

## **Solar voltaic research**

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*Photovoltaics Research at USC*  
*Center for Energy Nanoscience*  
*Emerging Materials For Solar Energy Conversion and Solid  
State Lighting*

P. Daniel Dapkus  
Director



www.CEN-EFRC.org

**CEN** CENTER FOR ENERGY NANOSCIENCE

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### Research Highlights

Earth abundant SnSe was used as an acceptor material in a hybrid polymer/nanocrystal solar cell.

[Previous](#) [Next](#)

### Calendar

< Dec **January 2010** Feb >

S	M	T	W	T	F	S
					1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28	29	30
31						

■ CEN Members-Only Events  
■ Public Events

### Research Goals and Approach:

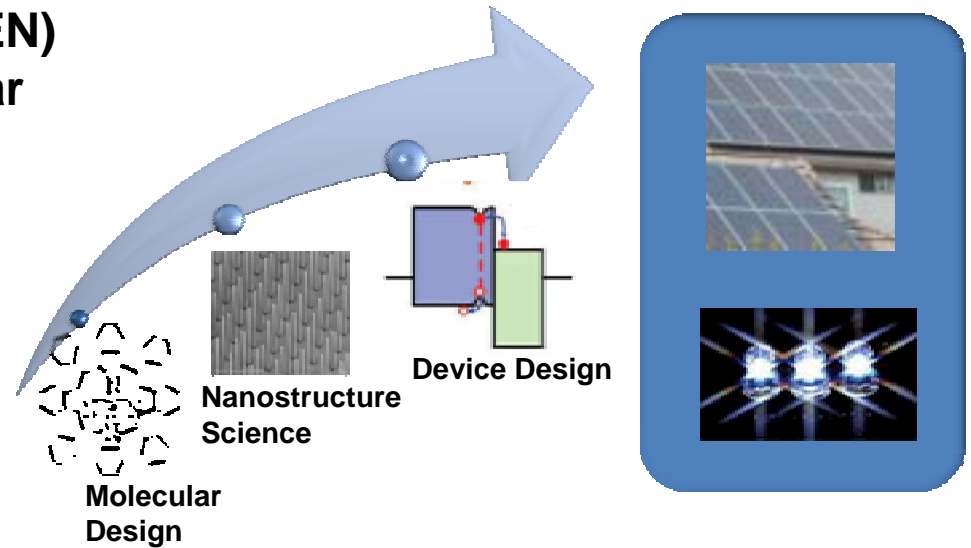
- Dramatically increase efficiency and reduce cost of solar cells and LEDs to create technologies that are cost competitive with the incumbent technologies.
- Develop new understanding of semiconductor nanoscience, organic molecule design, and device design to enable a new generation of low cost, efficient device designs.
- Engage a renowned team of scientists and engineers to accomplish goals.

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Center for Energy Nanoscience  
*P. Daniel Dapkus (USC)*

**The Center for Energy Nanoscience (CEN) will create low cost, high efficiency solar cells and light emitting diodes (LEDs):**

- *semiconductor nanotechnology*
- *organic molecular design*
- *innovative materials*
- *innovative device designs*
- *new understanding of issues controlling performance*

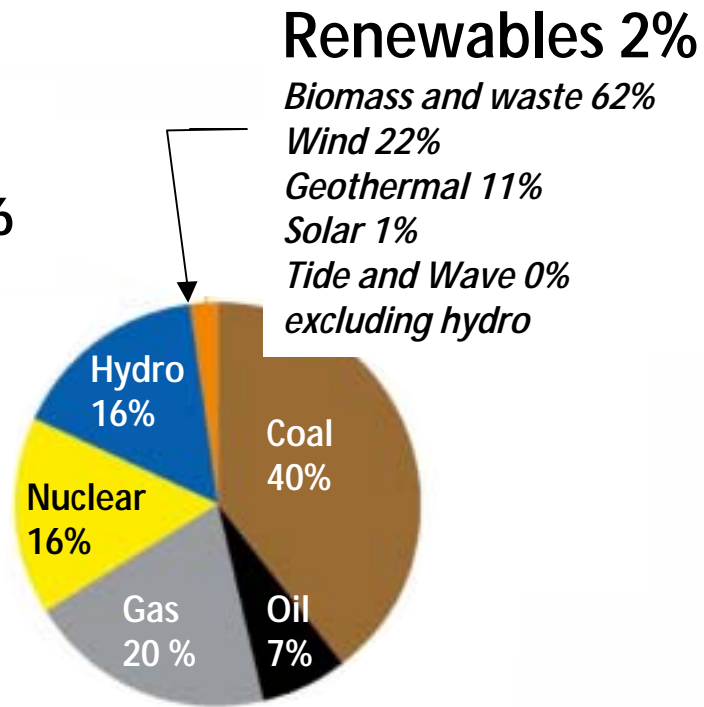


### **RESEARCH PLAN AND DIRECTIONS**

- **Increase efficiency and reduce cost of solar cells and LEDs to create technologies that are cost competitive with the incumbents.**
- **Develop new understanding of semiconductor nanoscience, organic molecule design, and device design to enable a new generation of low cost, efficient device designs.**
- **A renown team of scientists and engineers engaged to accomplish goals.**

# Motivation

Source:  
IEA, 2006



*World electricity production by energy source,  
2004*

- Fossil fuels are used to generate 67% of the electricity in the world.
- Climate change from CO<sub>2</sub> production is a threat to our way of life.
- Most sources of fuel are finite and insufficient to provide the world's demands for energy in the future.
- Renewable sources of energy account for only 2 % of the fuel used for electricity generation.

# Motivation

## Primary energy use in buildings

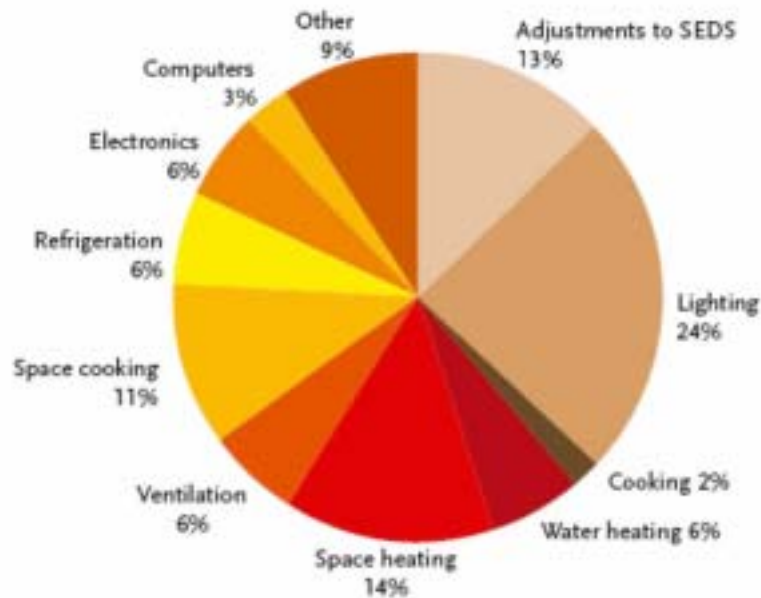


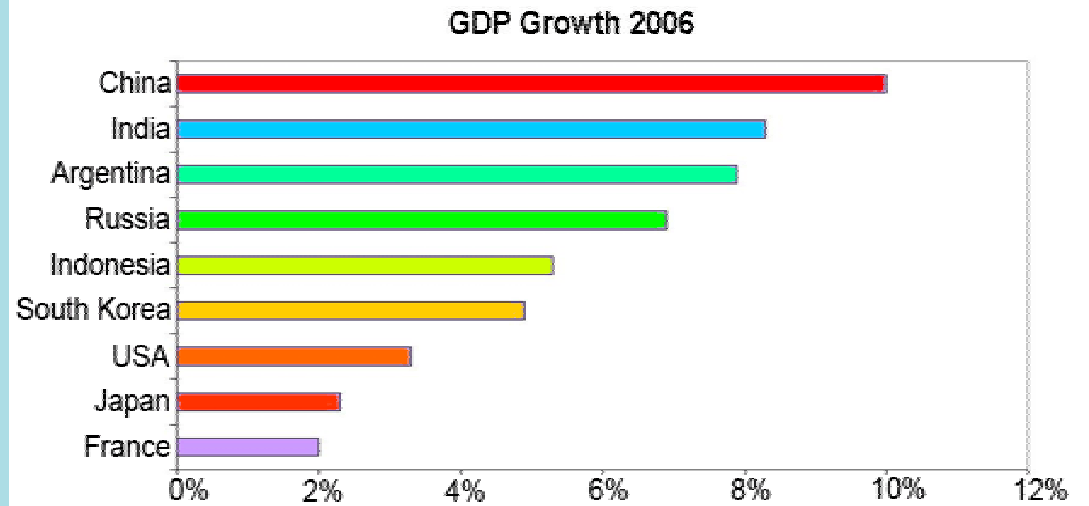
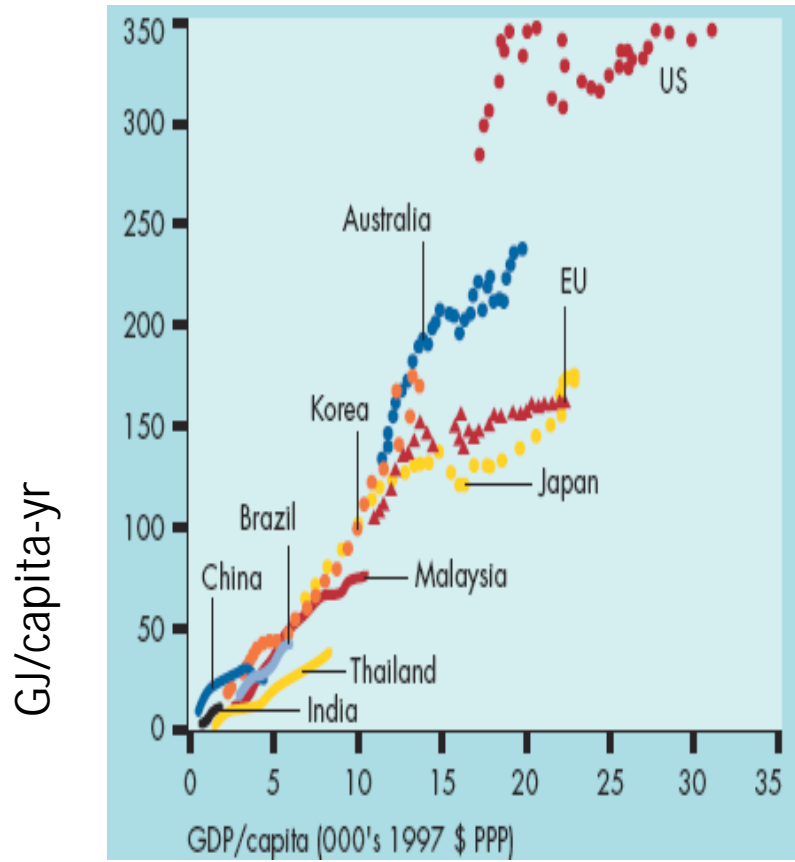
Figure 2.4 Shares of primary energy use in U.S. commercial buildings

Lighting accounts for 24% of the energy used in US buildings. (> 6 Quads\* in 1998)!

Improving the efficiency of lighting will dramatically reduce energy demand.

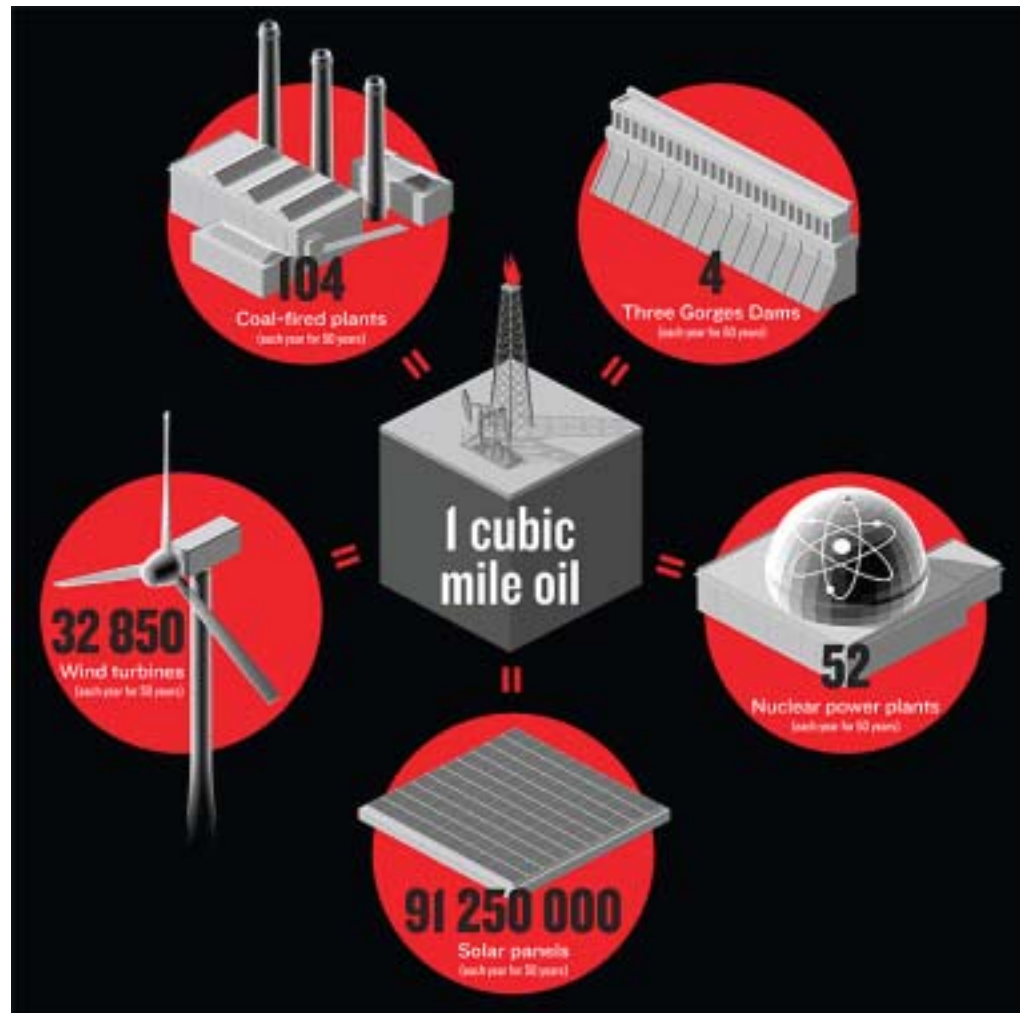
\*1 Quad of energy is  $10^{15}$  BTUs – the energy output of 60 coal fired power plants.

# Energy Consumption vs GDP



(Time)

# The Challenge is ENORMOUS!



# Solar Energy Potential

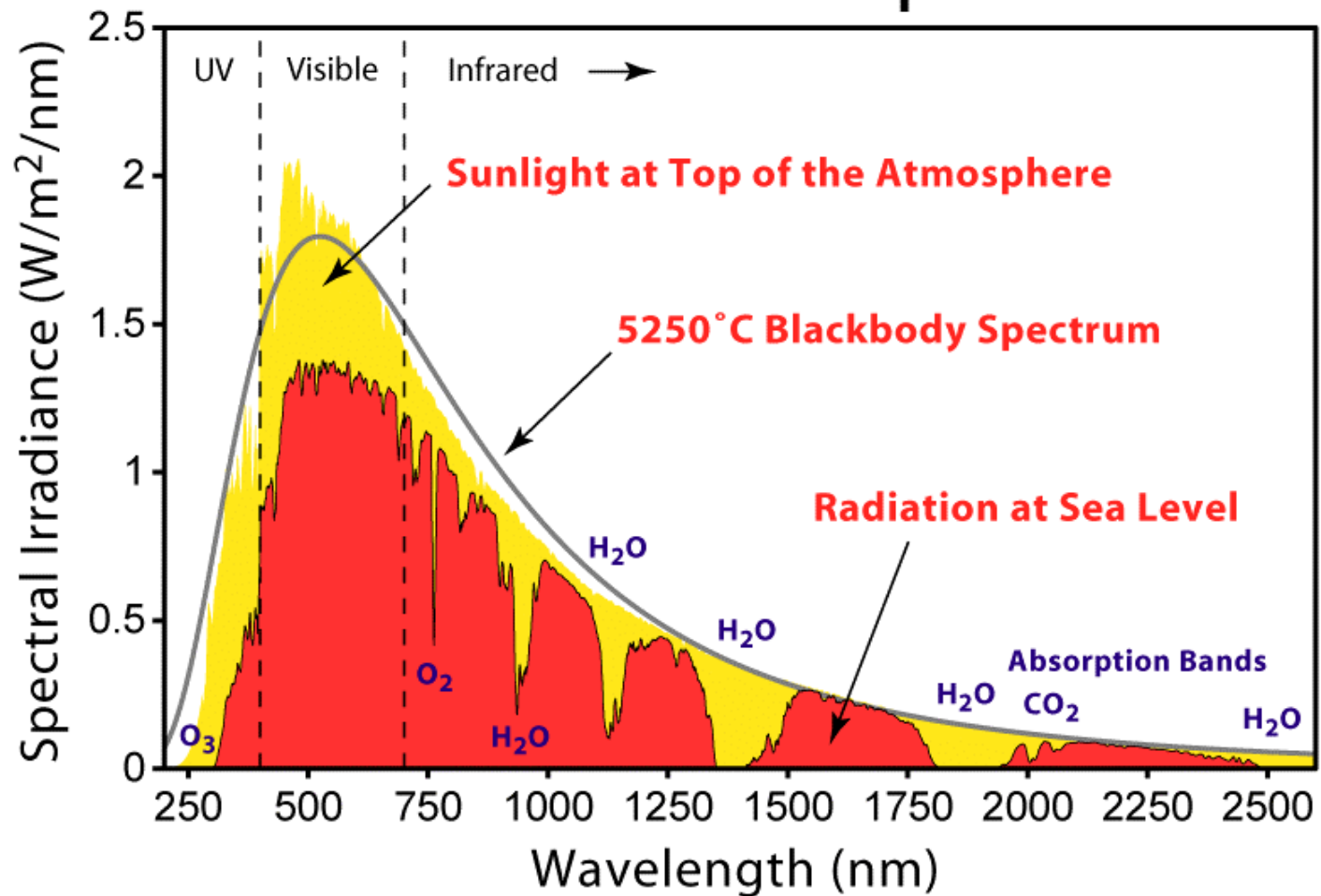
- Theoretical:  $1.2 \times 10^5$  TW solar energy potential  
( $1.76 \times 10^5$  TW striking Earth; 0.30 Global mean albedo)
  - Energy in 1 hr of sunlight  $\leftrightarrow$  14 TW
- Practical:  $> 600$  TW solar energy potential  
(50 TW - 1500 TW depending land fraction etc.)
- Onshore electricity generation potential of  $\approx 60$  TW  
(10% conversion efficiency)

# Solar Land Area Requirements

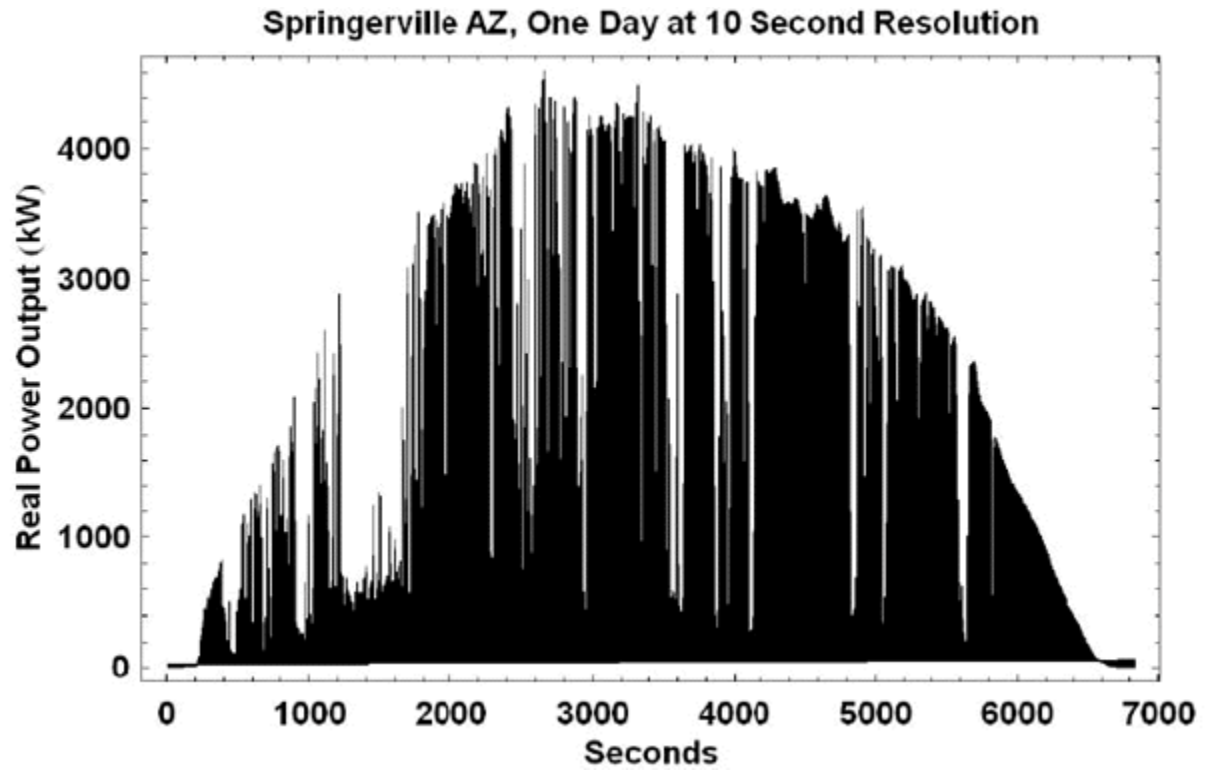




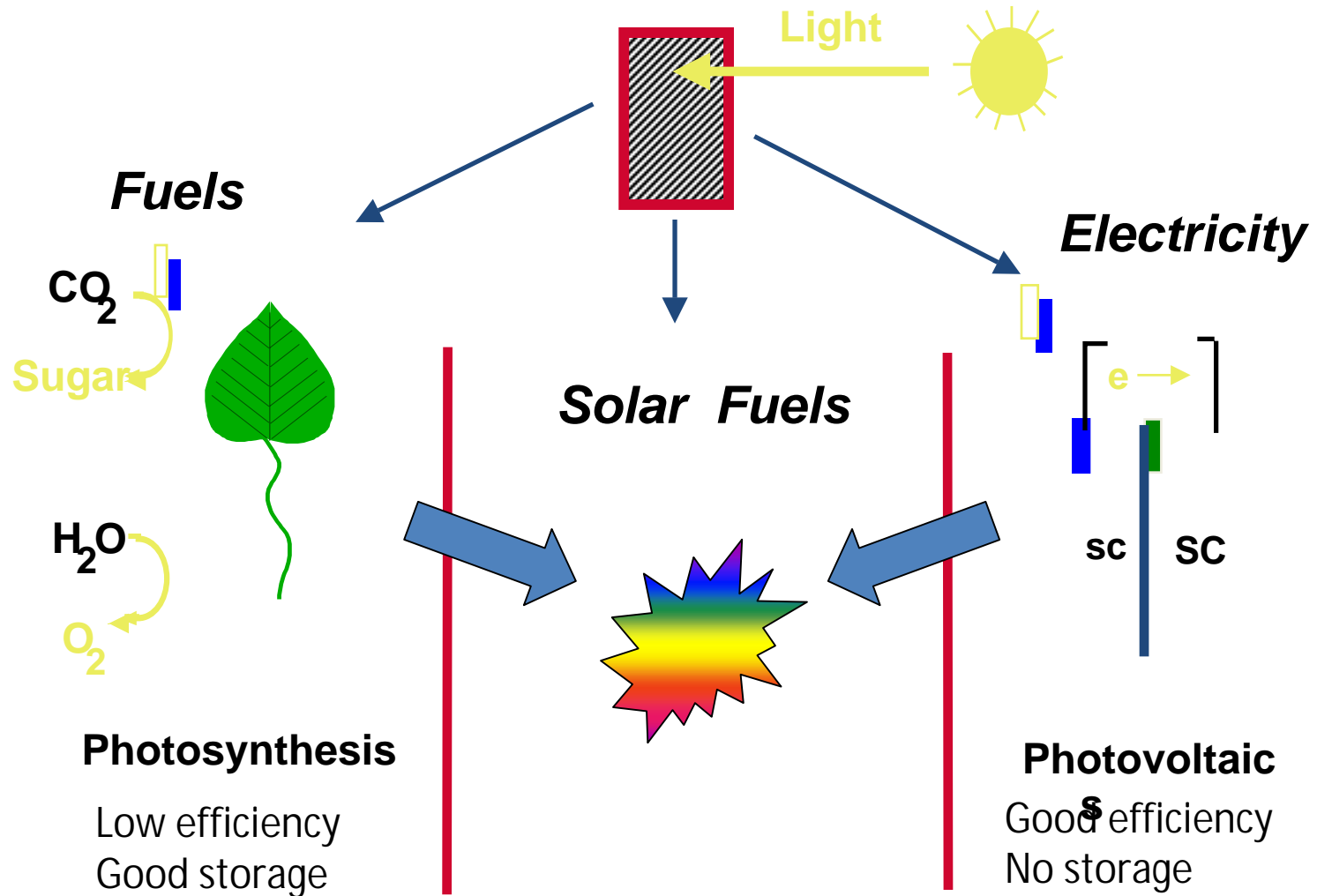
# Solar Radiation Spectrum



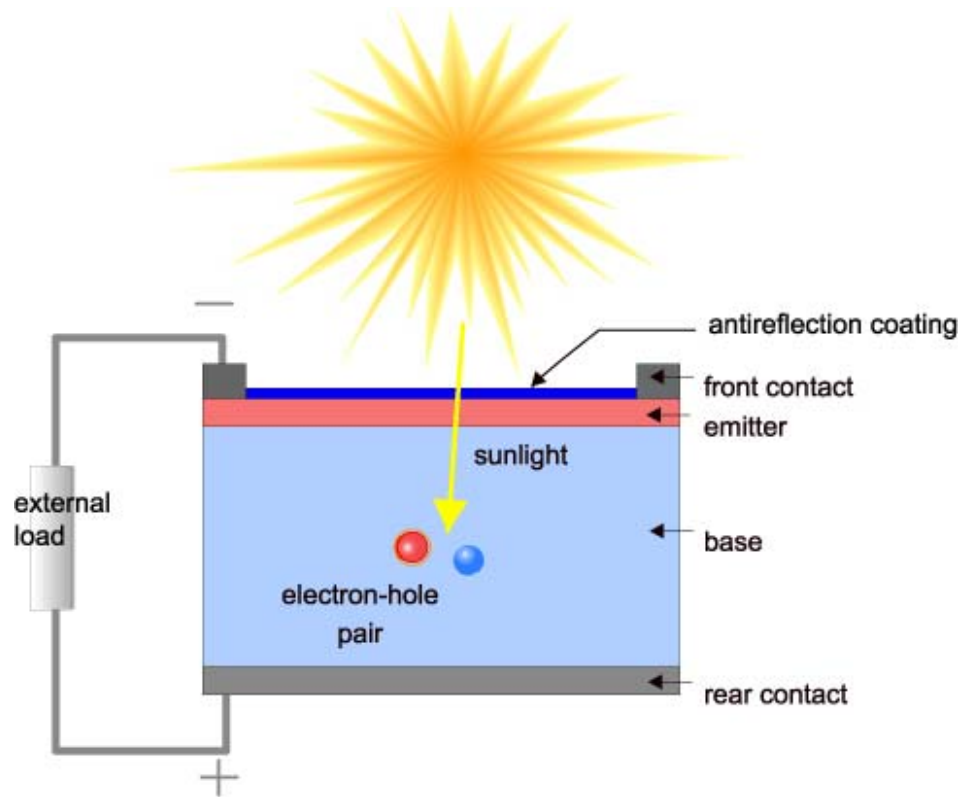
# Solar Energy Variability



# Energy Conversion Strategies



# Operation Principles of a Solar Cell



The basic steps in the operation of a solar cell are:

- the generation of light-generated carriers;
- the collection of the light-generated carriers to create a current;
- the generation of a large voltage across the solar cell;

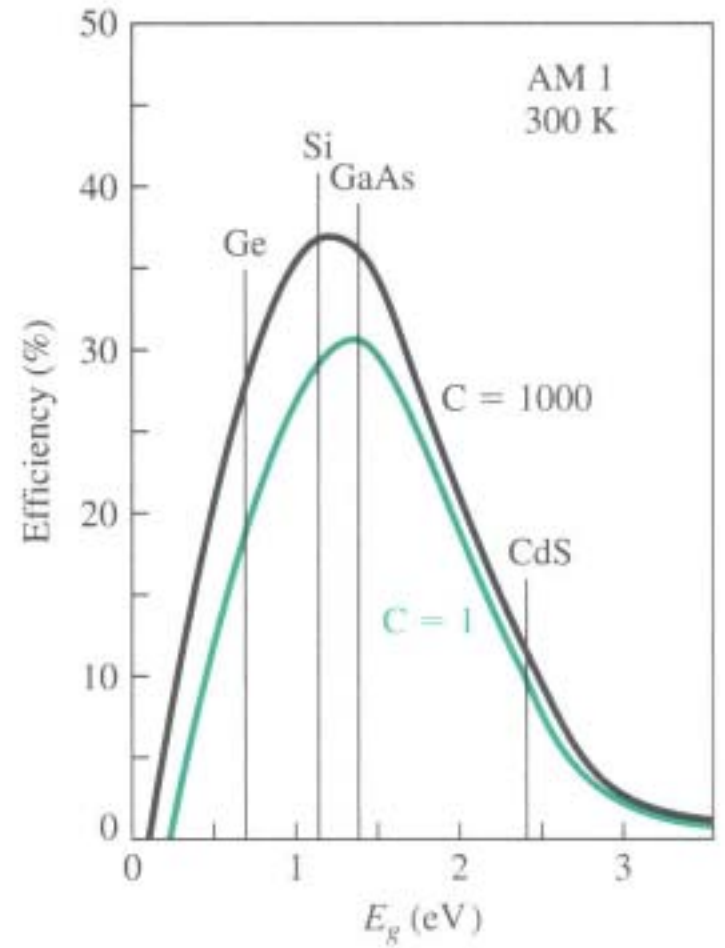
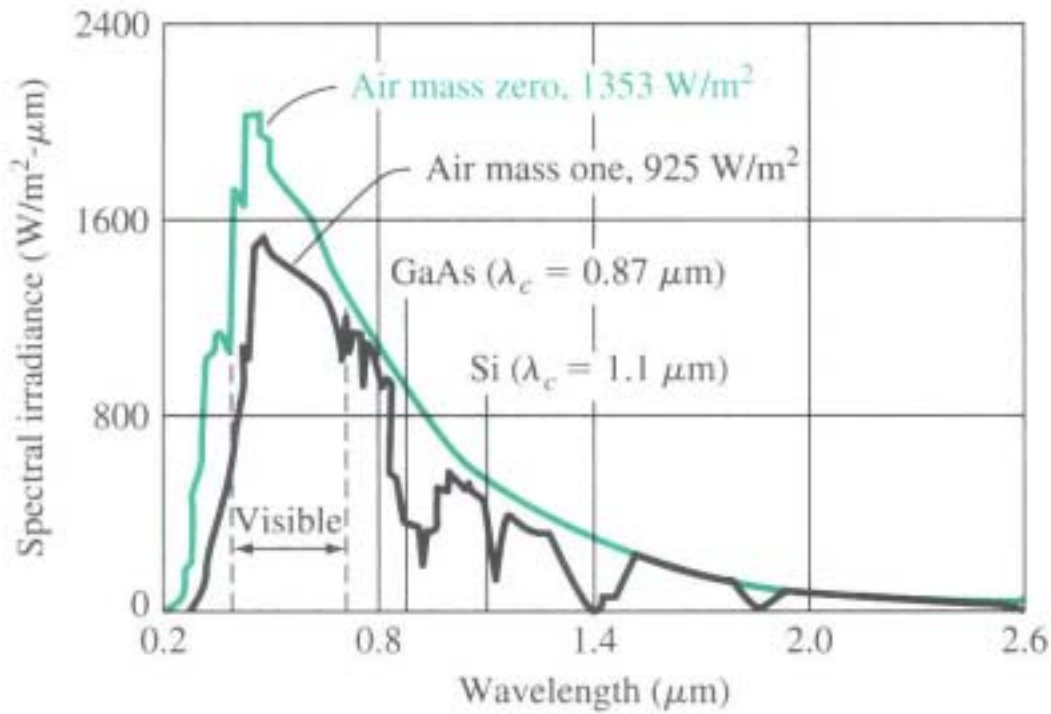
# Characteristics of Solar PV

- + Clean – No on-site byproducts generated
- + “Infinite” Supply – Energy source unlimited
- + “Distributed” energy source
- + Scalable Technology
  
- Dilute energy source –  $1\text{kW} / \text{m}^2$
- Intermittent source
- Not Cheap

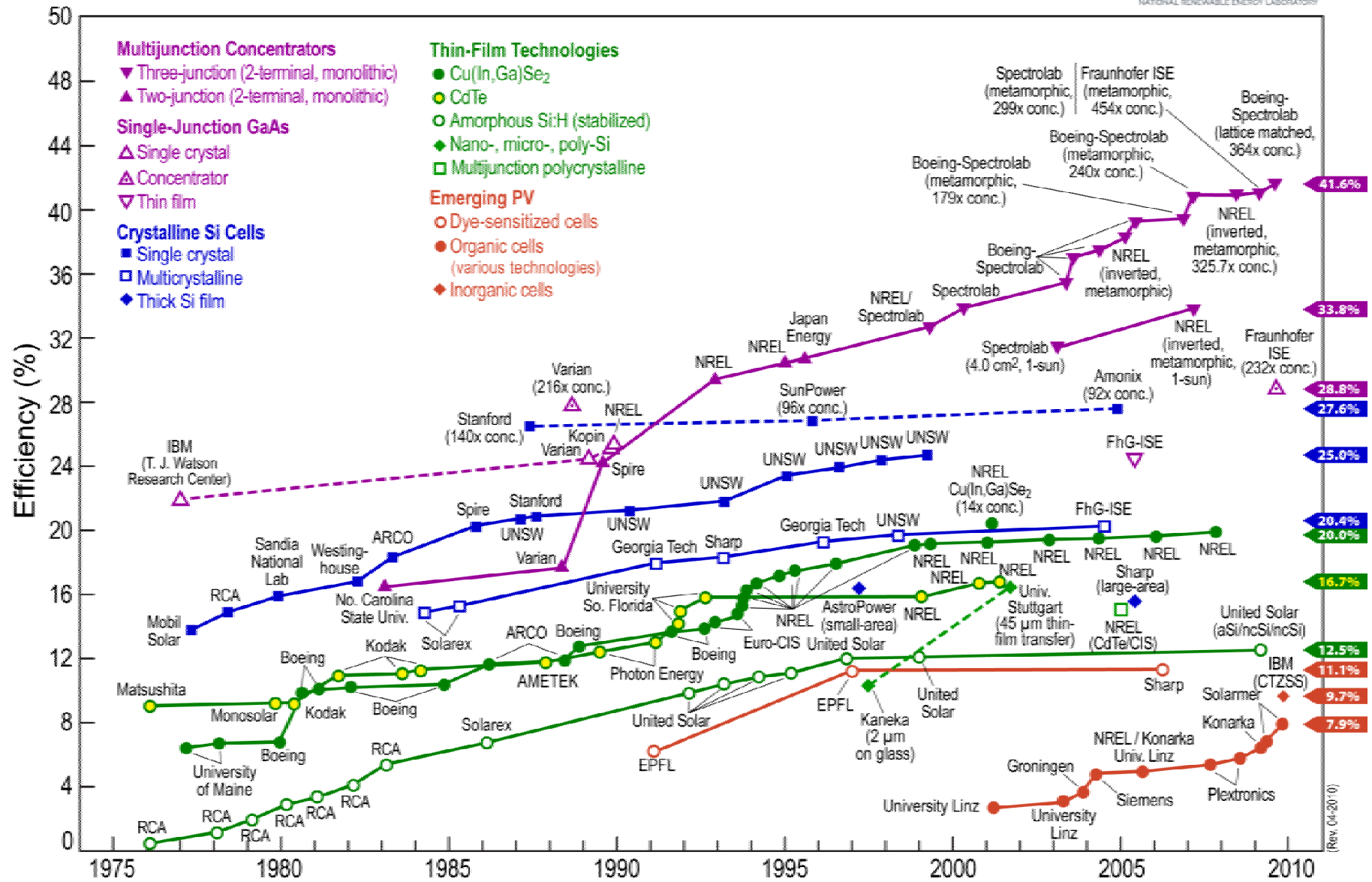
Useful Web Site for PV information:

<http://pvcdrom.pveducation.org/index.html>

# Optimal Solar Cells



# Best Research-Cell Efficiencies



(Rev. 04-2010)

# Status of Solar Photovoltaics

- **Silicon** based flat panel solar cells widely implemented in real and demonstration systems. (15 % to 25 % available at comparable \$/W )
- **Thin film** flat panel solar cells based on CIGS, CdTe, and Si emerging for commercial and household systems. (7% to 10% commercially available at lower \$/W )
- **Multijunction** solar cells widely implemented for satellite power systems and available for concentrator terrestrial systems . ( 35% to 45 % available from a few suppliers at high cost – predicted to lower cost in large concentrator installations to be competitive with conventional power systems.)

# Utility Scale Installation



# Concentrator Solar Cells



## Home Installations of Solar Panels Need Higher Efficiencies and Lower Costs



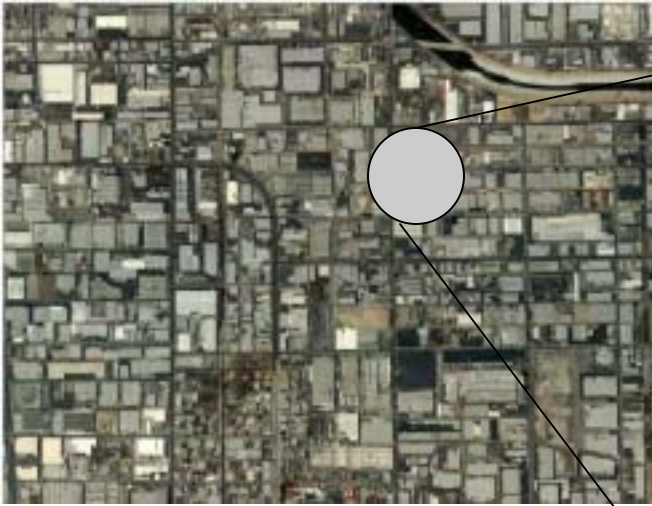
**3.5 KW  
Installation  
Generates  
6400 kWhr/year**

**\$1 - \$2.50 per peak W  
\$0.03 - \$0.08 / kWhr  
Subsidized**

**\$0.05 – \$0.12 /kWhr  
Unsubsidized**

**Over 20 year life**

# Solar Cells are emerging as growing part of the urban energy infrastructure



LA City Council  
votes for initiative  
to have DWP install  
100,000 solar roofs  
by 2013

Los Angeles Times | Business

Edison's rooftop solar project powers up



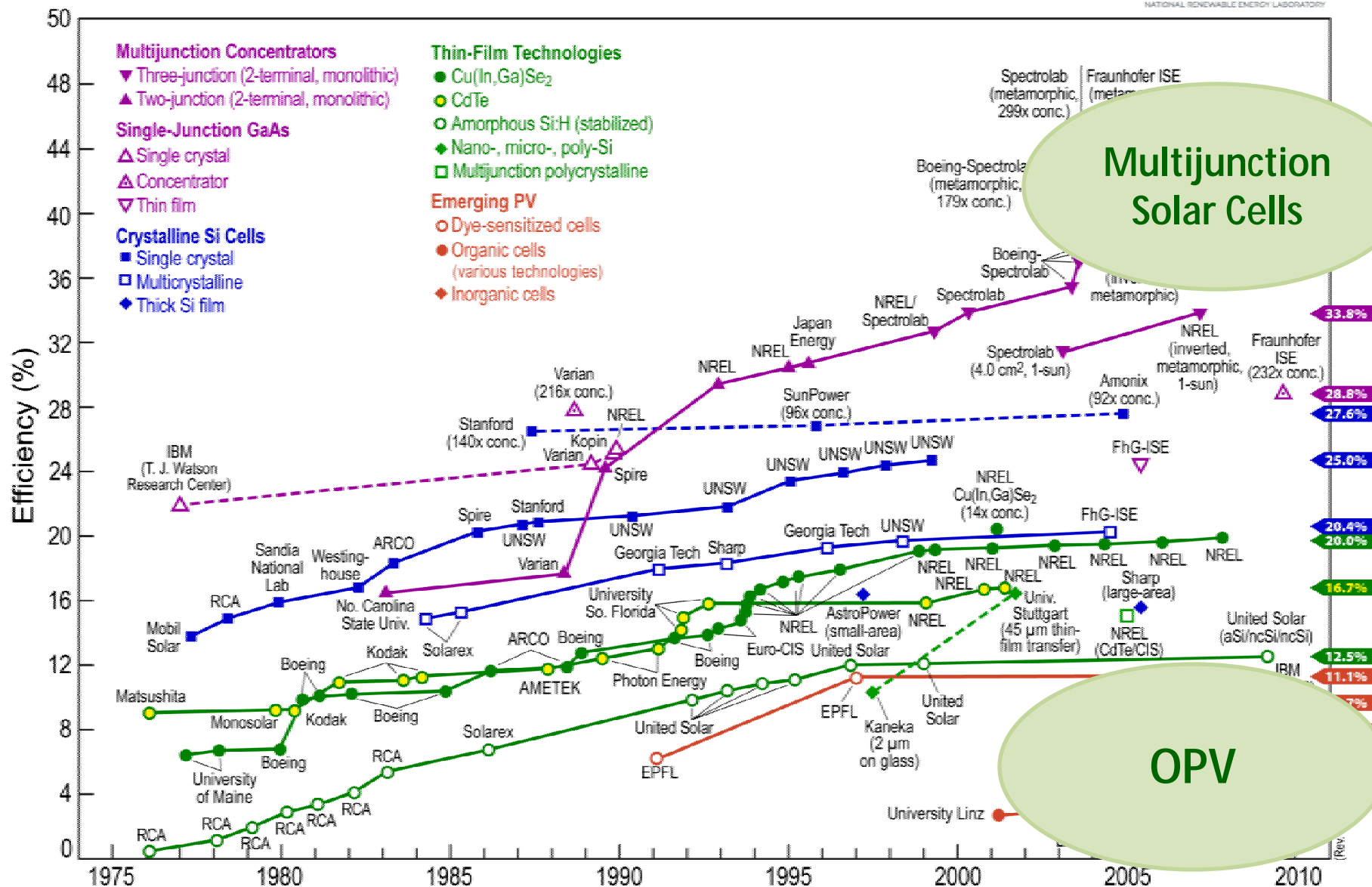
600,000 square foot installation  
CdTe Thin film cells  
First Solar

The utility's solar project...  
by business owners but criticized by consumer activists.

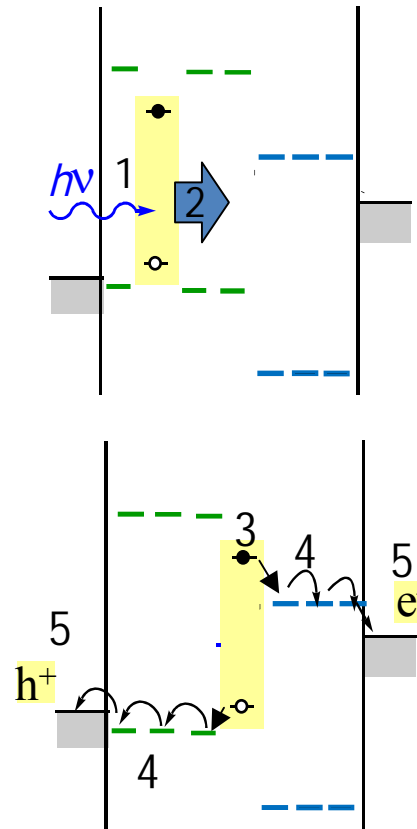
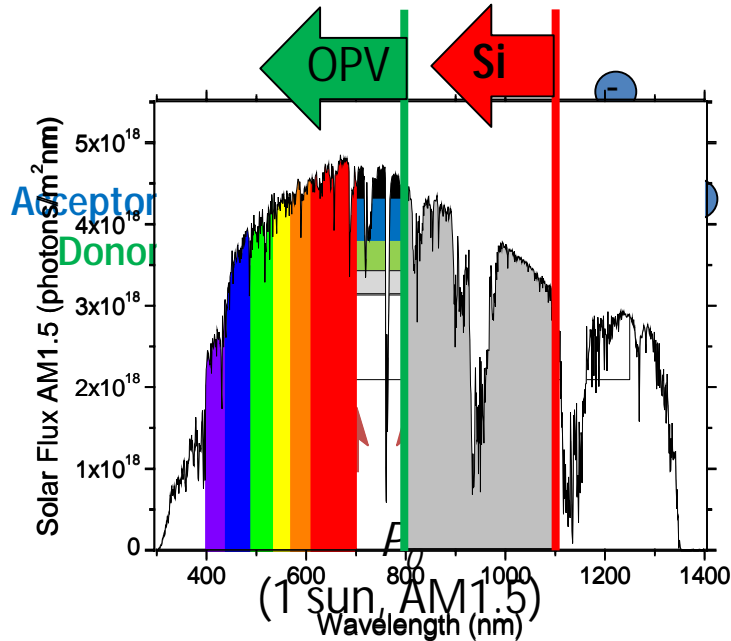
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# Best Research-Cell Efficiencies



# Limitations of Current OPVs (being attacked by CEN)



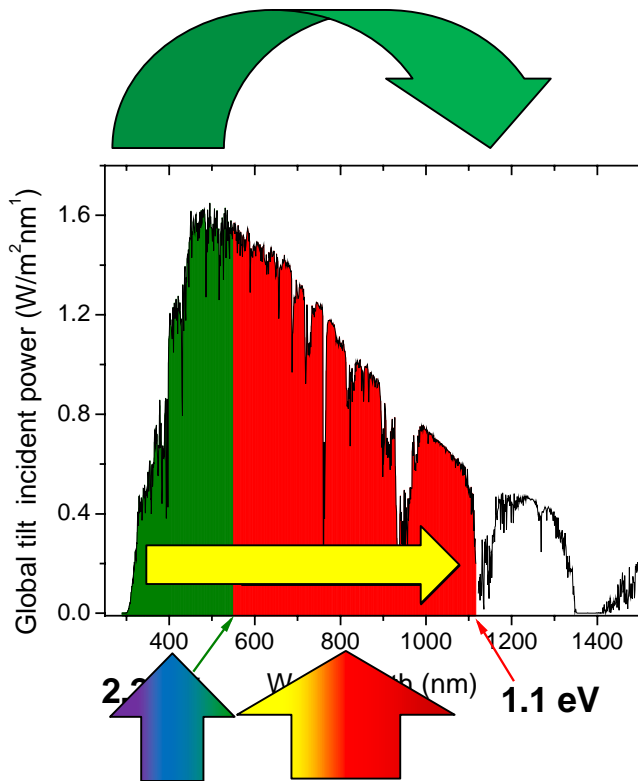
$$\eta_p = \frac{J_{sc} \times V_{oc} \times FF}{P_o}$$

- Limit  $J_{sc}$ 
  - Poor spectral overlap with solar spectrum
  - Exciton migration, typical  $L_D$  10-30 nm
- Limit FF
  - Carrier conductivity must be high
- Limit  $V_{oc}$ ,  $J_{sc}$ 
  - Exciton binding energy requires an energy offset at D/A interface
  - Singlet-triplet nature of the exciton and  $S_1/T_1$  gap is critical

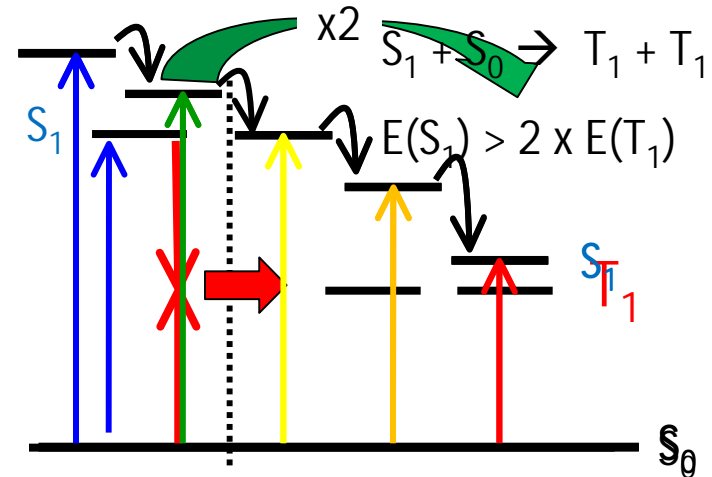


# Singlet fission routes around the Shockley-Queisser limit

1 photon in  
2 excitons out



Theoretical efficiency > 45%!  
A. Nozik, *Appl. Phys. Lett.* (2006)



- Incomplete absorption and thermalization to band gap energy limit  $\eta < 31\%$
- Singlet Fission solution:
- $h\nu > 2.2 \text{ eV} \Rightarrow 2 \text{ excitons at } 1.1 \text{ eV}$
- $h\nu < 2.2 \text{ eV}$  internally converts to 1.1 eV
- **You MUST absorb ALL photons**
- We need to understand the dynamics of singlet and triplet energy transfer to make these systems work

# Nanowire Multijunction Solar Cells

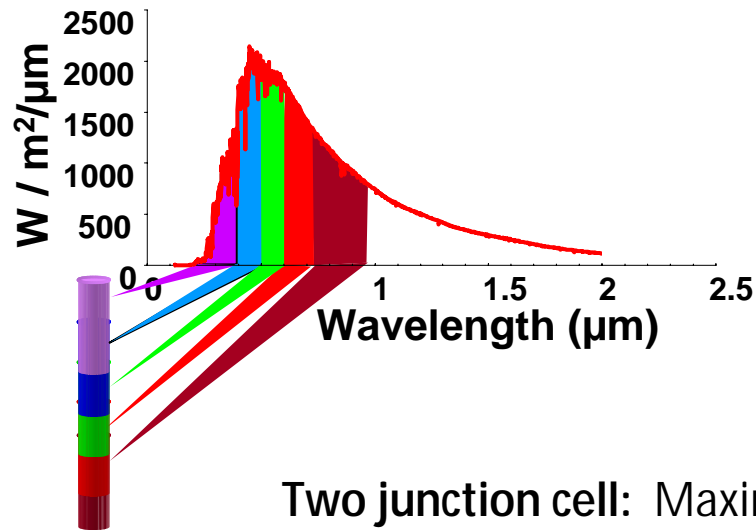
## Scientific Goals

*Understanding the physics and carrier dynamics of nanowire structures*

## Technological Goals

*Develop high-efficiency, low-cost nanowire-enabled tandem multi-junction solar cells*

Why Multijunction ? *Reduce thermal loss associated with conversion of high energy part of solar spectrum to improve solar cell efficiency.*



No. of Cells	Optimal Bandgaps (eV)						Max. Eff. %
	E <sub>1</sub>	E <sub>2</sub>	E <sub>3</sub>	E <sub>4</sub>	E <sub>5</sub>	E <sub>6</sub>	
1	1.31						31
2	0.97	1.70					42.5
3	0.82	1.30	1.95				48.6
4	0.72	1.10	1.53	2.14			52.5
5	0.66	0.97	1.3	1.7	2.29		55.1
6	0.61	0.89	1.16	1.46	1.84	2.41	57.0

Two junction cell: Maximum efficiency of **42.5%**

Three junction cell: Maximum efficiency of **48.6%**

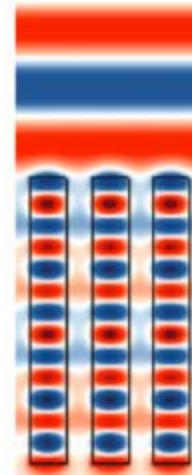
*C. H. Henry J. Appl. Phys. 51(8), August 1980*

# Nanowire based multijunction solar cells

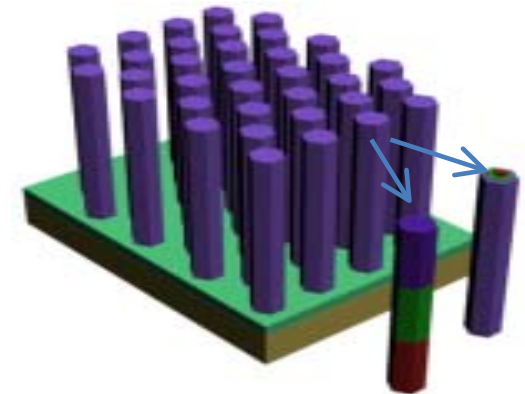
Traditional multijunction solar cell: III-V semiconductor films on 'Ge' due to lattice-mismatch constraint

## Why Nanowires?

- **Natural Strain relief in the radial direction**
- Relax lattice-match requirement for the choice of n
- Enable growth of III-V (GaAs, GaAsP, InGaP) nanowire films due to lattice mismatch)
- Eliminate expensive Ge substrates in film-based multijunction cells
- Leverage silicon solar cell infrastructure
- **Tunable bandgap and absorption threshold of each junction**
- **Optical Concentration of light**
- **"Natural" Antireflection Properties**

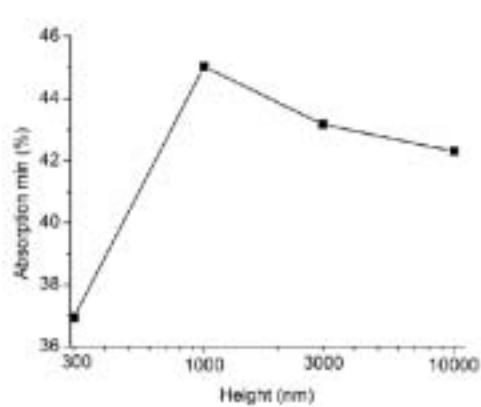


possible to grow as  
cells

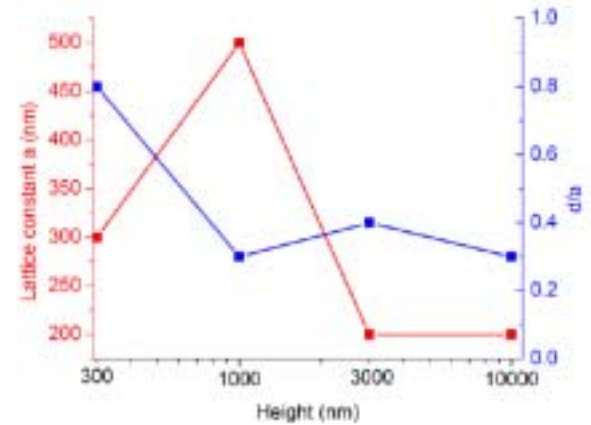
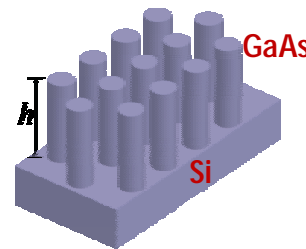
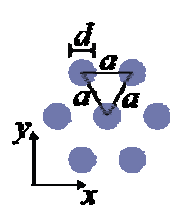


# Optimized geometry GaAs on Si

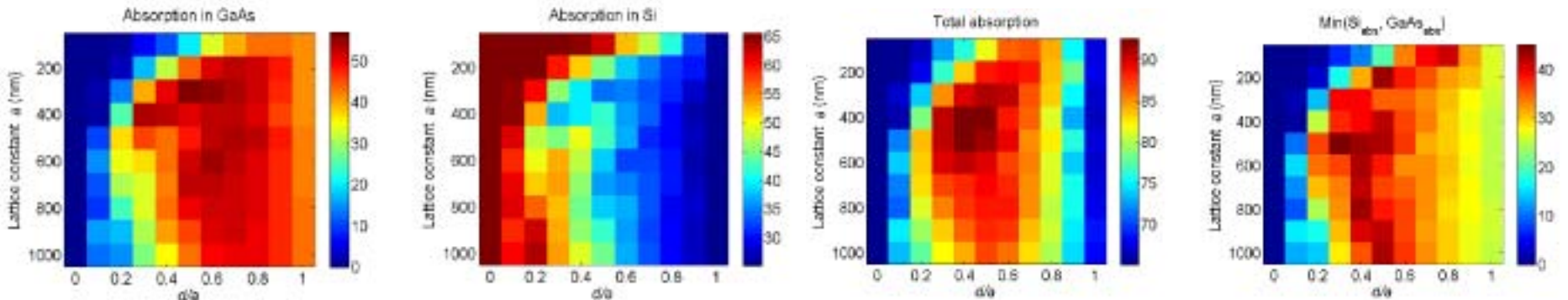
Weighted absorption: absorption in percentage of photons of AM1.5 illumination between 300nm to 1127nm (1.12eV)



$$Abs = \frac{\int_{300nm}^{1127nm} A(\lambda)I(\lambda)\lambda d\lambda}{\int_{300nm}^{1127nm} I(\lambda)\lambda d\lambda}$$

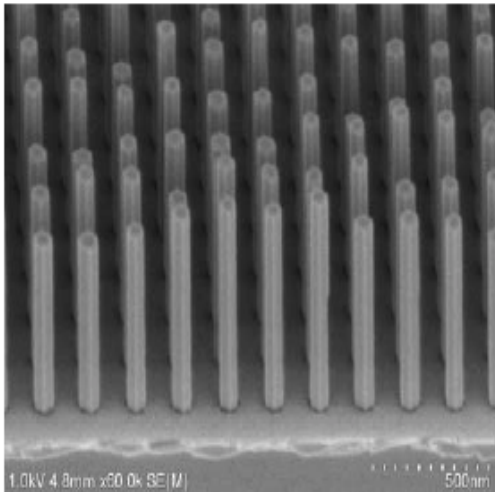


h=1μm

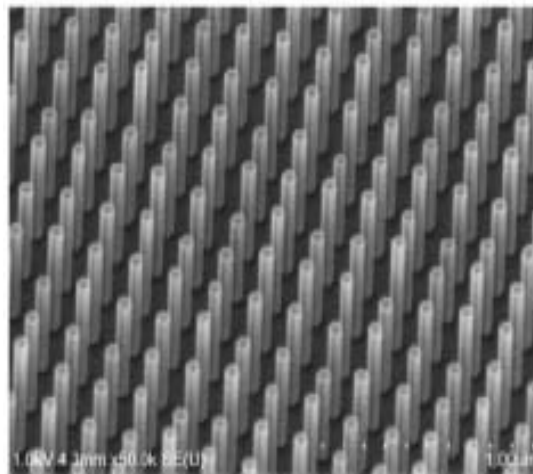


# Semiconducting Nanowires

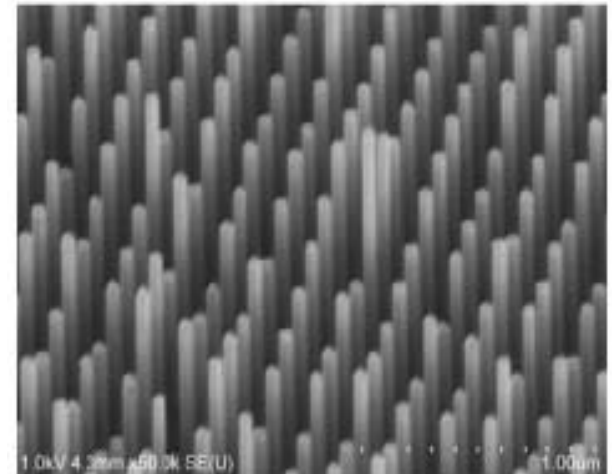
Various nanowires (NW) were synthesized using selected area growth (SAG).



**InP NW on InP (111) A substrate**



**GaAs NW on GaAs (111) B substrate**

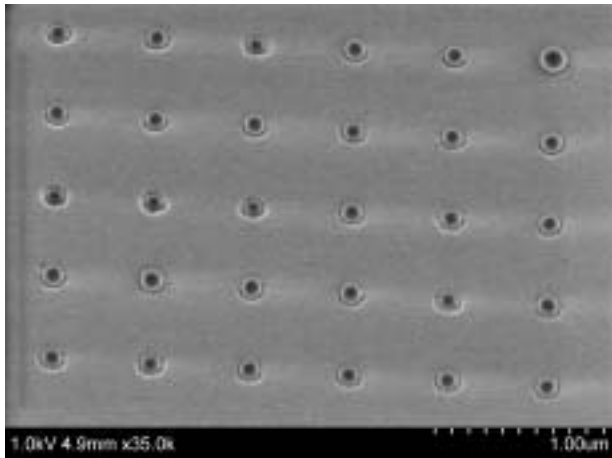


**InAs NW on GaAs (111) B substrate**

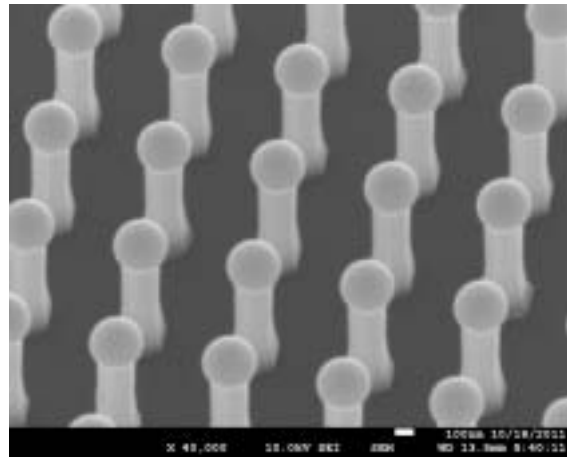
## Progress to date:

1. Demonstrated synthesis of a wide range of nanowire materials.
2. Carried out simulation for various material combination
3. Currently synthesizing GaAs nanowires on Si (111) substrates for the fabrication of tandem solar cells.

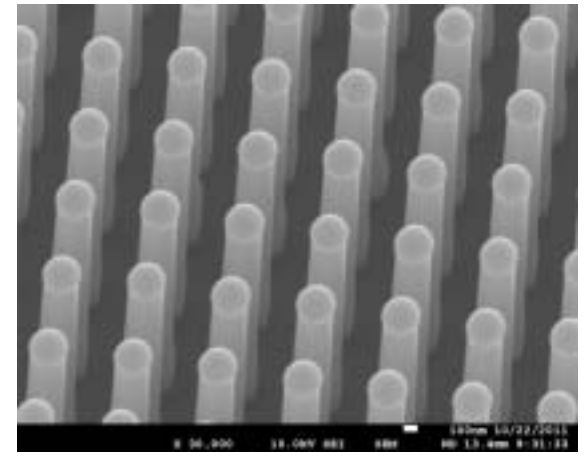
# NW growth via in-situ formed metal droplet



In-situ deposition of Ga droplets



Self-catalyzed growth

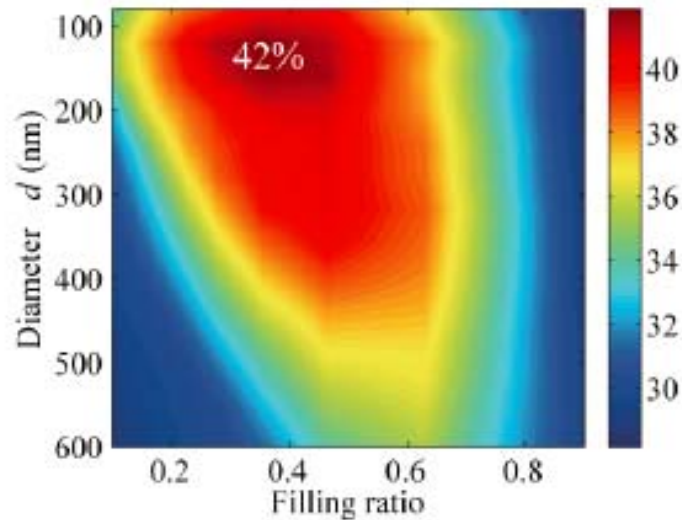


Longer nanowires

- Relatively fast growth rate
- Relatively low growth temperature (600 °C)
- Growth from liquid metal droplet may reduce defects in NW.

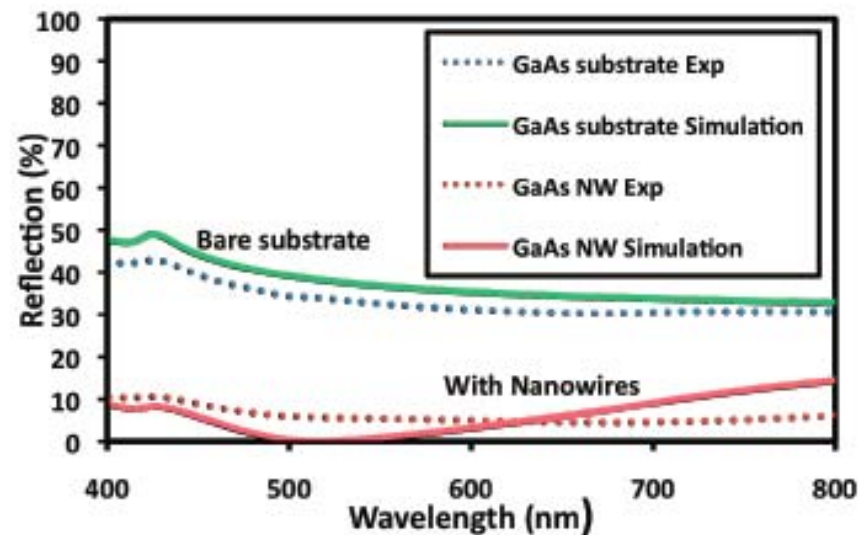
## Model verification & direct comparison with experiment

*Calculated ultimate efficiency  
GaAs nanowire arrays on  
substrate ( $h=100\text{nm}$ )*



*vs. flat substrate: 27%*

*Comparison of reflection*



Zhou/Dapkus/Povinelli groups