracy
10. Population

"To give all 10 billion people on the planet the level of energy prosperity we in the developed world are used to, a couple of kilowatt-hours per person, we would need to generate 60 terawatts around the planet – the equivalent of 900 million barrels of oil per day."

"When we look at a prioritized list of the top 10 problems, with energy at the top, we can see how energy is the key to solving all of the rest of the problems – from water to population."

-Richard E. Smalley
Nobel Laureate in Chemistry (1996, for the discovery of fullerenes)

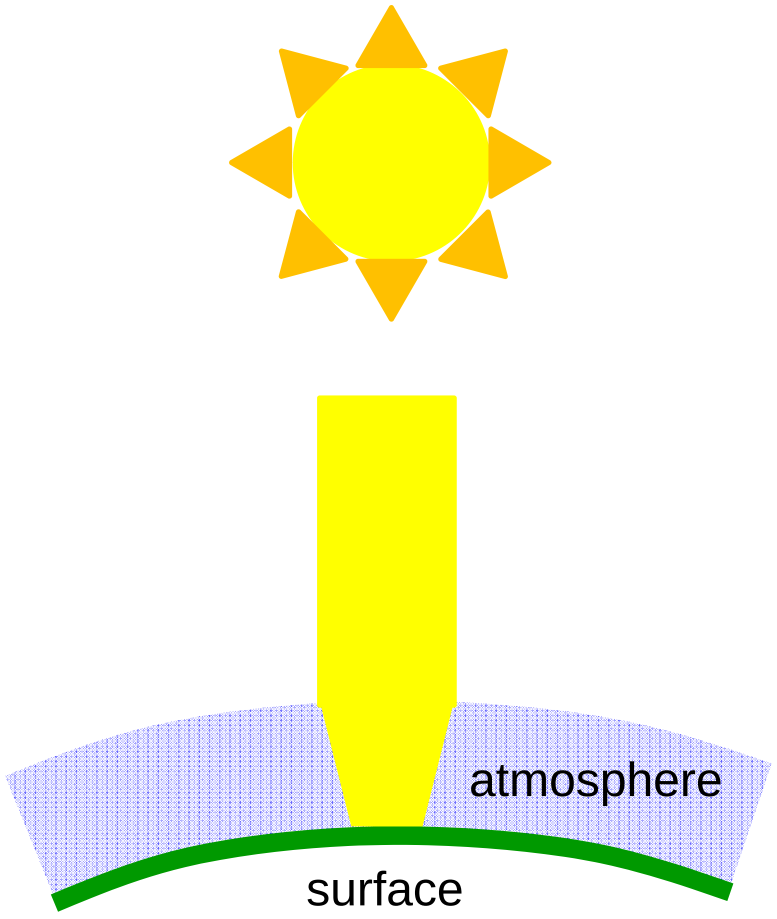
Solar Radiation

1366 W/m^2: Power density of the sunlight striking the Earth's outer atmosphere. Known as the solar constant.

1000 W/m^2: Power at Earth's surface on a clear day with the sun directly overhead.

300 W/m^2: Approximate amount available on Earth when averaged over 24 hours.

153,000 TW …way more than enough!



Using the Sun's Energy

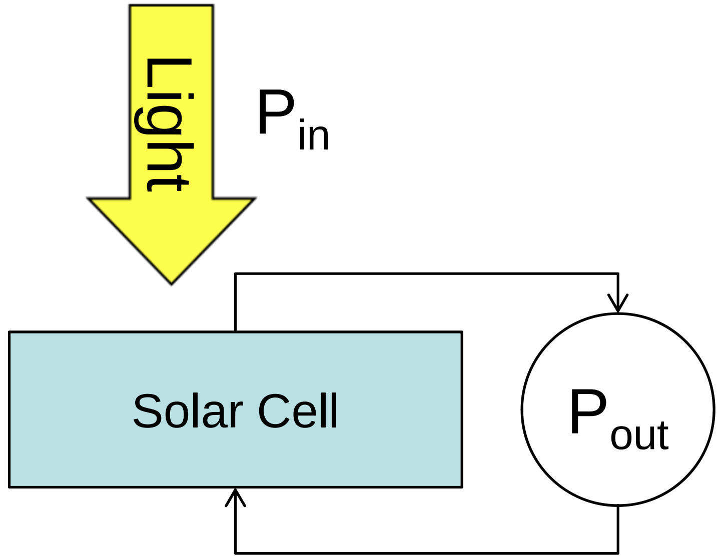
The basic processes in converting the sun's energy into usable electricity are:

1. Absorption of light
2. Creation of free charge carriers: e^- and h^+
3. Transport and collection of charge
4. Using the electrical energy
   - To power a device (e.g., a calculator)
   - To recharge a battery (energy storage)

Power Conversion Efficiency

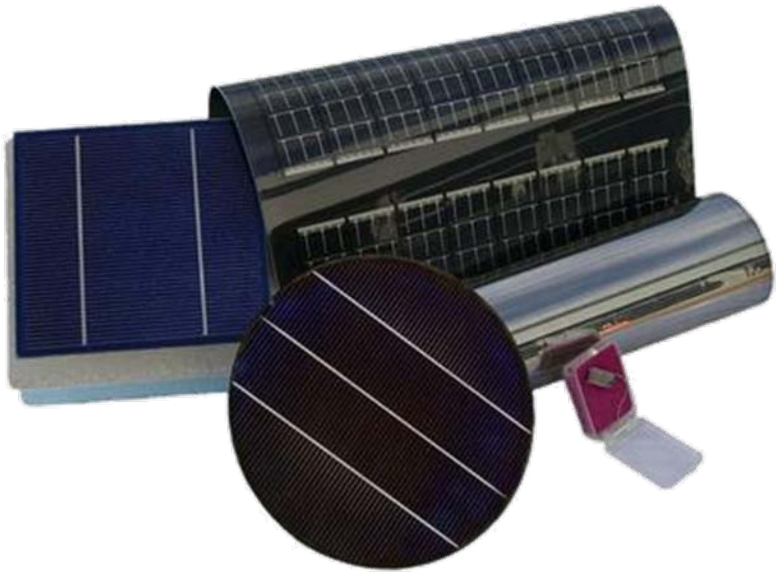
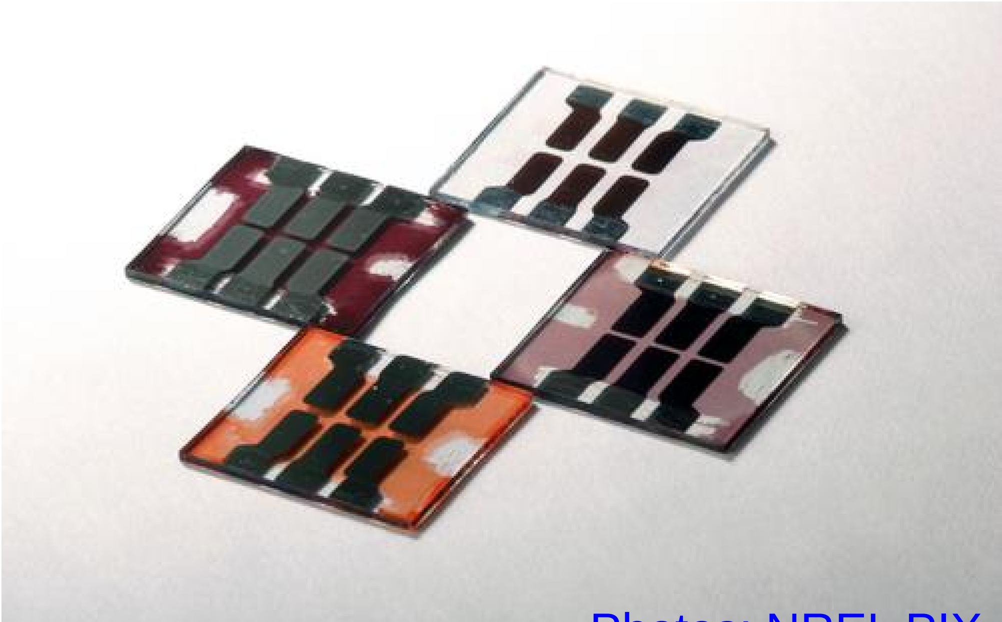
- Abbreviated PCE
- Ratio of power density obtained from solar cell to the incident solar power density
- The incident light is often produced by a solar simulator and P_{in} is commonly fixed at 100 mW/cm^2

$$PCE = \frac{P_{out}}{P_{in}}$$

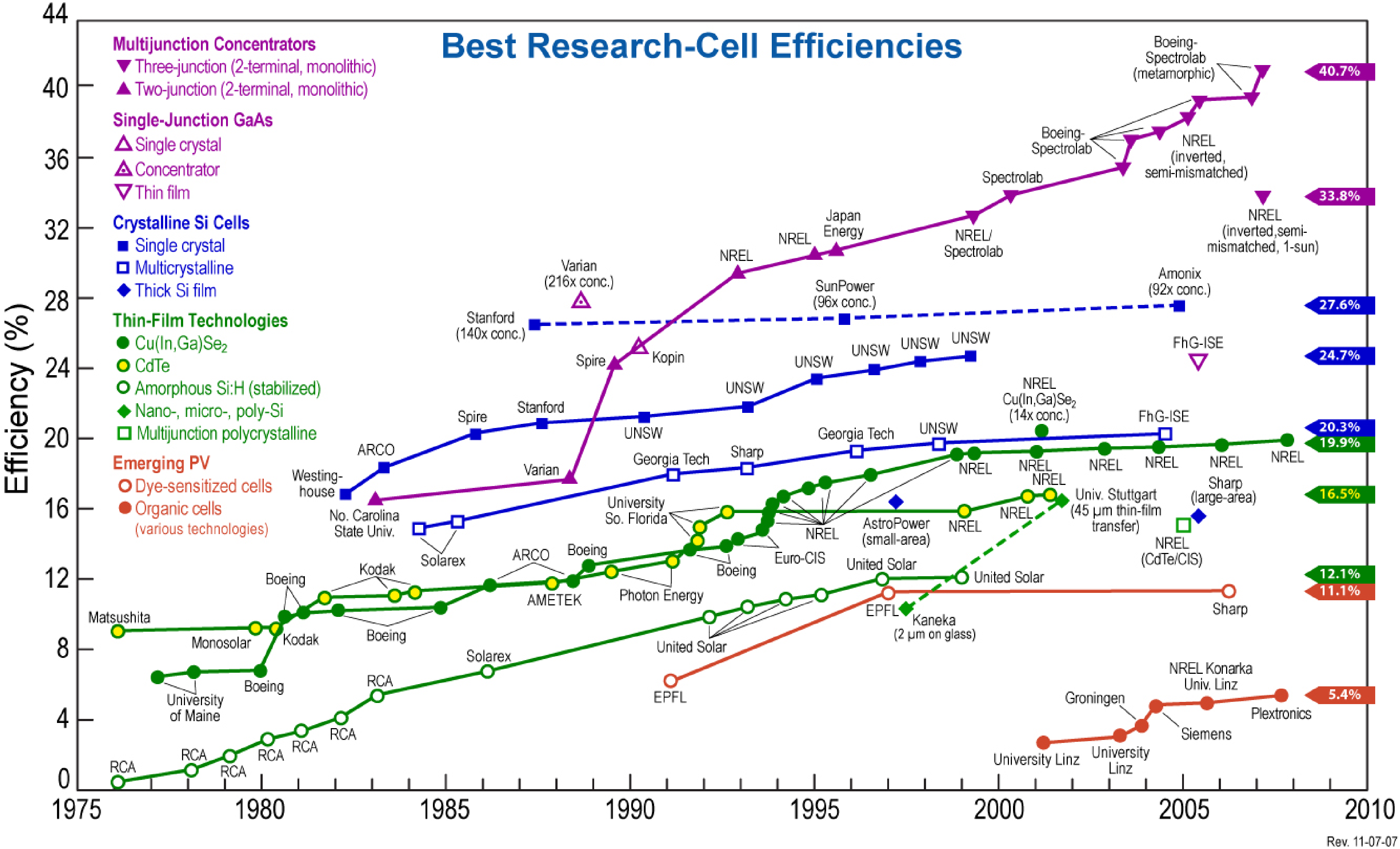


Solar Cell Technologies

- 1st Generation: Crystalline silicon
- 2nd Generation: amorphous silicon, CdTe, CIGS (thin film technologies)
- 3rd Generation: organic and dye sensitized

Photos: NREL PIX

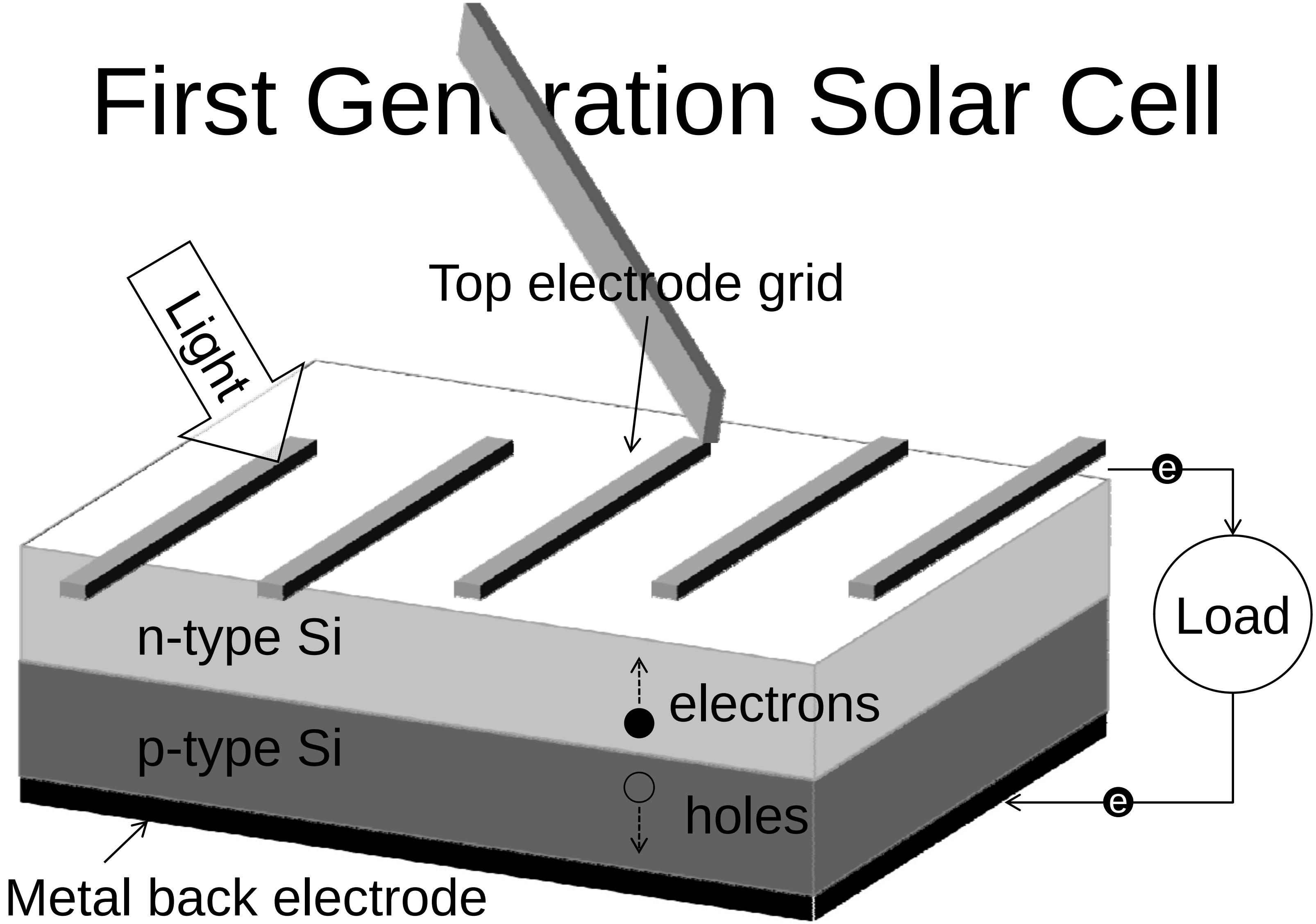


Best Research-Cell Efficiencies
Efficiency (%)
Multijunction Concentrators
Three-junction (2-terminal, monolithic)
Two-junction (2-terminal, monolithic)
Single-Junction GaAs
Single crystal
Concentrator
Thin film
Crystalline Si Cells
Single crystal
Multicrystalline
Thick Si film
Thin-Film Technologies
Cu(In,Ga)Se2
CdTe
Amorphous Si:H (stabilized)
Nano-, micro-, poly-Si
Multijunction polycrystalline
Emerging PV
Dye-sensitized cells
Organic cells
(various technologies)
40.7%
33.8%
27.6%
24.7%
20.3%
19.9%
16.5%
12.1%
11.1%
5.4%
Boeing-Spectrolab (metamorphic)
NREL (inverted, semi-mismatched)
NREL (inverted,semi-mismatched, 1-sun)
Amonix (92x conc.)
SunPower (96x conc.)
Stanford (140x conc.)
Varian (216x conc.)
NREL Cu(In,Ga)Se2 (14x conc.)
Univ. Stuttgart (45 μm thin-film transfer)
Sharp (large-area)
NREL (CdTe/CIS)
Kaneka (2 μm on glass)
NREL Konarka Univ. Linz
Rev. 11-07-07

Source: NREL

Questions?

First Generation Solar Cell



First Generation Solar Cell

- One p-n junction
- Made of very high purity silicon
- Can be single crystal or multicrystalline

Principle of Operation

1. Light absorption creates free charge carriers (electrons and holes)
2. The p-n junction directs current to flow in only one direction
3. Charge carriers are collected at the electrodes, which allow current to flow through an external circuit

First Generation Solar Cell

<u>Advantages</u>

- High efficiency
- Long lifetime

<u>Disadvantages</u>

- Expensive materials
- Expensive production processes
- Rigid structures
- Fragile

Nanostructured Solar Cell

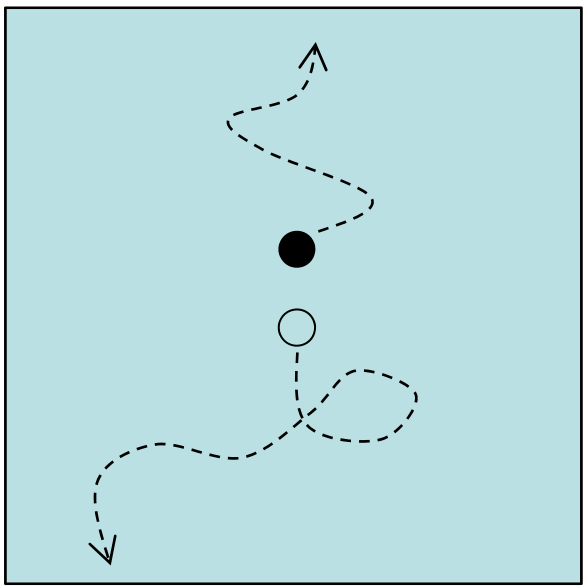
or Micro

Driving Force:

- Making solar cells from less expensive materials, using less expensive processes, means that new devices may not be as efficient.
- Nanotechnology may be able to improve efficiency, while keeping costs low.

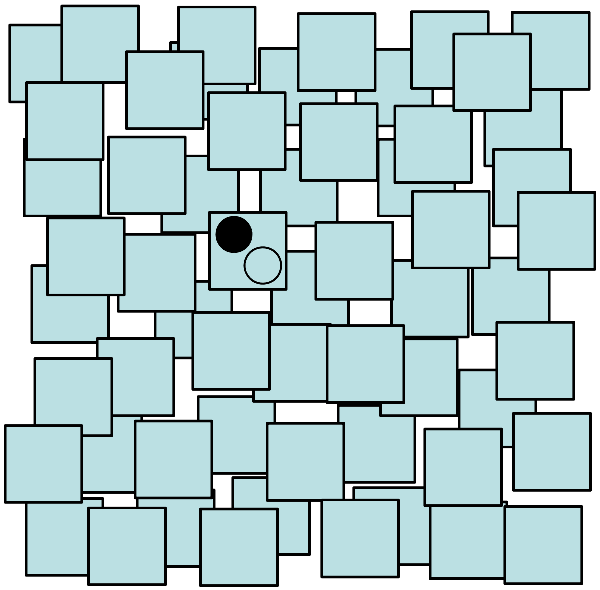
Nano~~s~~structured Solar Cell

Single Crystalline Material



Charge carriers can travel long distances without being lost to recombination or traps (impurities, defects)

Polycrystalline or Amorphous

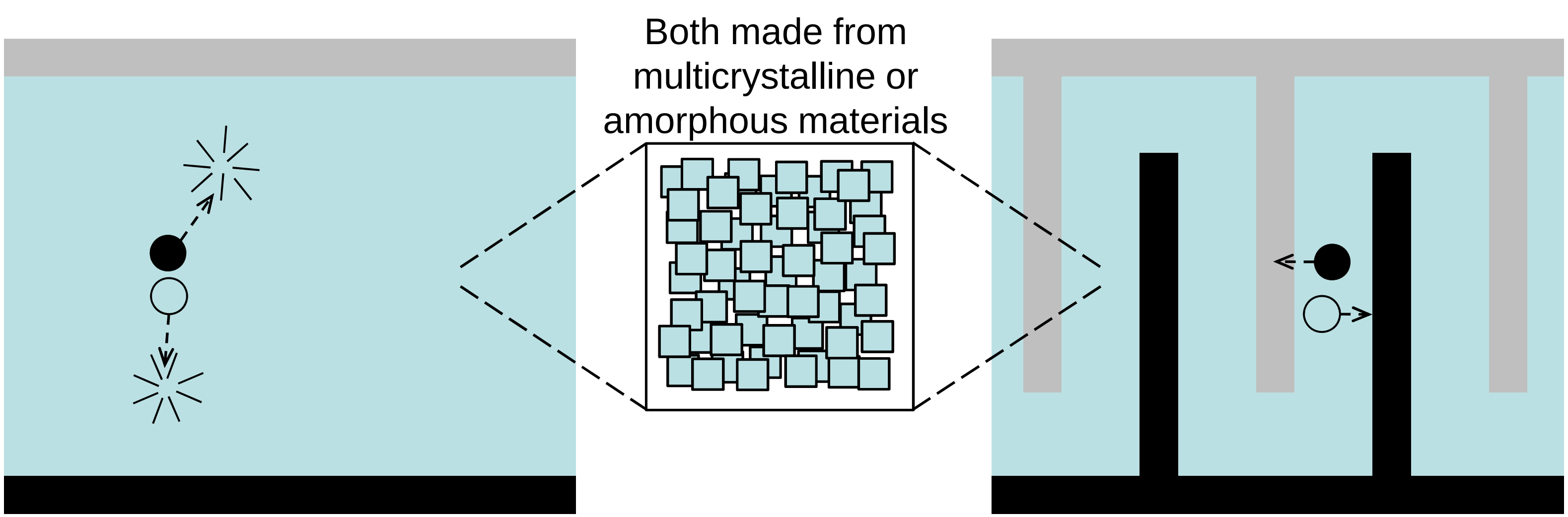


Increased disorder and number of defects lead to shorter collection distances

Nanostructured Solar Cell

or Micro

The shortcomings of polycrystalline and amorphous materials can be overcome by incorporating <u>**micro- and nano-scale structures**</u> into devices.



Without nanostructures, many charge carriers recombine before reaching the electrodes.

Nanostructures allow for efficient collection of electrons and holes, regardless of short collection lengths.

Using the Tools of Nanotechnology…

Two Examples of Recent/Ongoing Work:

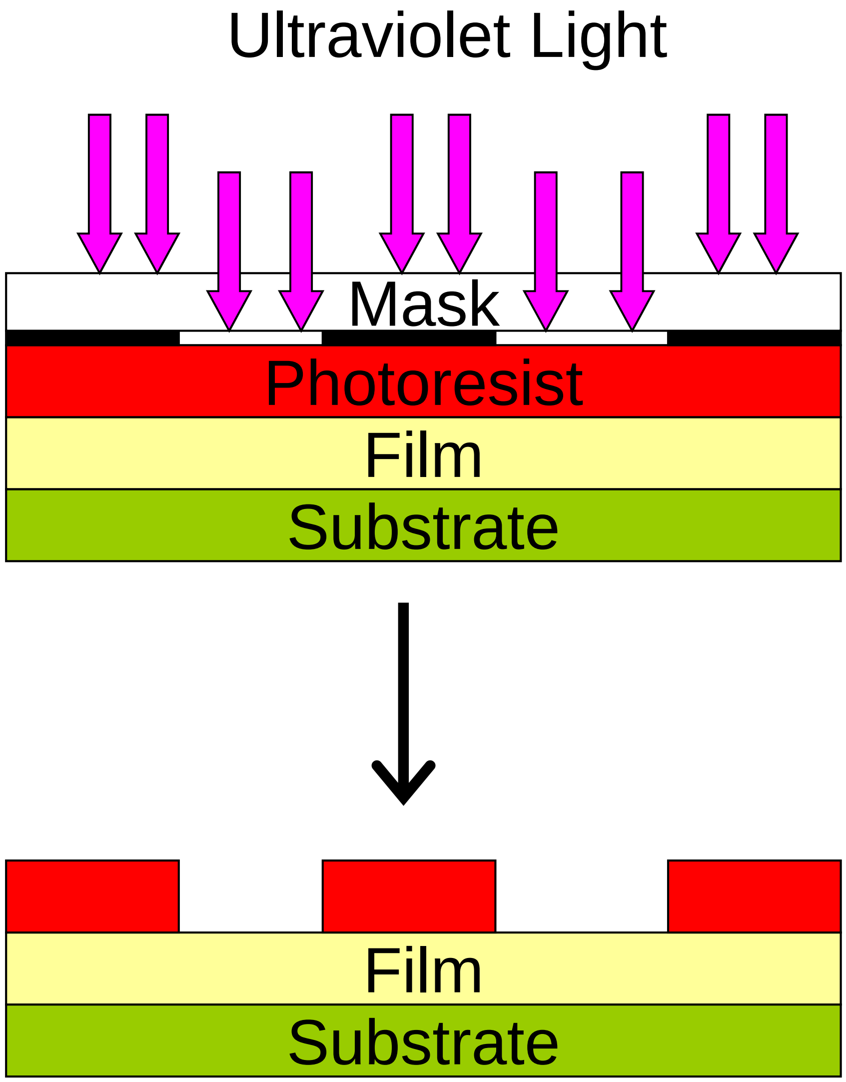
- Micro (microns in size)
- Nano (1 um = 1000 nm)
- NACK resources available to you

…First Example: Using **Conventional Optical Lithography** to Create Microstructures

Basic Steps of Photolithography

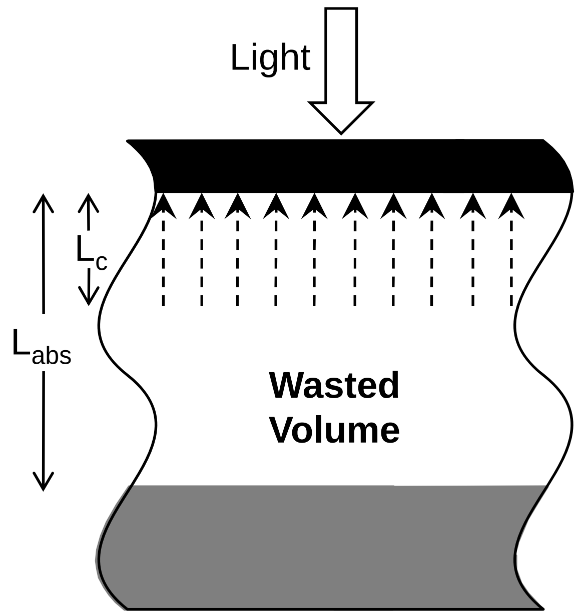
Objective: Transfer a pattern from the mask to the photoresist layer.

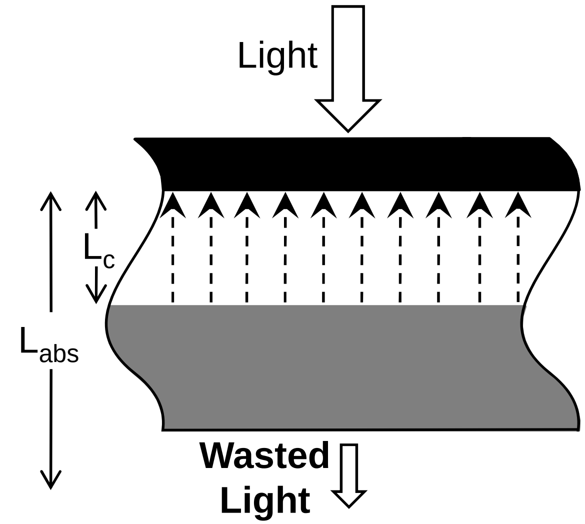
1. Clean substrate
2. Apply photoresist
3. Soft bake
4. Exposure
5. Develop



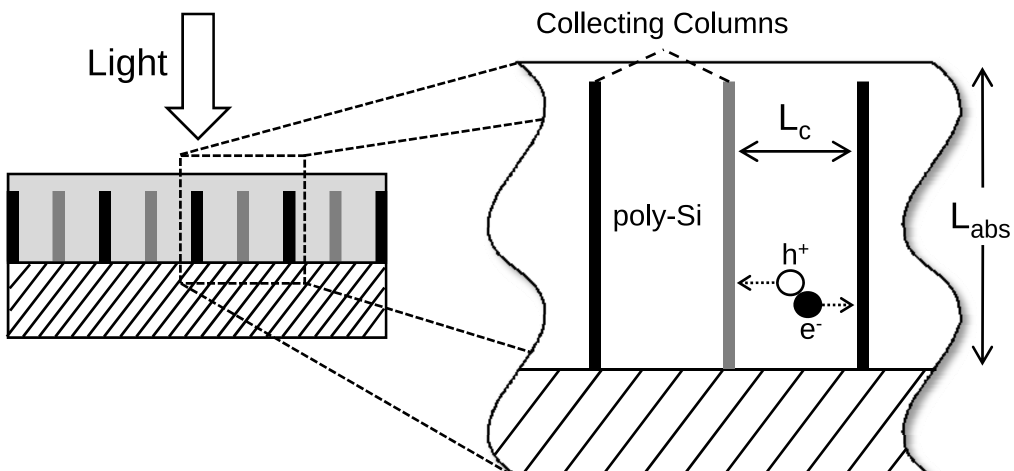
Example 1: Micro-scale

<u>Thick</u>
Able to absorb all light



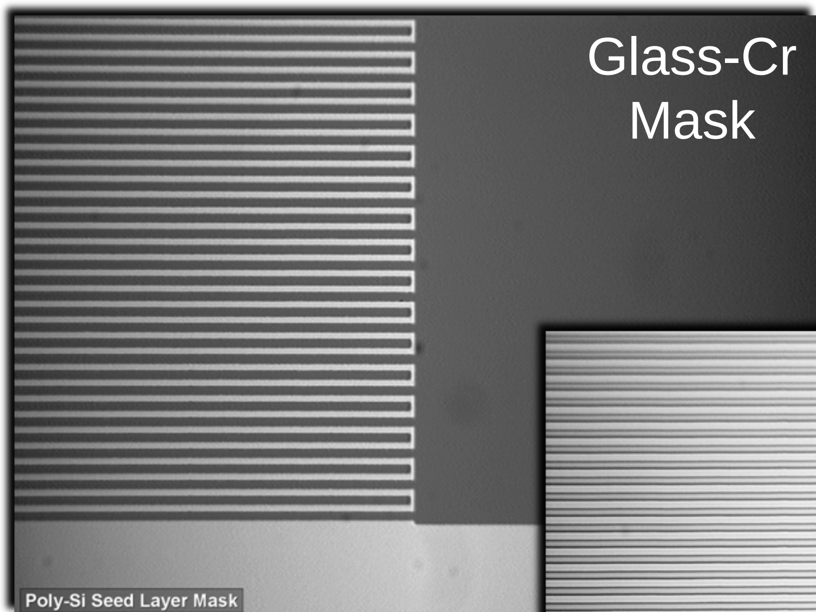


<u>Thin</u>
Able to collect all charge carriers



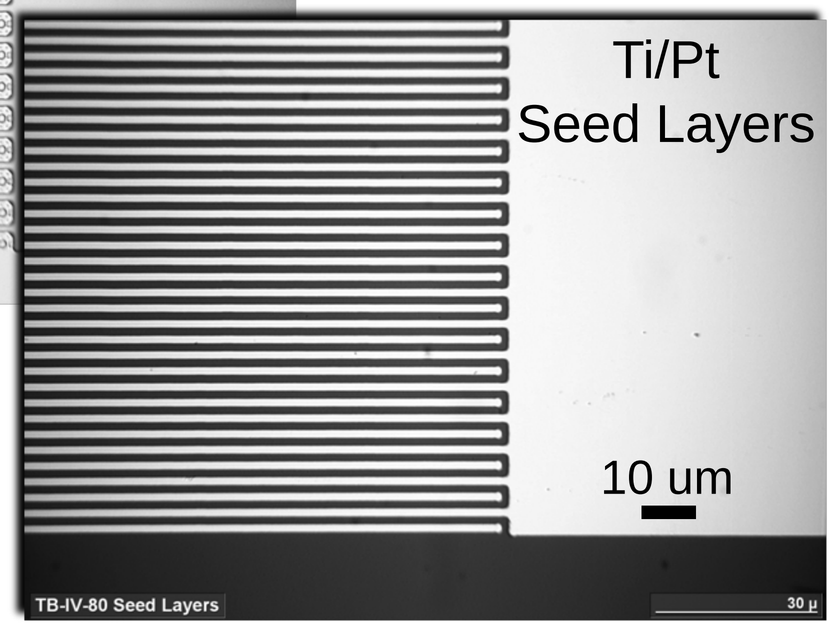
<u>Re-design</u>
Good absorption and good collection

Seed Layer Fabrication via Photolithography



UV-exposure

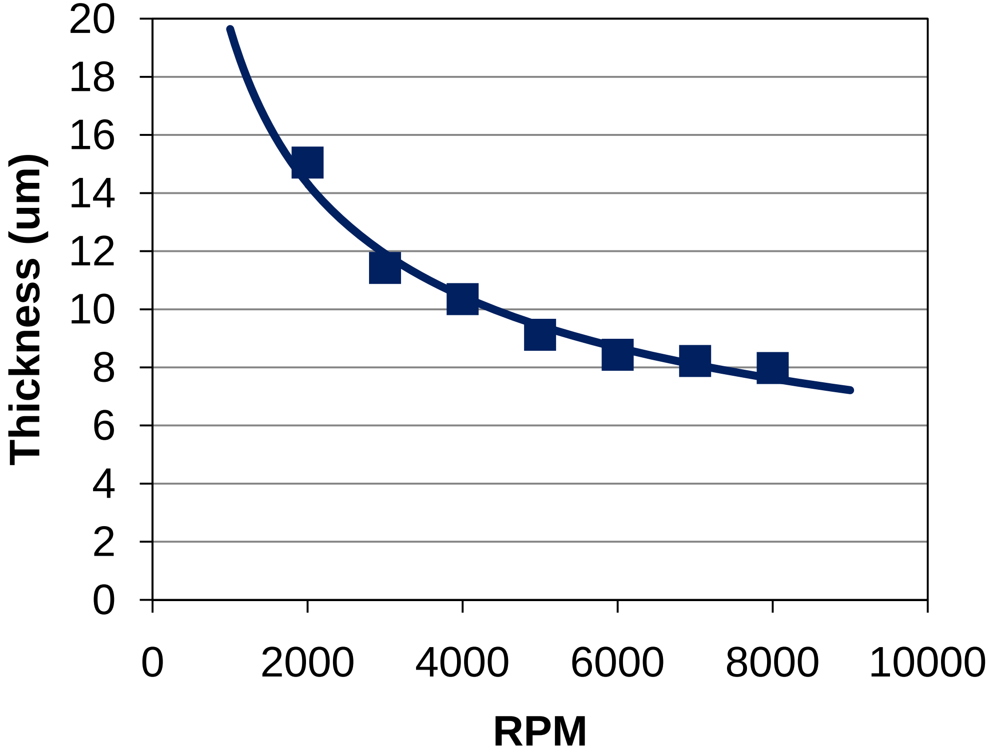
Metal evap &
lift-off

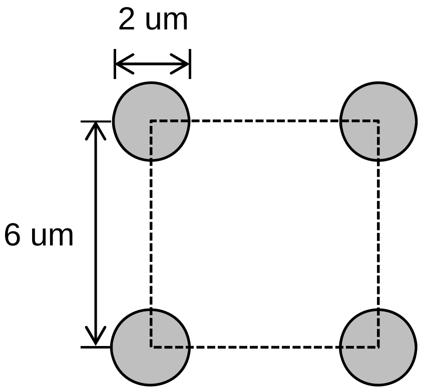


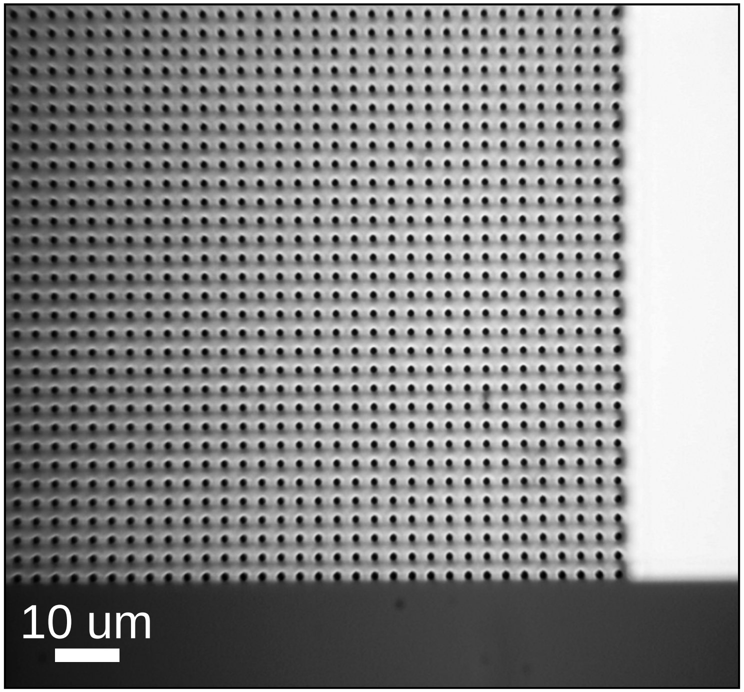
- 3 um lines and spaces
- Seed layers will act as conductive surface for electrodeposition.

Template Fabrication: Stepper

Resist viscosity and spin-casting RPM allow control over template thickness



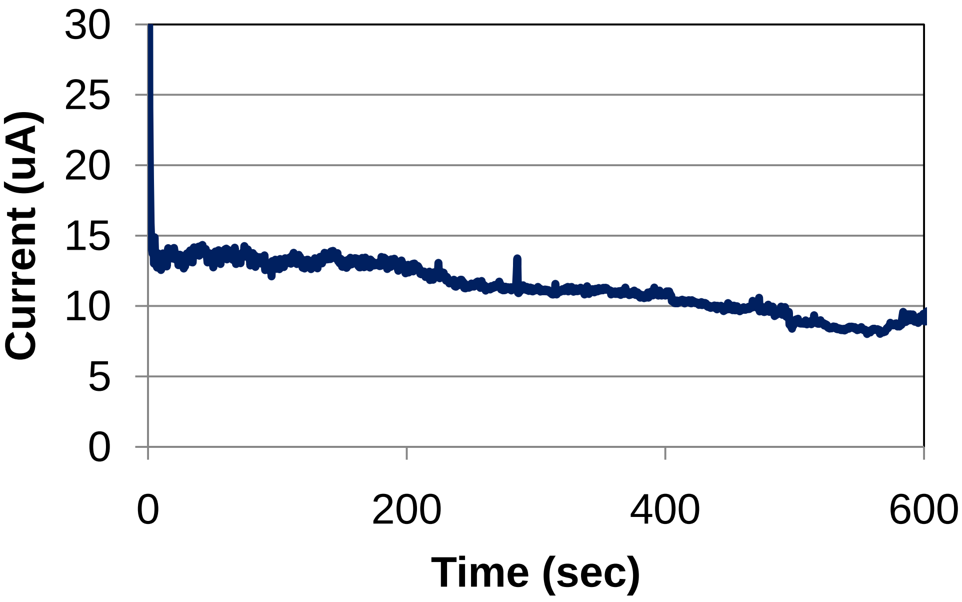




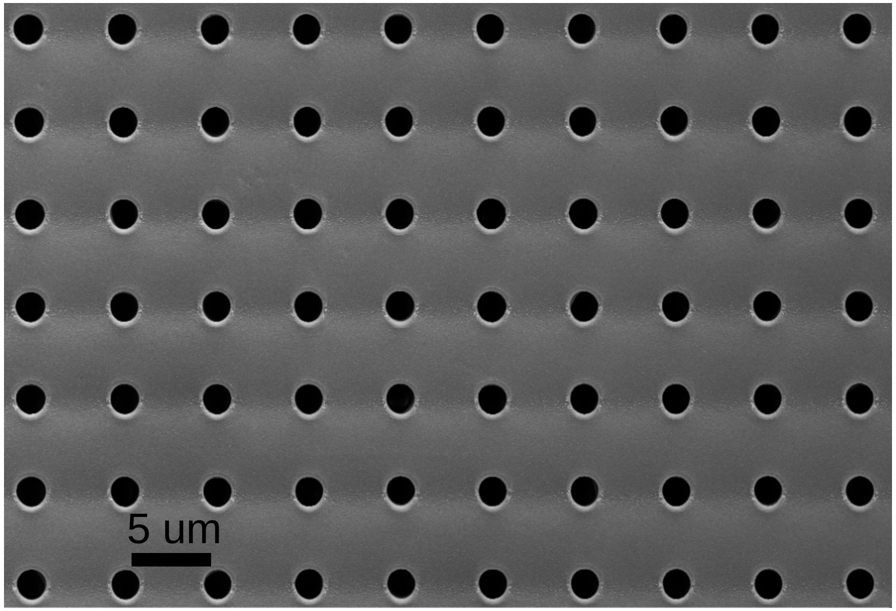
Electrodeposition

Can measure current vs. time and correlate to thickness/height.

Remove template material with solvent or plasma etching (RIE).



FESEM Images



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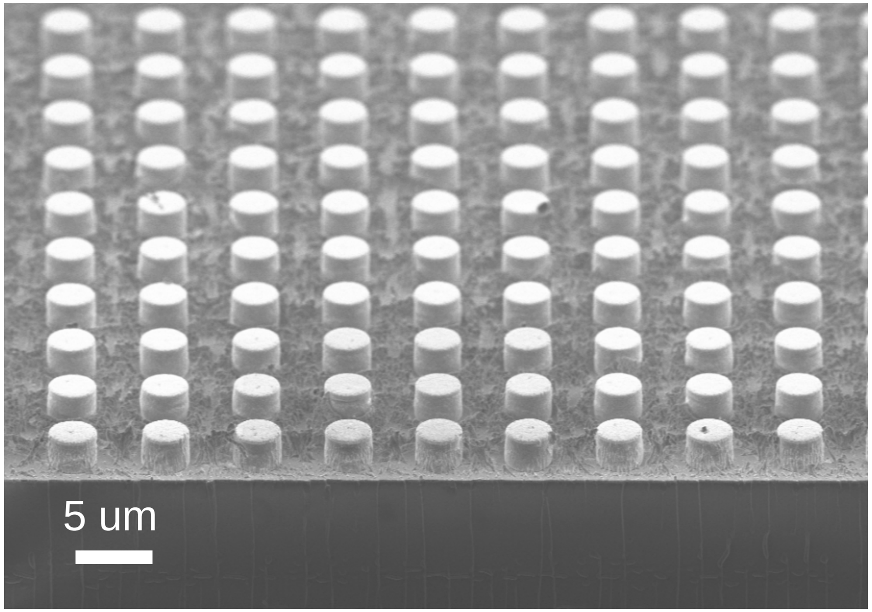

Questions?

NACK resources available from nano4me.org:

Laboratory Activities

- Photolithography
- Electrodeposition of Ni Nanowires (Univ. of Wisc. + NACK Handout)

Remote Access to Tools

- FESEM: visualize and measure
- Profilometer: thickness of photoresist

Questions?

NACK resources available from nano4me.org:

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ESC 213 Laboratories

Lab Overview

Lab 1 & 2: Block Copolymer Films

Lab 3 & 4: Catalytic Growth of Silicon Nanowires

Lab 5: Dye-Sensitized Nanocrystalline Solar Cells

Lab 6: Colloidal Chemistry - Nanoparticles

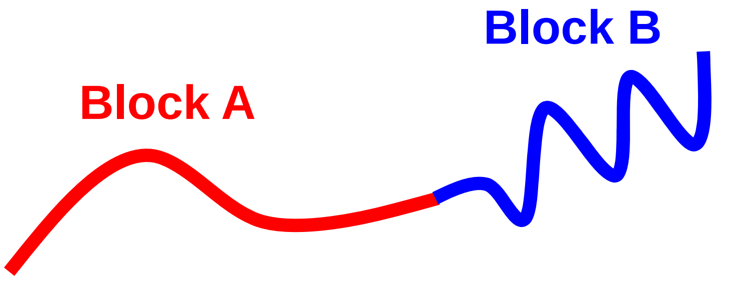
Lab 7: Nickel Nanowires

Lab 8: Statistical Process Control

NACK CENTER

Using the Tools of Nanotechnology…

Example 2: Using **Block Copolymer Lithography** to Create Nanostructures

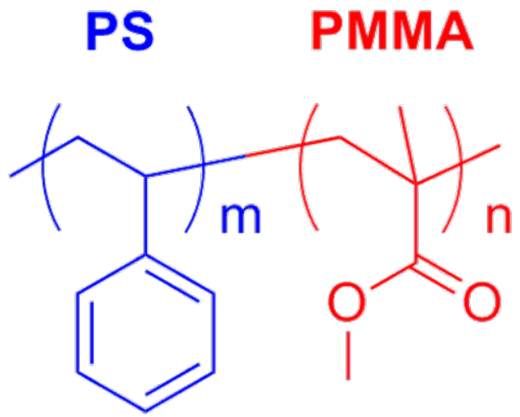


A Block Copolymer Molecule
“Microphase Separation”

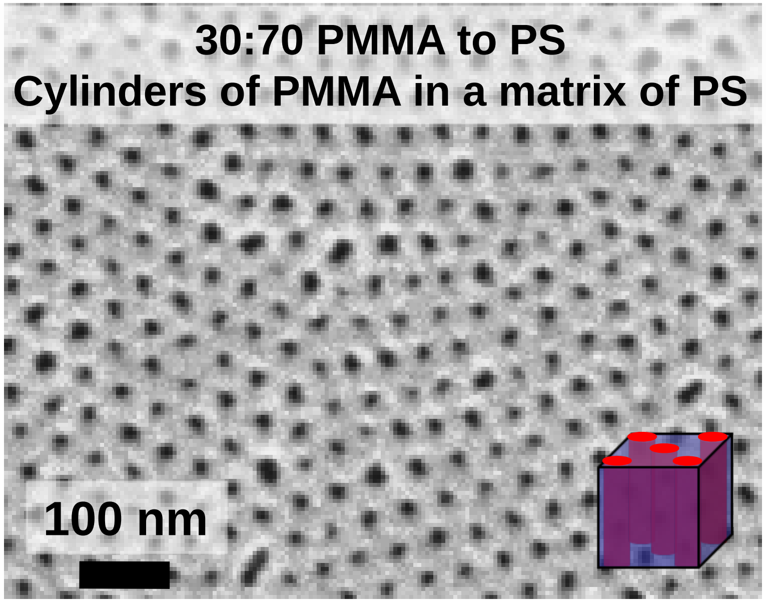
Example Process

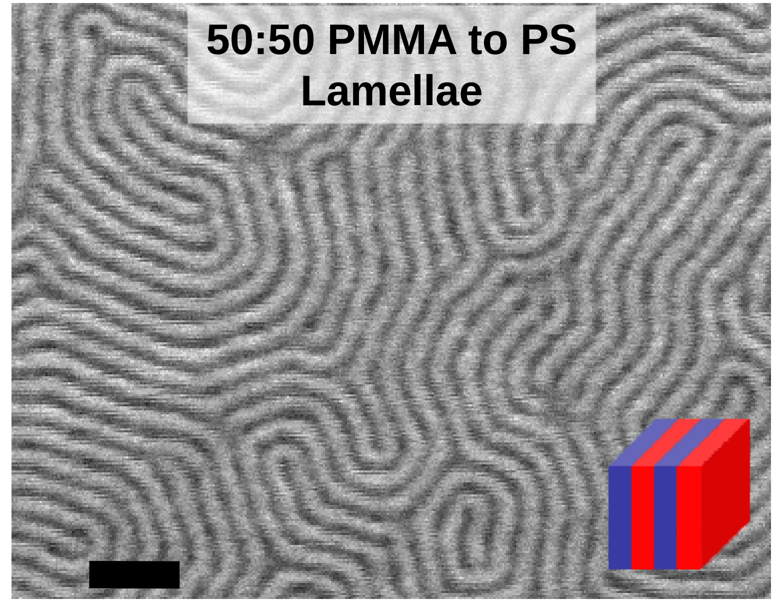
The exact process route depends on the properties of the block copolymer being used to create the pattern. This example is for PS-b-PMMA, which self-assembles when heated to about 175 °C (above the T_g of both blocks, but not totally melted).

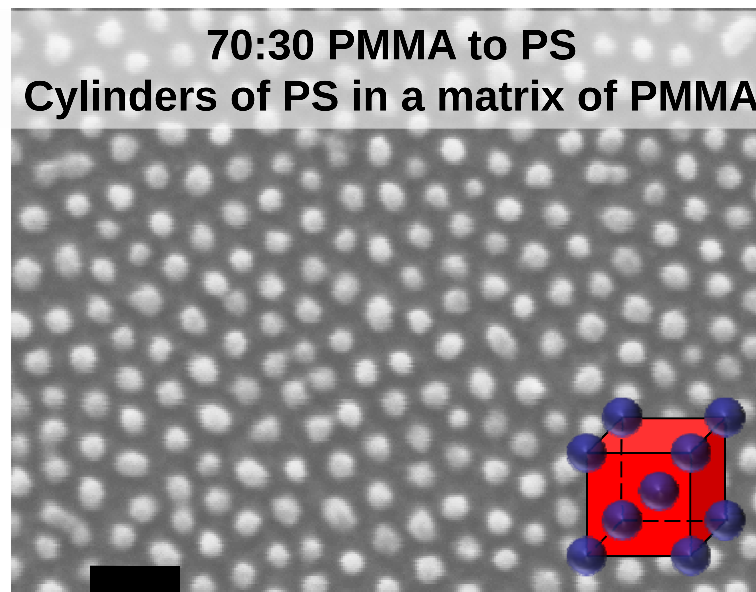
- Clean the substrate.
- Neutralize (randomize) the surface.
- Dissolve the polymer in a solvent.
- Spin coat a thin film.
- Anneal (heat) the sample.
- FESEM or AFM.



FESEM Images of Block Copolymers







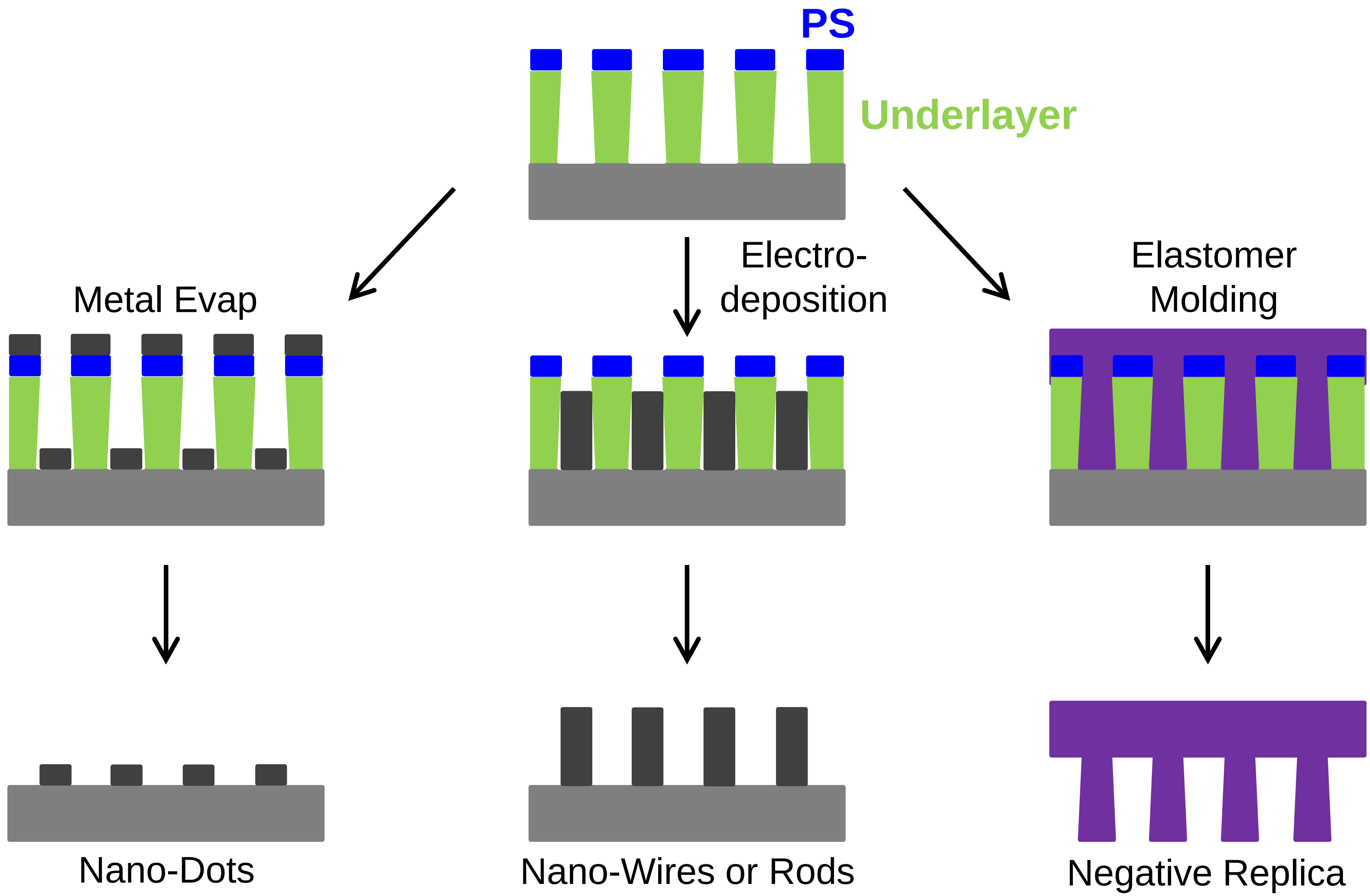
Increasing size of **PMMA block**

Decreasing size of **PS block**

Overall size (PS + PMMA) remains constant

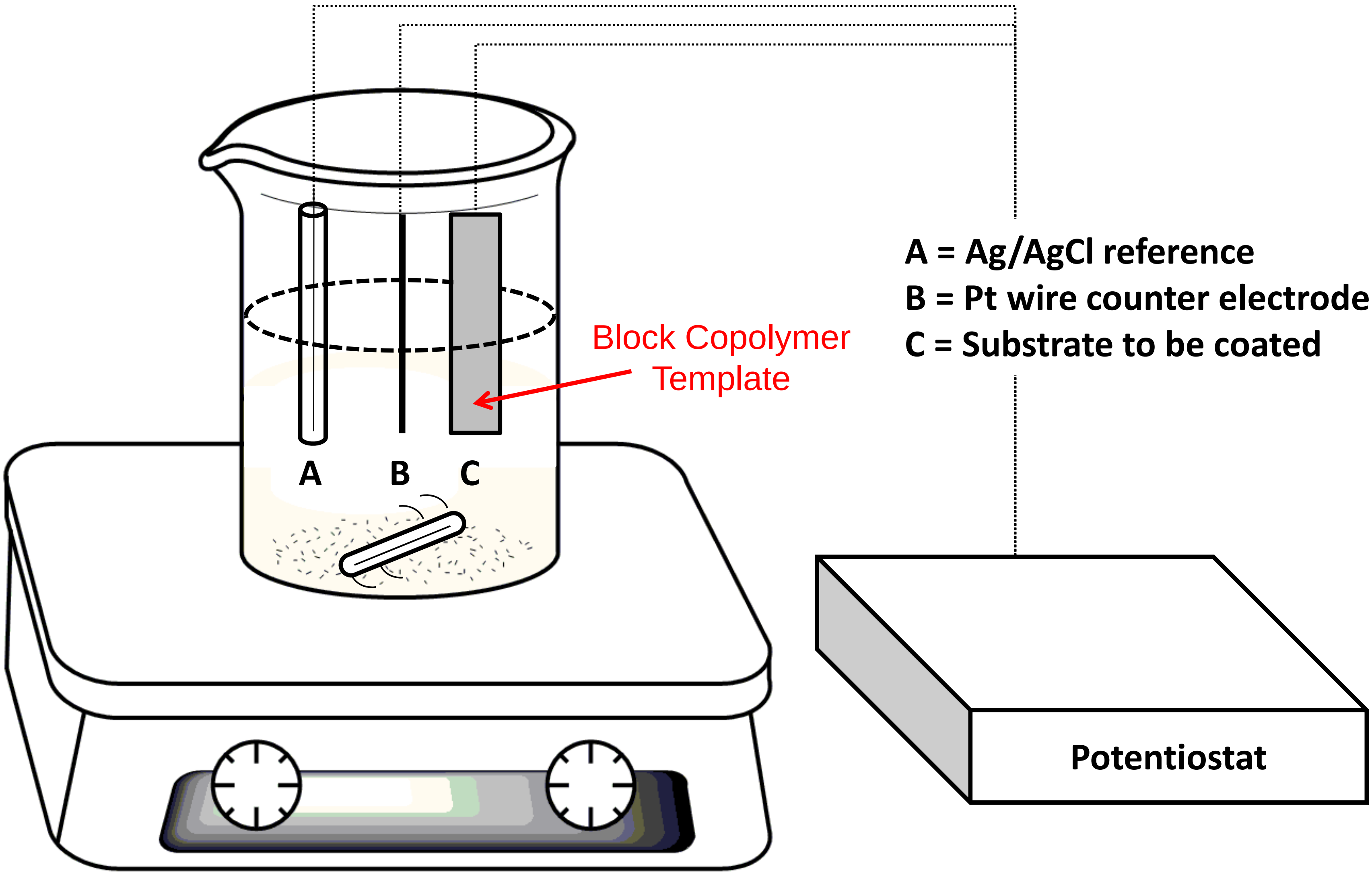
Light gray: PS
Dark gray: PMMA

Applications: Building Nano-Structures

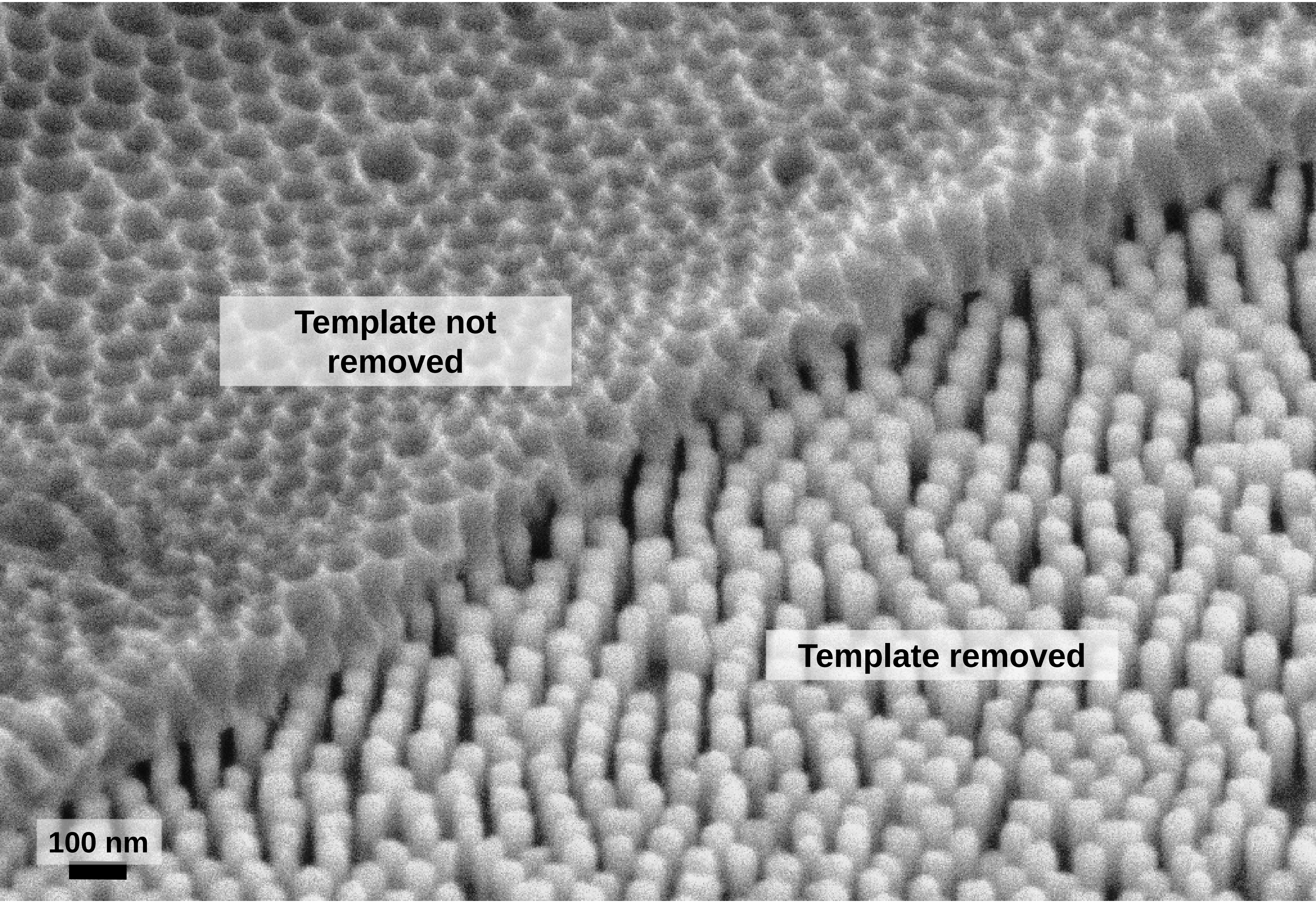


Appl. Phys. Lett. **2001**, *79(2)*, 257.

Electroplating Experimental Apparatus



Journal of Applied Electrochemistry **23**, 339 (1993)
Advanced Materials **12**, 582 (2000)
Advanced Materials **20**, 4470 (2008)


Template not removed
Template removed
100 nm

Nano-Wires via Electrodeposition

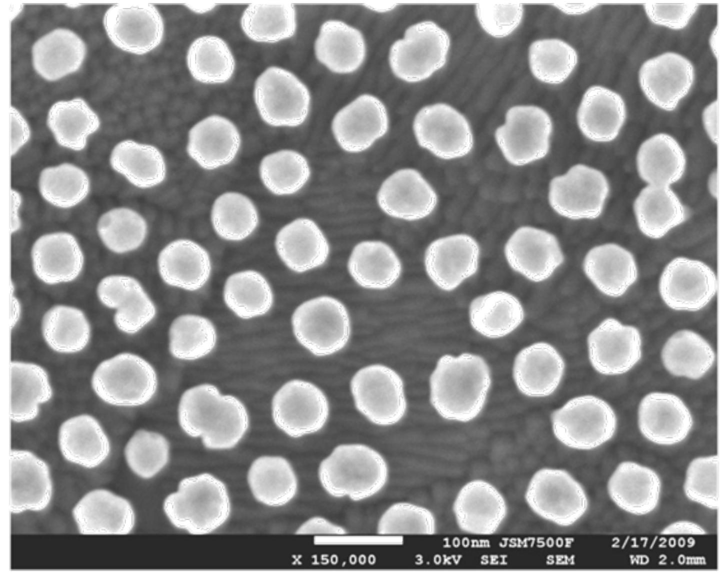
Top and side views of Ni nano-wires

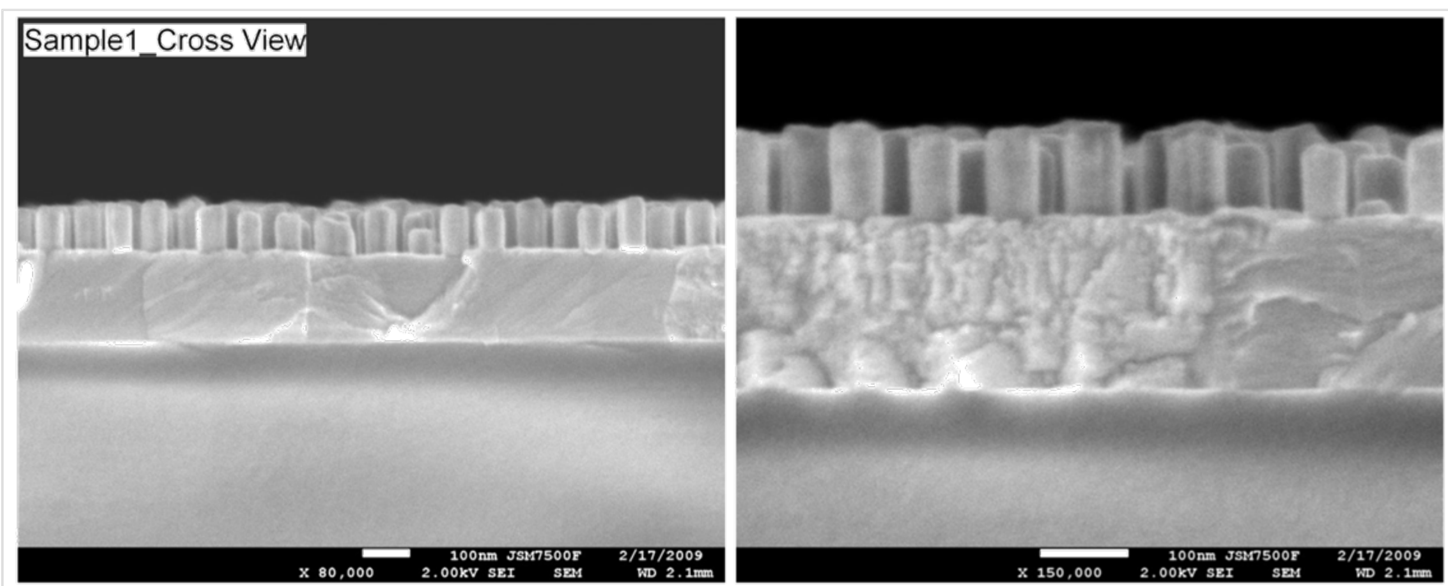
Substrate is indium tin oxide (ITO)

Electrodeposited into block copolymer templates

All scale bars are 100 nm

Nano-wire diameter is about 65 nm





Questions?

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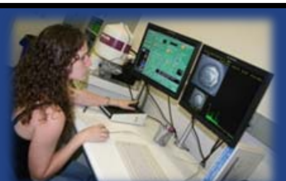
<u>Laboratory Activities</u>

- Block Copolymer Films
- Electrodeposition

<u>Remote Access to Tools</u>

- FESEM: visualize and measure
- AFM: measure nanoscale features

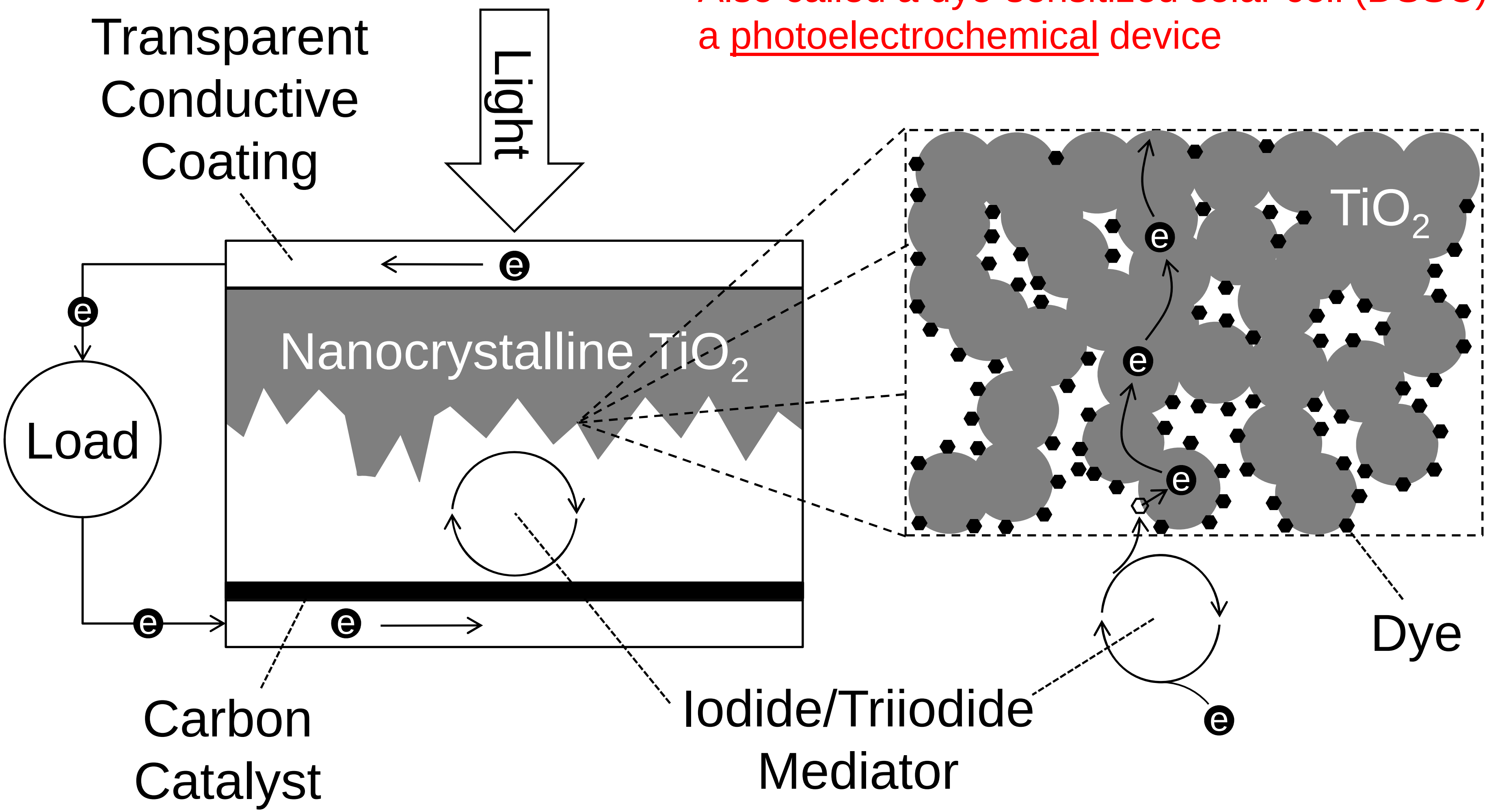


Other Types of Solar Cells

- Researchers are continuously looking for alternatives to silicon.
- Several popular types employ nanotechnology:
  - Dye-sensitized solar cell (Grätzel)
  - Organic solar cell
  - Quantum dot and intermediate band

Grätzel Cell

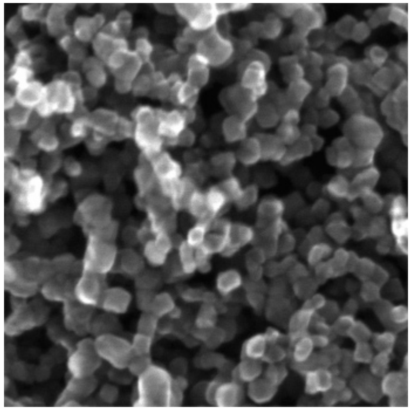
Also called a dye-sensitized solar cell (DSSC): a photoelectrochemical device

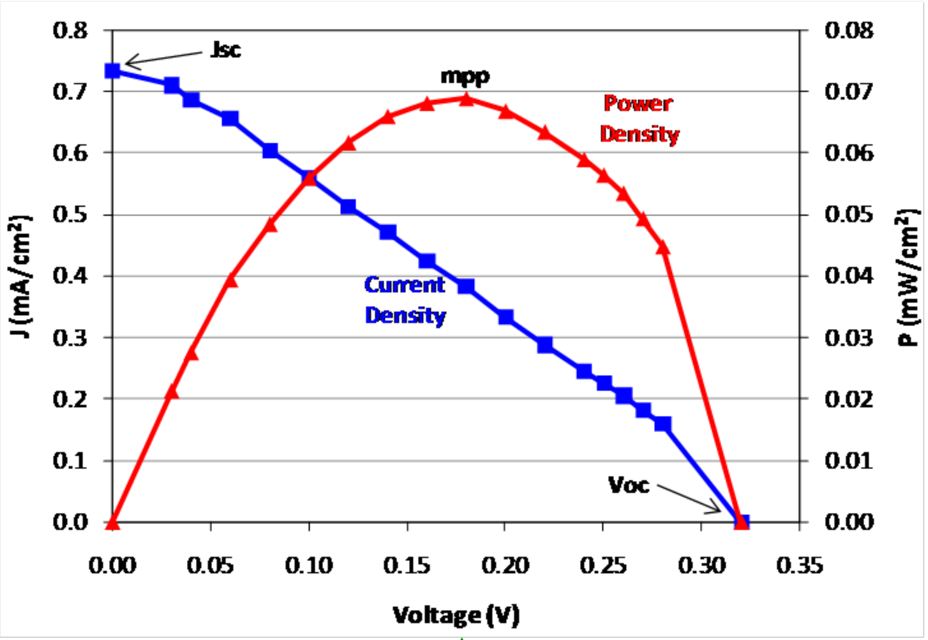


Inorg. Chem. **2005**, *44(20)*, 6841.
J. Chem. Ed. **1998**, *75(6)*, 752.
JChemEd.chem.wisc.edu

Example of DSSC Lab

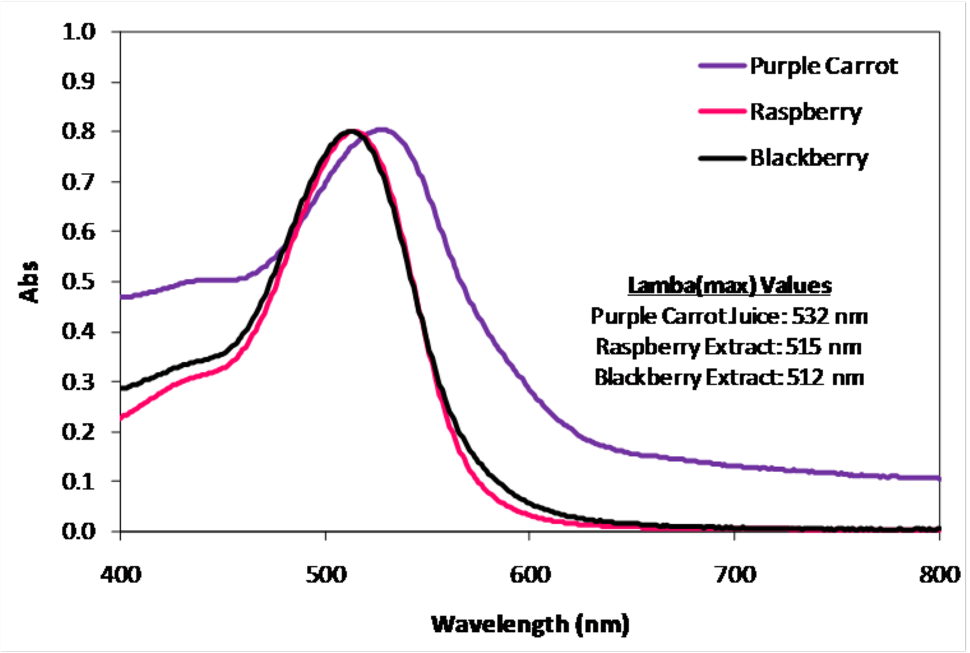
Avg. Particle Size = 20 nm





Current-Voltage Characterization

Actual data from a working solar cell made by students

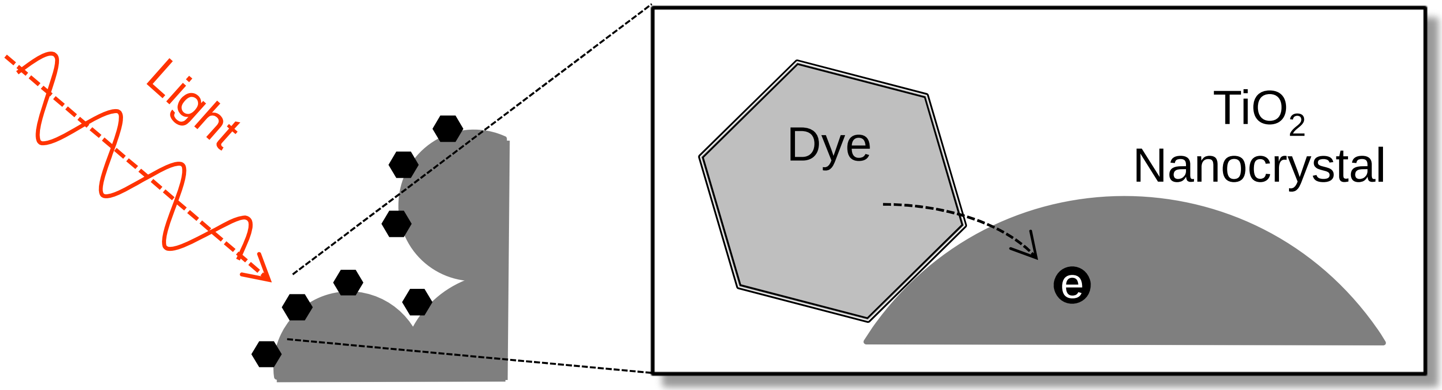


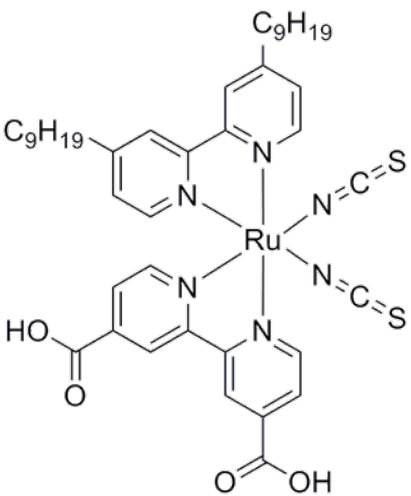
UV-vis of Dye Solutions

Various berry extracts and juices (anthocyanins)

Improving DSSC: Light Absorption

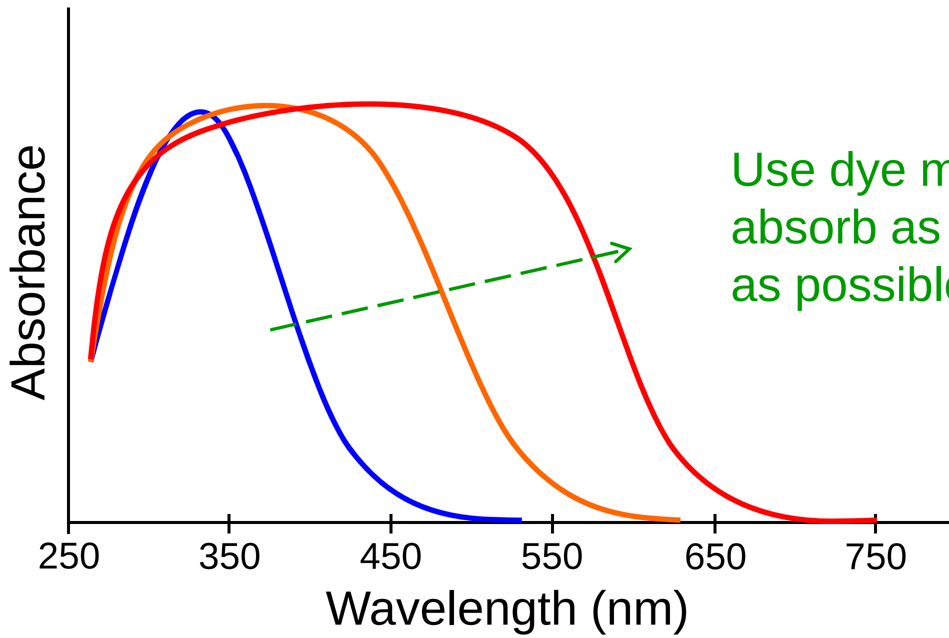
Dye molecules absorb light and inject electrons into TiO_2





Z-907

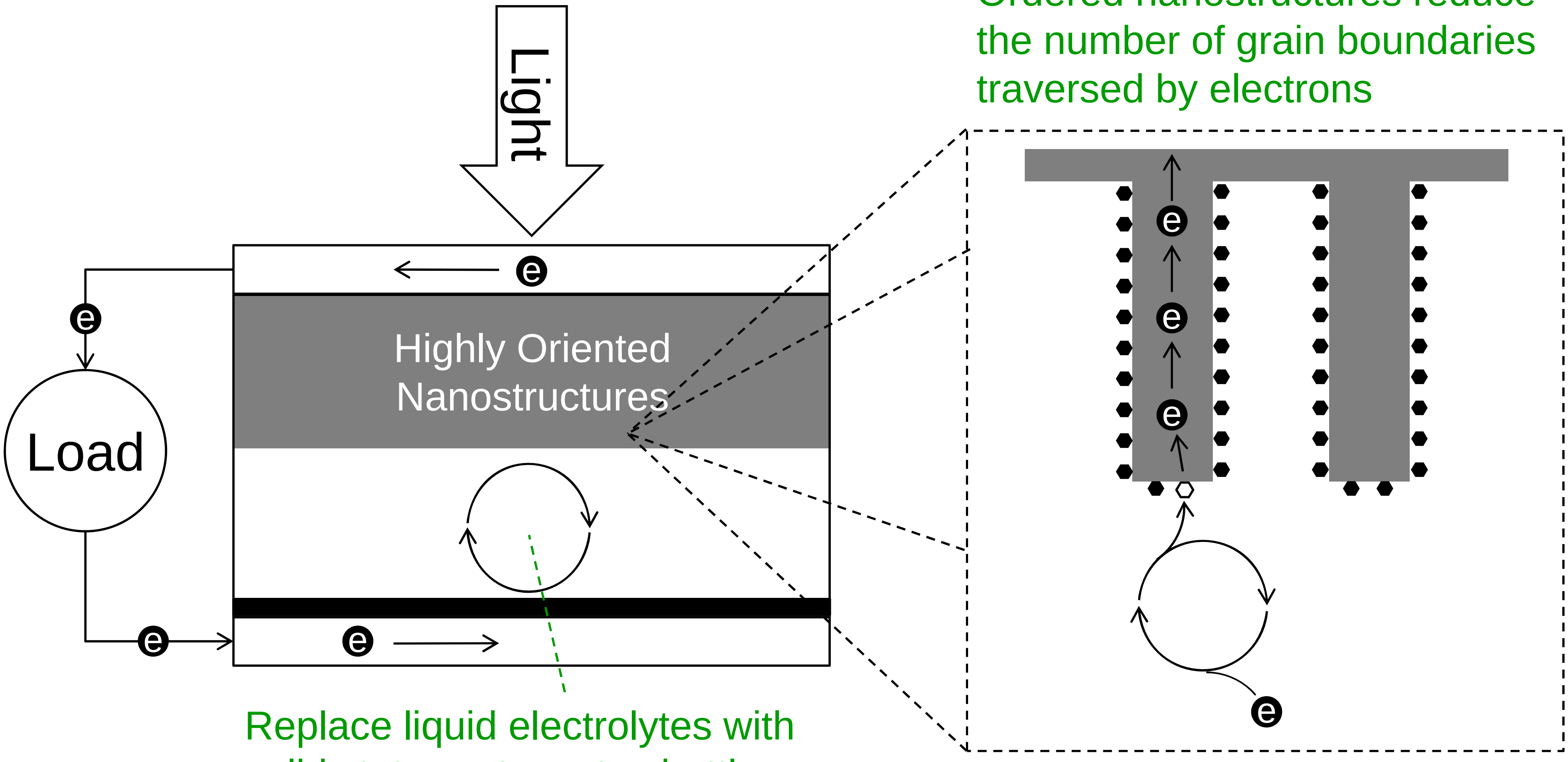
Ru-Based Dye



Use dye molecules that absorb as much sunlight as possible

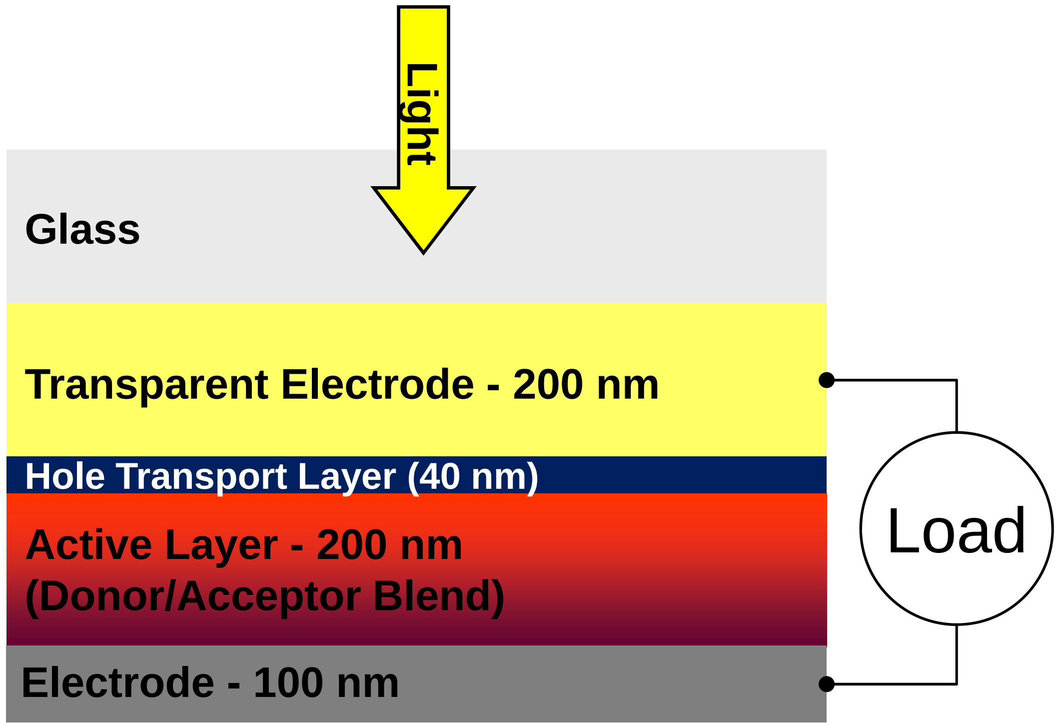
Improving DSSC: Charge Transport

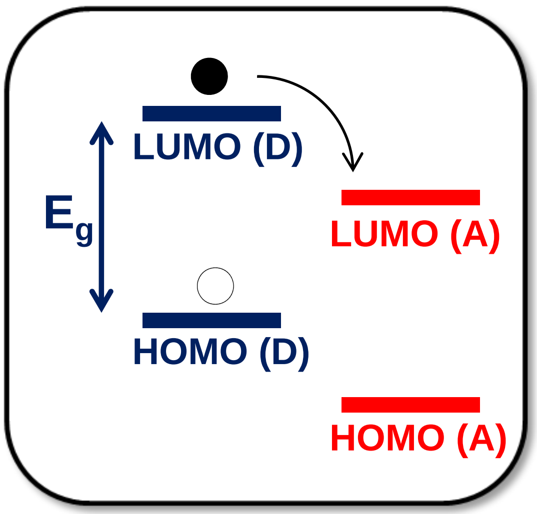
Ordered nanostructures reduce the number of grain boundaries traversed by electrons



Replace liquid electrolytes with solid state systems to shuttle electrons from anode to oxidized dye molecules

Organic Solar Cells

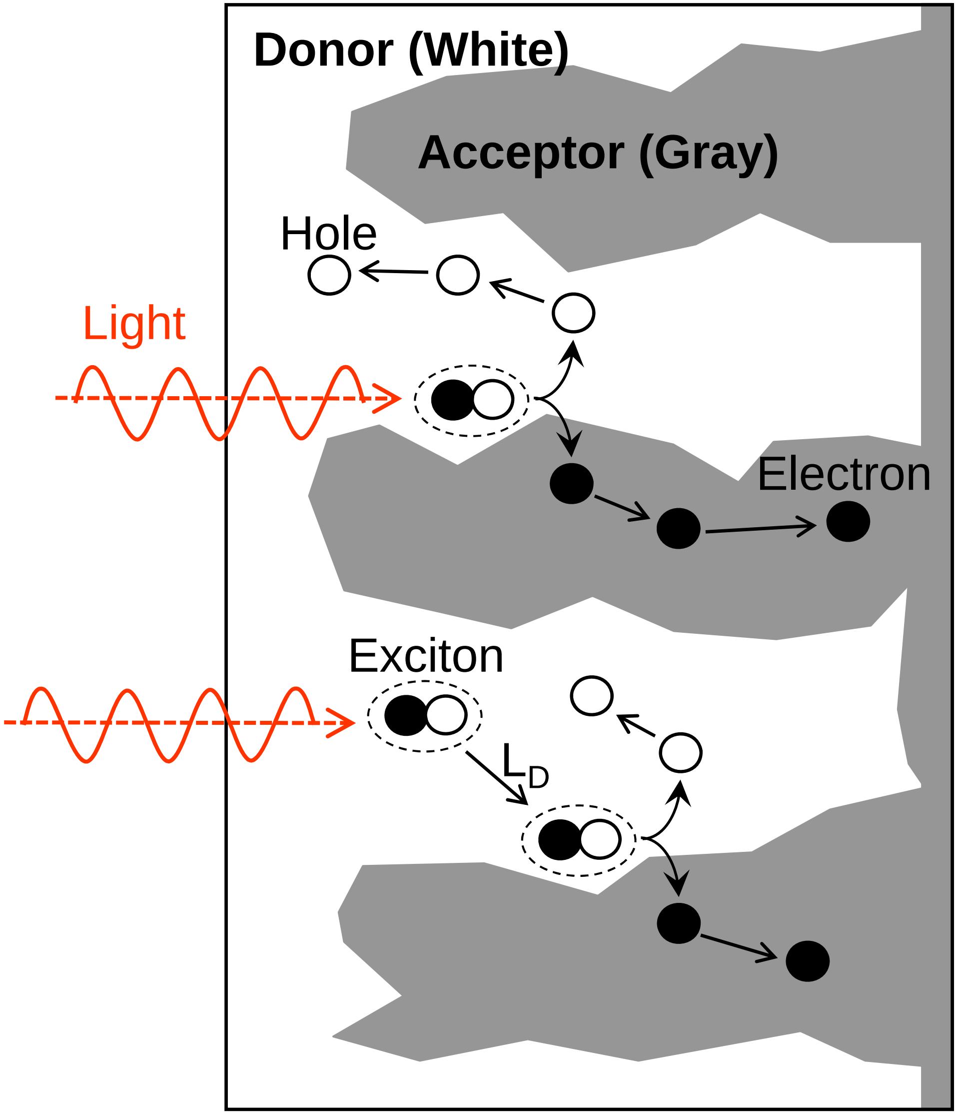




Sometimes called plastic solar cells

Heterojunction: mixture of Donor and Acceptor

Organic Solar Cells



Light absorption creates excited species called excitons

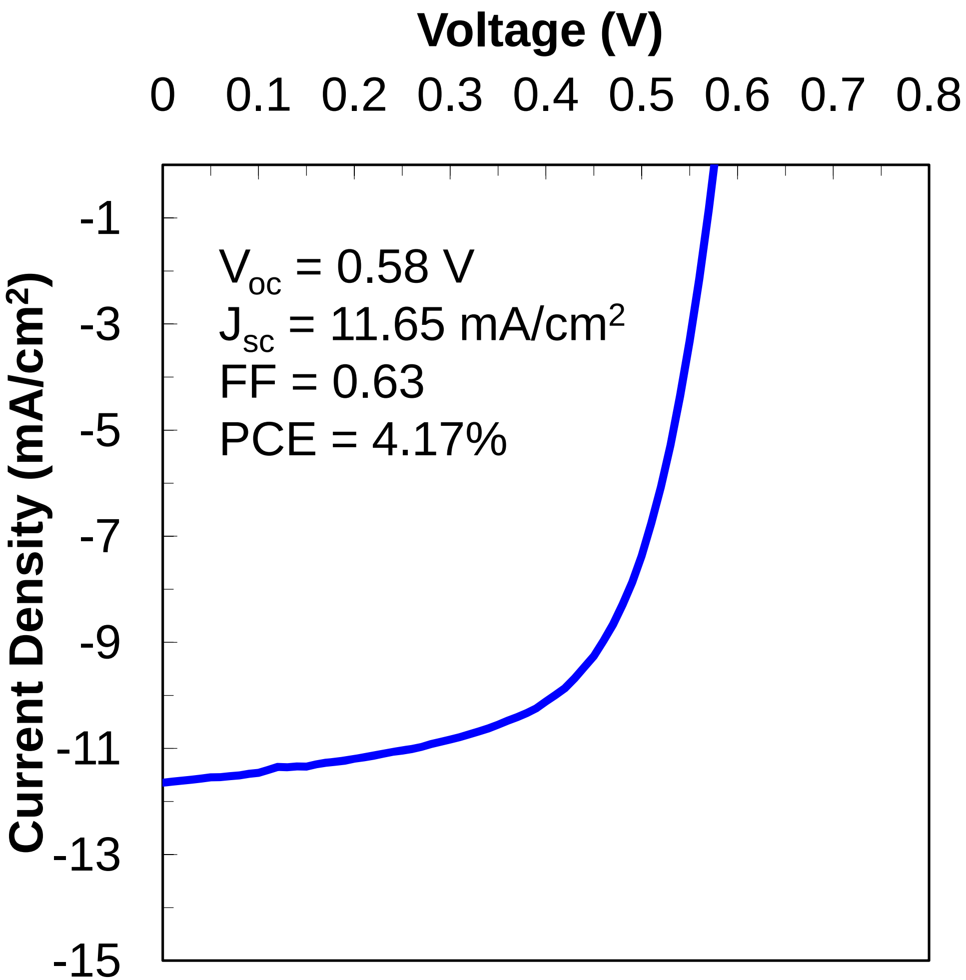
Excitons must dissociate at donor-acceptor interface in order to create free charge carriers

Excitons have a limited lifetime and a limited diffusion distance (L_D)

L_D is on the order of nanometers

Excitons are lost if they do not dissociate into free electrons and holes

Organic PV Results



Process Outline

1. Pattern ITO (Photolithography)
2. Spin cast PEDOT:PSS
3. Spin cast P3HT:PCBM
4. Thermal anneal
5. Evaporate cathode (LiF/Al)
6. Characterize

4 Devices per Slide: 0.09 cm^2

Organic Solar Cells

Advantages

- Materials are amenable to low-cost processing
- Polymeric materials can be tailored to meet specifications (e.g., band gap, solubility)

Disadvantages

- Less efficient (so far) than other technologies
- Long term stability needs to be proven
- Viewed as cutting edge, but risky, technology

Questions?

NACK resources available from nano4me.org:

<u>Laboratory Activities</u>

- Dye-Sensitized Solar Cell
- Organic Solar Cell (Coming Soon)

<u>Remote Access to Tools</u>

- FESEM: Nanocrystalline TiO_2
- AFM: morphology of P3HT
- UV-vis: light absorption of devices
- Current-Voltage Characterization

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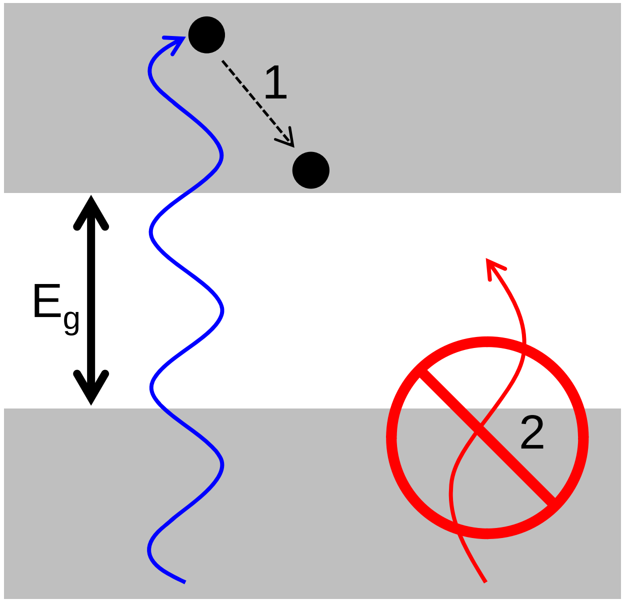
Shockley-Queisser Limit

- Maximum thermodynamic efficiency ~31%
- Single band gap (E_g) absorber
- Thermal equilibrium between electrons and phonons

<u>**Two major loss mechanisms:**</u>

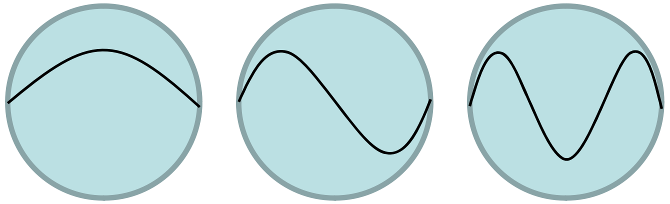
1. Excess energy of photo-generated carriers lost as heat
2. Photons with energy less than the band gap are not absorbed

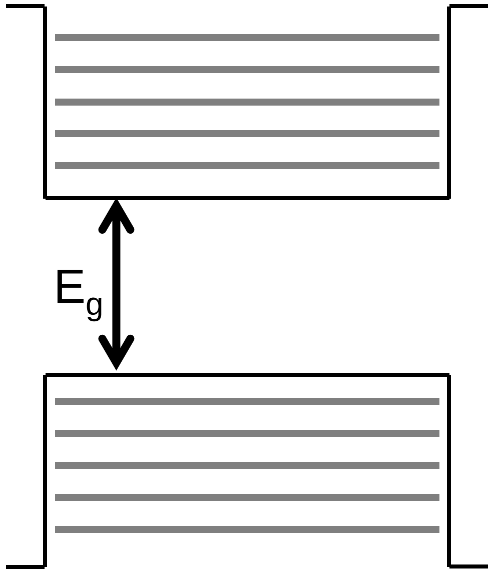


J. Appl. Phys. **1961**, *32*, 510.

Quantum Dots (QD)

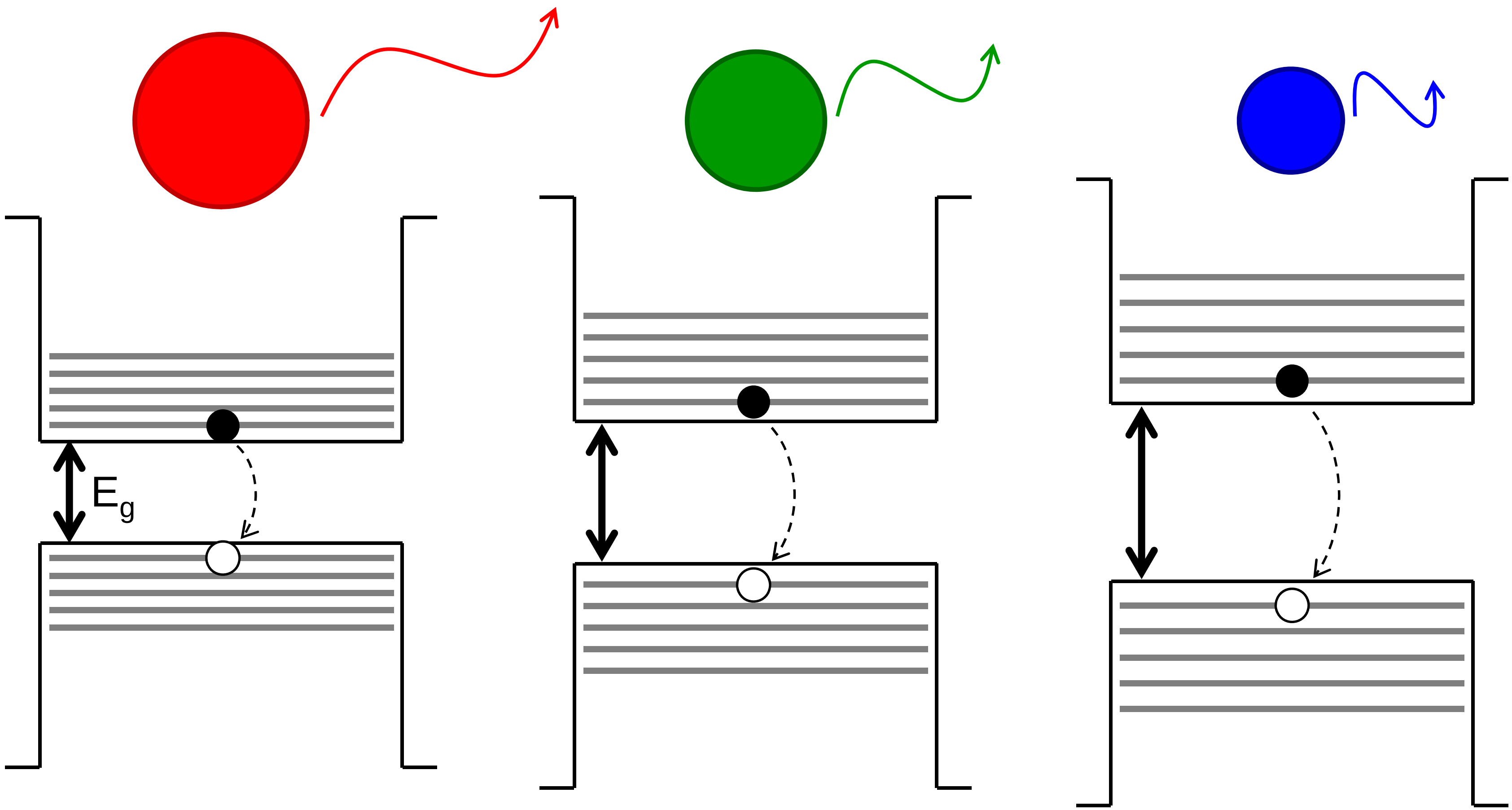
- Nanocrystals (2-10 nm) of semiconductor compounds
- Small size leads to confinement of excitons (electron-hole pairs)
- Quantized energy levels and altered relaxation dynamics
- Examples: CdSe, PbSe, PbTe, InP





Quantum Dots

Absorption and emission occur at specific wavelengths, which are related to QD size



Quantum Dot Solar Cells

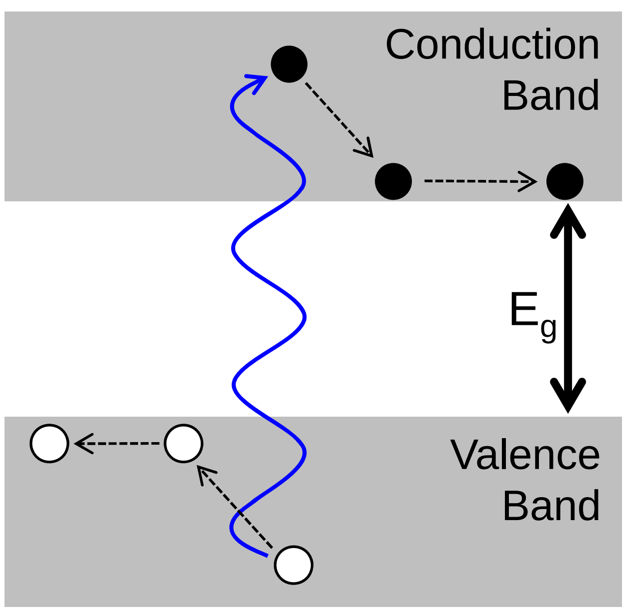
Possible benefits of using quantum dots (QD):

- “Hot carrier” collection: increased voltage due to reduced thermalization
- Multiple exciton generation: more than one electron-hole pair per photon absorbed
- Intermediate bands: QDs allow for absorption of light below the band gap, without sacrificing voltage

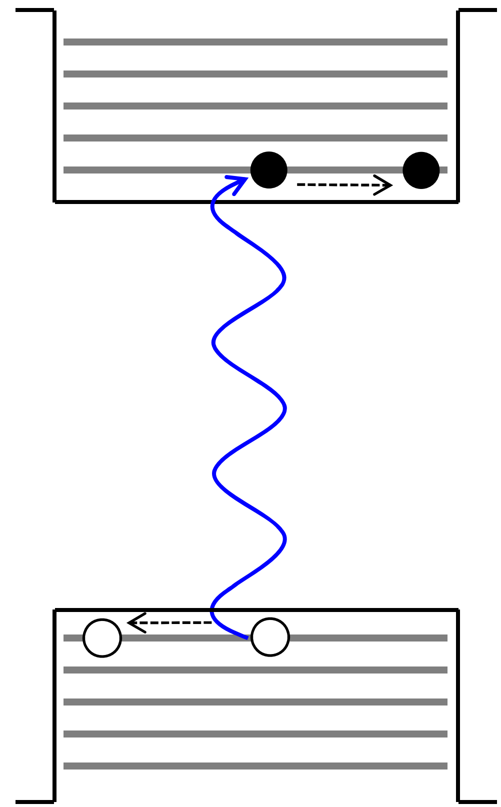
MRS Bulletin **2007**, *32(3)*, 236.

QDs: Collect Hot Carriers

Band structure of bulk semi-conductors absorbs light having energy > E_g. However, photo-generated carriers thermalize to band edges.

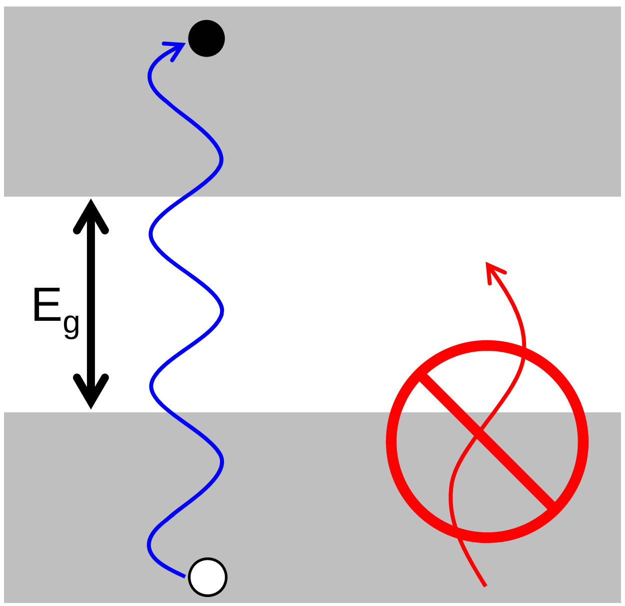


1. Tune QD absorption (band gap) to match incident light.
2. Extract carriers without loss of voltage due to thermalization.

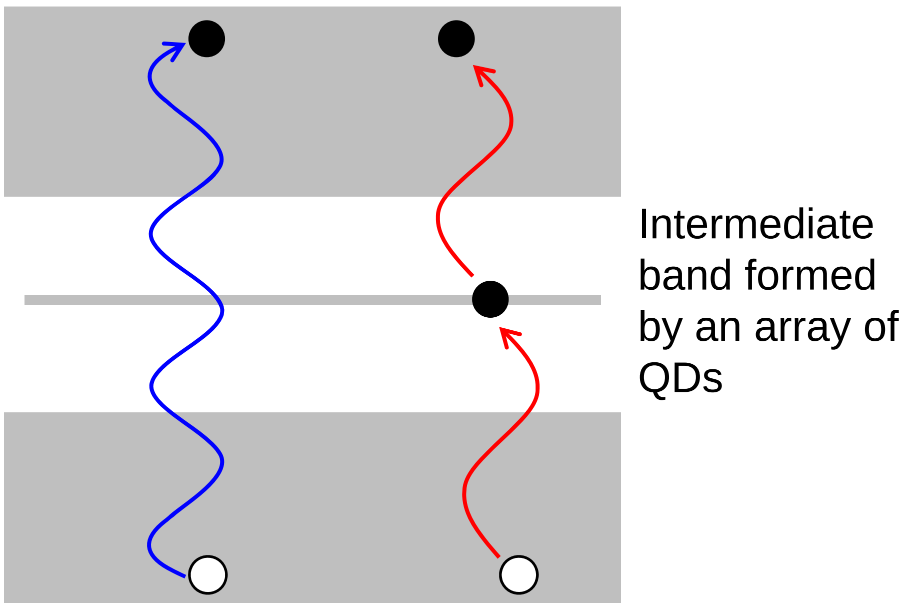


QDs: Intermediate Bands

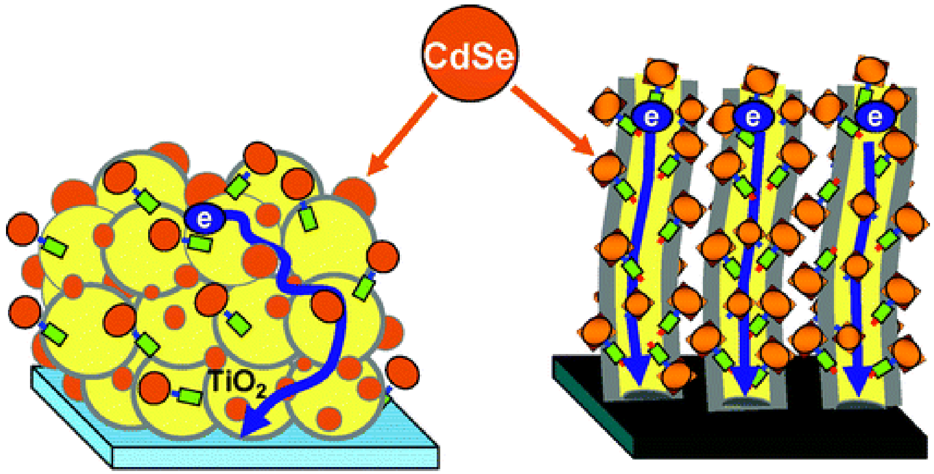
Conventional band structure does not absorb light with energy < E_g

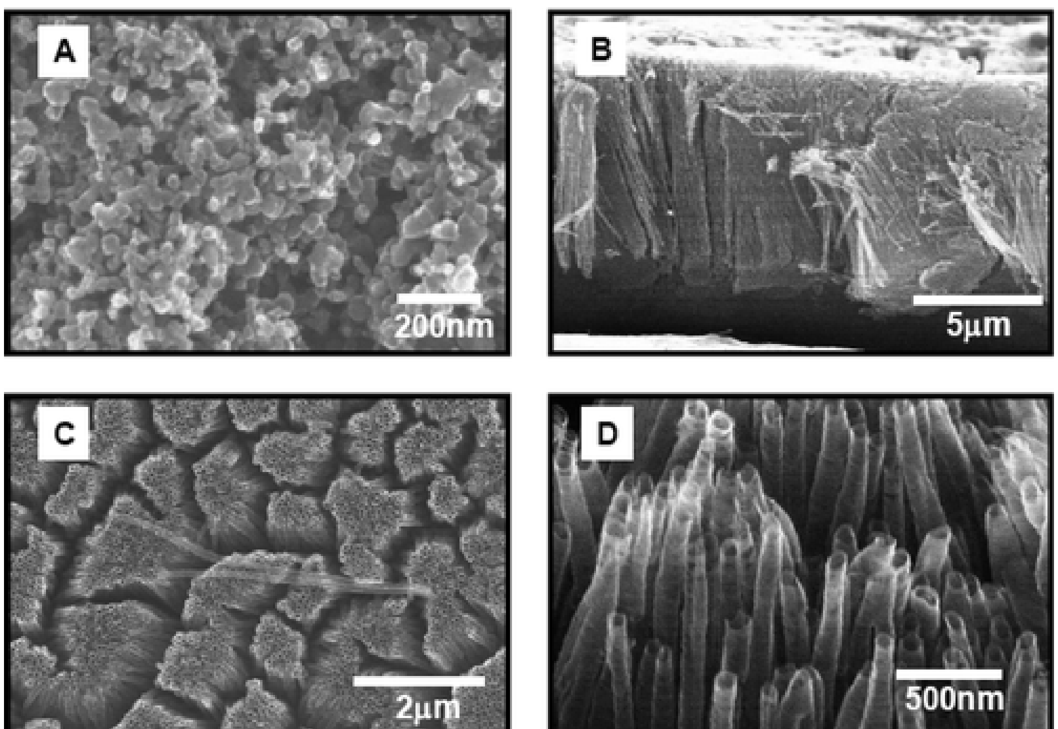


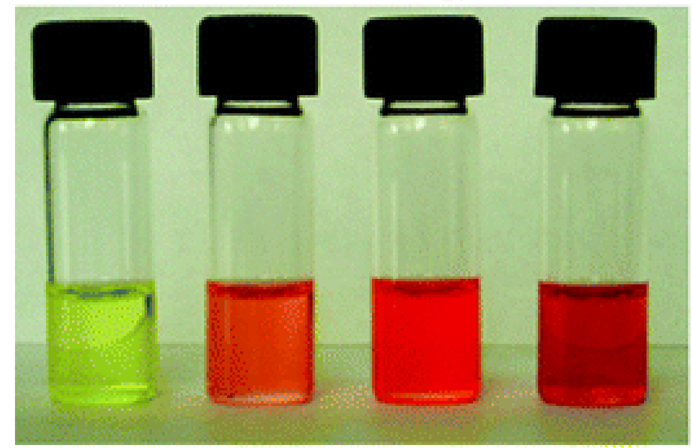
Intermediate bands in the band gap allow for absorption of low energy light



CdSe Sensitizers/Nano TiO_2

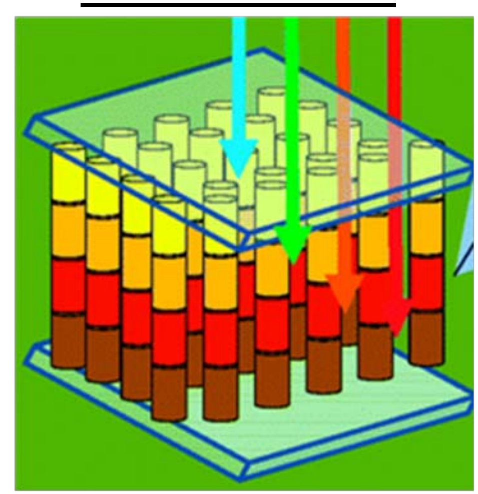






2.3 2.6 3.0 3.7 nm

“Rainbow Cell”



J. Am. Chem. Soc., **2008**, *130(12)*, 4007.

Questions?

NACK resources available from nano4me.org:

Laboratory Activities

- Colloidal Gold NPs
- CdSe QDs (Univ. of Wisc.)

Remote Access to Tools

- FESEM: visualize nanostructures
- AFM: measure size of NPs
- UV-vis: light absorption of QDs and NPs

Conclusions

- Solving issues related to energy production, storage, and distribution will take a concerted effort.
- Plenty of challenges for all areas of science and technology.
- Nanotechnology is poised to make major contributions to the energy sector.

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Oct.	4-7	Train the Trainer (211-212)
Nov.	16-18	Hands on Intro to Nano Workshop



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