EE80J/180J

Spring 2015,

Lecture #4

Personal Energy Audit

The goal of this project is for students to get a full picture of the supply and demand of energy used in their daily life. While working on this report, students will identify all energy services and their energy sources, obtain records of their energy usage, determine the energy consumption for each service, analyze the information, compare, draw conclusions and make recommendations.

Two parts:

- report (due in class)
- on-line questionnaire (completed on campus)

Report Format

- Abstract
- Introduction (should include information about the student)
- Calculations
  - List of energy services and sources
  - Transportation
  - Hot water consumption
  - Electricity usage (Wh/week)
    - Calculated from labels
    - Measured with "Kill a Watt" meter
      - When appliances are on
      - When appliances are off
- Analysis
  - If student has access to their PG&E bill and Smart Meter
    - Look for peaks of energy consumption, what do they consist of? What appliances were on during those particular hours.
    - How does your home compare to others
    - How does your energy consumption vary with weather
  - If student does not have access to their PG&E bill
    - Make a plot of energy consumed throughout the week
    - Make a plot of peak outside temperatures throughout the week
    - Compare the two plots for similarities
- Conclusion (should include qualitative and quantitative analysis summary from previous section). It has to answer specific list of questions.

Calculations and Analysis
List of energy services and sources

Services	Sources

Calculations and Analysis
List of energy services and sources

Services	Sources
Water Heating	Natural gas
Space Heating	Natural gas
Lighting	Electricity
….	….

Calculations and Analysis Transportation

Driving

- 5 mi daily Scotts Valley to Santa Cruz
- 10 mi * 4 days/week = 40 mi / week
- Car: 30 miles / gallon
- 1.33 gallons = 5 L of gas / week
- **35 MJ/L energy content 86 Octane gas**
- 35 MJ/L * 5 L = **175 MJ**
- Carpool: 175 MJ / 2 = **87.5 MJ**

Busses, Trains

- **1.6 MJ / km** for each passenger

Hot Water Consumption

Heat Energy

- $Q = m \times c_p \times (T_1 - T_2)$
  - c_p : specific heat constant, 4190 J / kg C
  - T_1 : temperature of the hot water
  - T_2 : temperature of the cold water

Example

James uses 50 L of hot water per day from an electric hot water system. The water is heated from 18C to 60C.

The heat energy contained in the water,

$Q = m \times c_p \times (T_1 - T_2)$

Efficiency of Electric Water Heater is 0.7 to 0.8

Efficiency of Gas Water Heater is 0.6 to 0.75

Hot Water Consumption

Heat Energy

- $Q = m \times c_p \times (T_1 - T_2)$
  - c_p : specific heat constant, 4190 J / kg C
  - T_1 : temperature of the hot water
  - T_2 : temperature of the cold water

Example

James uses 50 L of hot water per day from an electric hot water system. The water is heated from 18C to 60C.

The heat energy contained in the water,

$Q = m \times c_p \times (T_1 - T_2)$

$Q = 50\ kg \times 4190 \times (60\ C - 18C)$

Q = 8.8 MJ / day

Q = 61.6 MJ/ week

Efficiency of Electric Water Heater is 0.7 to 0.8

61.6 MJ / 0.8 = 77 MJ

Efficiency of Gas Water Heater is 0.6 to 0.75

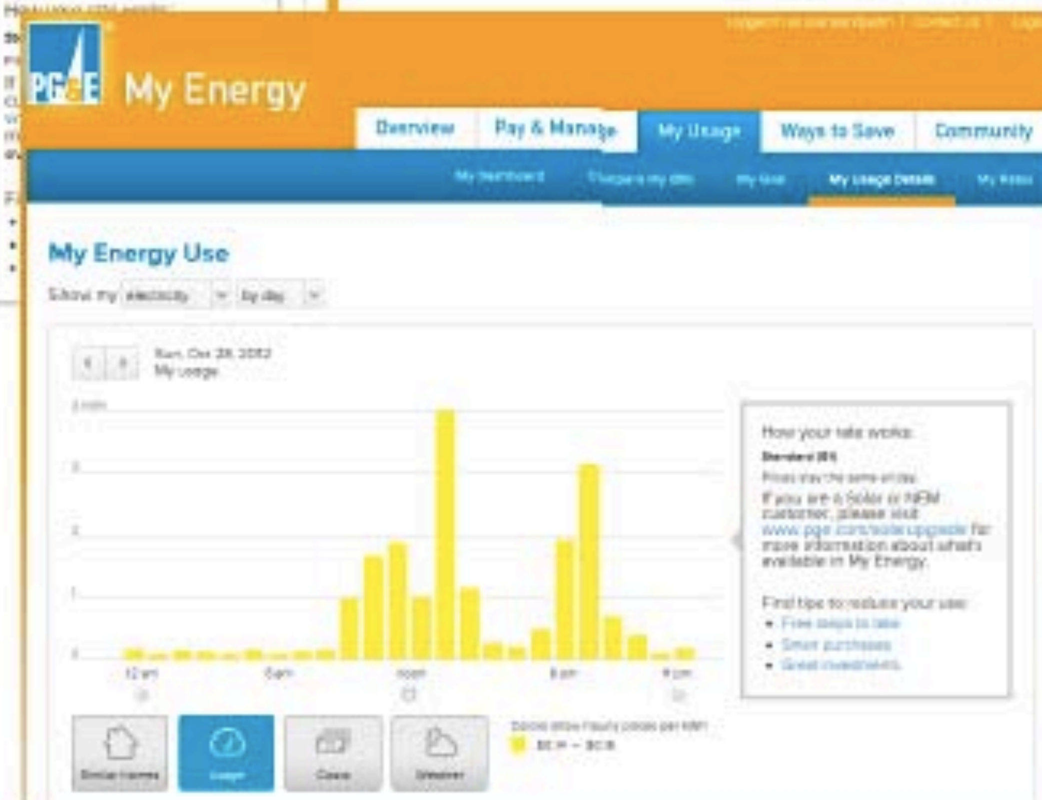
Electricity Usage

Appliance	#	Power (W)	Daily Usage (h)	Daily Energy (Wh)	Weekly Energy (Wh)	Weekly Energy (J)
Computer	1	120	3	**360**	2520	**9.07 M**
Vacuum Cleaner	1	1000	0.14	**140**	140	**0.5 M**
Electric Drill	1	600	0.07	**42**	42	**0.15 M**
Total				**542 W*h**		**9.72 MJ**

Electricity Usage

- Confirmed with "Kill a Watt" meter
  - When appliances are **on**
  - When appliances are **off**

Electricity Usage
As seen on PG&E Web-site



- Compare to homes in your area
- Compare to weather patterns

Conclusion

Should include qualitative and quantitative analysis summary from previous sections

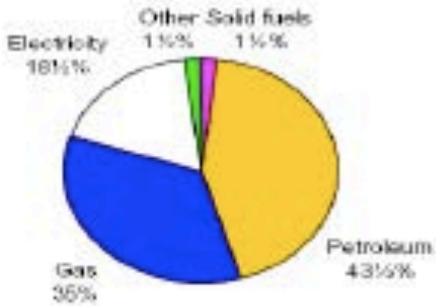
Should answer the following set of questions:

- Which energy services are the biggest energy users?
- How would you expect energy use for each service to change though out the year?
- Any surprises or noteworthy points?
- From working on this project, would you now consider alternative energy sources for particular services?
- From the calculations above, suggest a replacement for one of the high energy appliances? How much would it off set your energy consumption by?
- Would you now consider a habit or lifestyle change?
- Compare your results to the data collected by David MacKay.

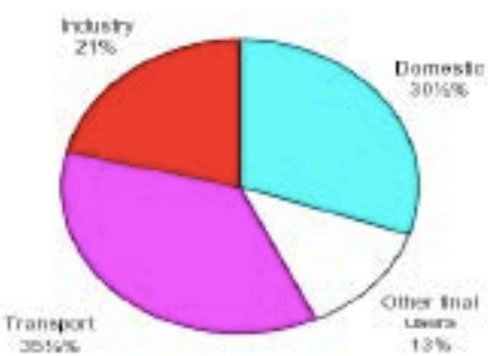
Conclusion

- Compare your results to the data shown below.

Average Power Consumption (UK)



2004



125 kWh/day (Europe)
250 kWh/day (USA)

(Not including embodied energy in imports nor solar energy used by agriculture)

For CO_2 pollution, divide by 10:
100 kWh/day $\simeq$ 10 tonnes CO_2/y

David MacKay, Sustainable Energy –Without the Hot Air

Part II

Complete an online questionnaire on campus (~45 questions).

http://classes.soe.ucsc.edu/ee080j/Spring11/Labs/Questionnaire/forms.html


QUESTIONNAIRE

* Denotes a required field.

1. Name *
2. Student ID Number *
3. What is your major? *
   - Engineering
   - Economics
   - Environ. Studies
   - Undeclared
   - Other:
4. Do you have a minor? *
   - Yes
   - No
5. Do you have a double major? *
   - Yes
   - No
6. What is your age? *
   - Below 18
   - 19-20
   - 21-22
   - 23-24
   - 25 and up

- Due Dates:

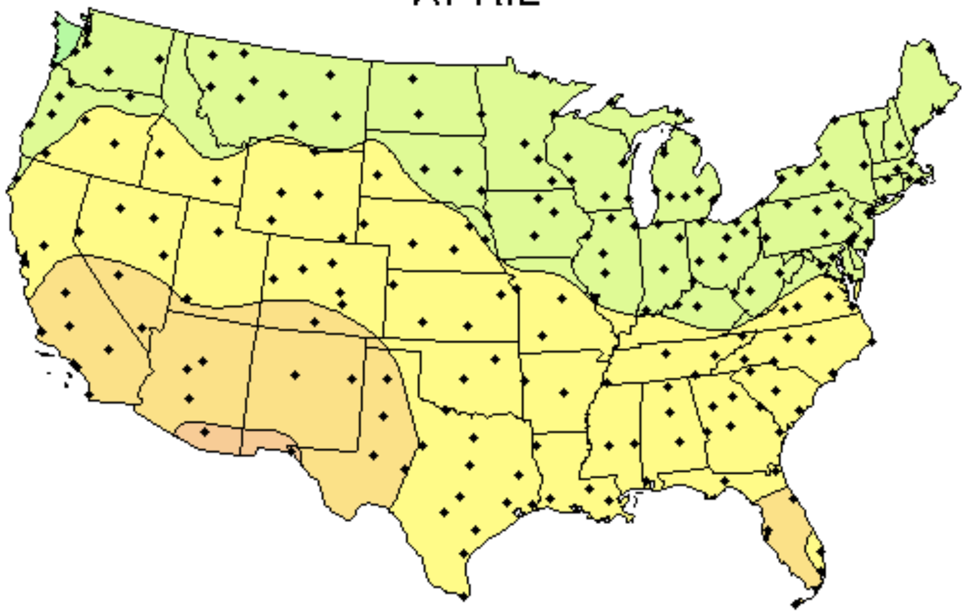
- April 27, in class

Photovoltaics:

Direct conversion of solar radiation to electricity

Average Daily Solar Radiation Per Month

APRIL



Horizontal Flat Plate

This map shows the general trends in the amount of solar radiation received in the United States and its territories. It is a spatial interpolation of solar radiation values derived from the 1961-1990 National Solar Radiation Data Base (NSRDB). The dots on the map represent the 239 sites of the NSRDB.

Maps of average values are produced by averaging all 30 years of data for each site. Maps of maximum and minimum values are composites of specific months and years for which each site achieved its maximum or minimum amounts of solar radiation.

Though useful for identifying general trends, this map should be used with caution for site-specific resource evaluations because variations in solar radiation not reflected in the maps can exist, introducing uncertainty into resource estimates.

Maps are not drawn to scale.

National Renewable Energy Laboratory
Resource Assessment Program

$kWh/m^2/day$

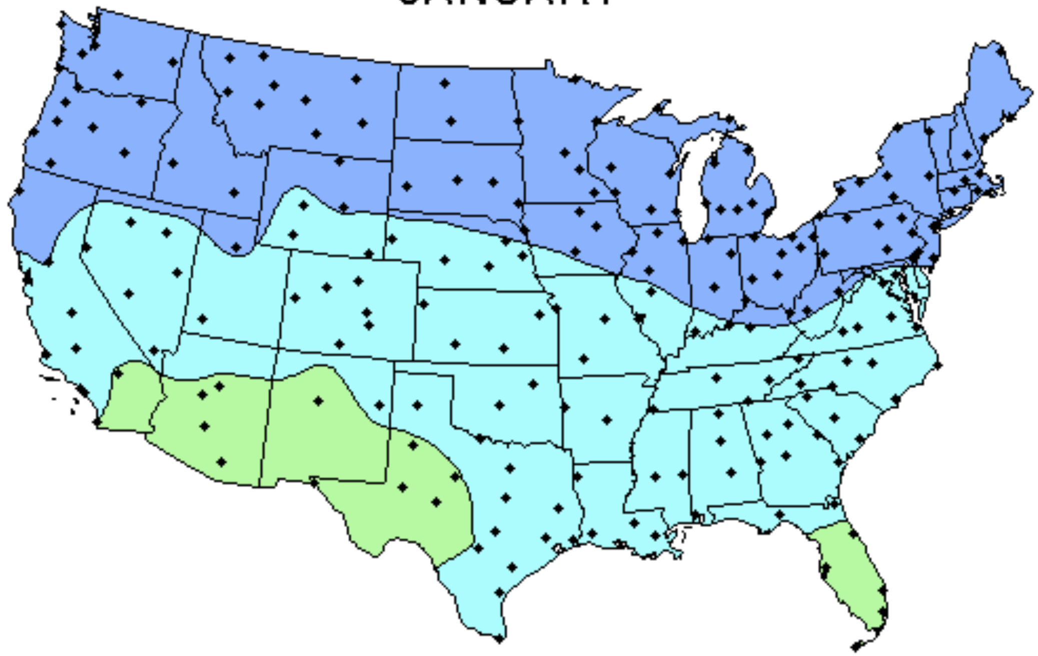
- 10 to 14
- 8 to 10
- 7 to 8
- 6 to 7
- 5 to 6
- 4 to 5
- 3 to 4
- 2 to 3
- 0 to 2
- none

FT00A04-316

http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/atlas/Table.html

Average Daily Solar Radiation Per Month

JANUARY



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- none

National Renewable Energy Laboratory
Resource Assessment Program

FT00A01-313

Figure 3.10

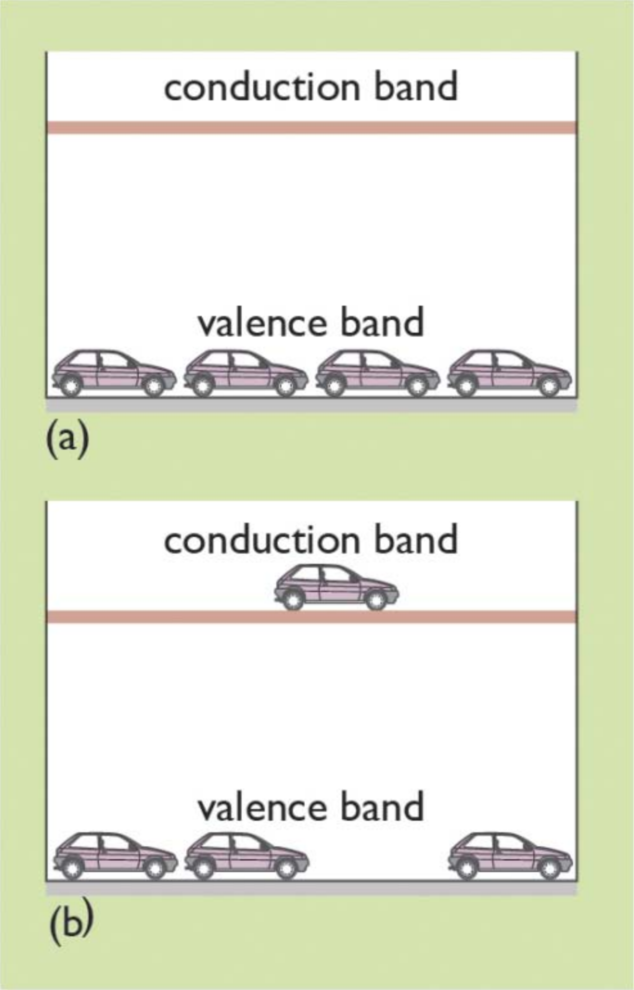
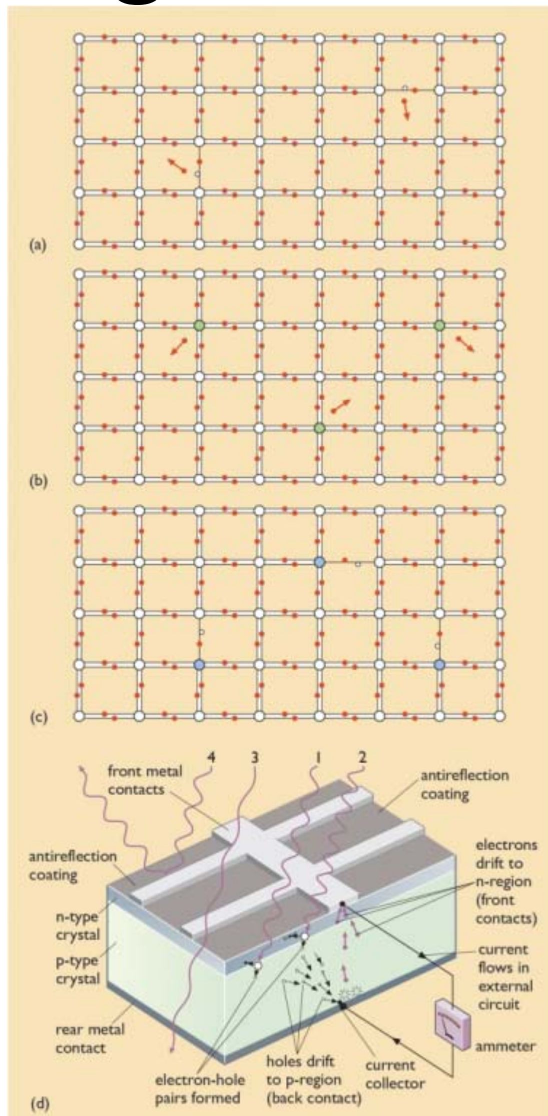

conduction band
valence band
(a)
conduction band
valence band
(b)

Figure 3.11



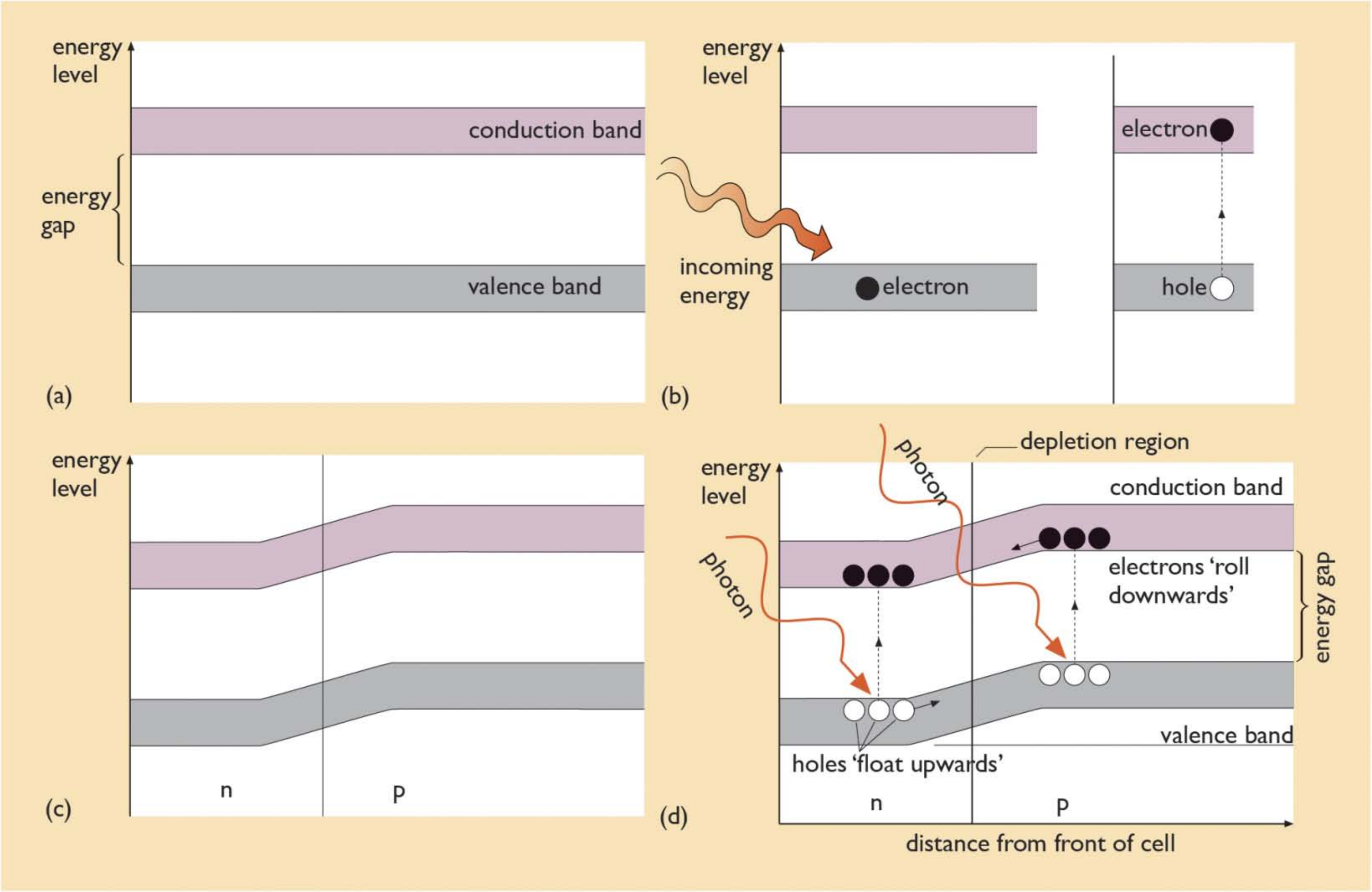
Green, M. (1982) Solar Cells, Prentice-Hall

Pure silicon

N type silicon
(Phosphorus doping)

P type silicon
(Boron doping)

Figure 3.12



energy level
conduction band
energy gap
valence band
(a)
energy level
incoming energy
electron
electron
hole
(b)
energy level
n
p
(c)
depletion region
energy level
photon
photon
conduction band
electrons 'roll downwards'
energy gap
valence band
holes 'float upwards'
n
p
(d)
distance from front of cell

light energy

- sunlight as a form of "radiation"
- radiation comes in packets of energy
  photons (massless "particles")

$$E = \frac{hc}{\lambda}$$

, h = Planck's constant
c = velocity of light
λ = wavelength

- rule of thumb /

$$E(eV) \cong \frac{12345}{\lambda(\text{Å})}$$

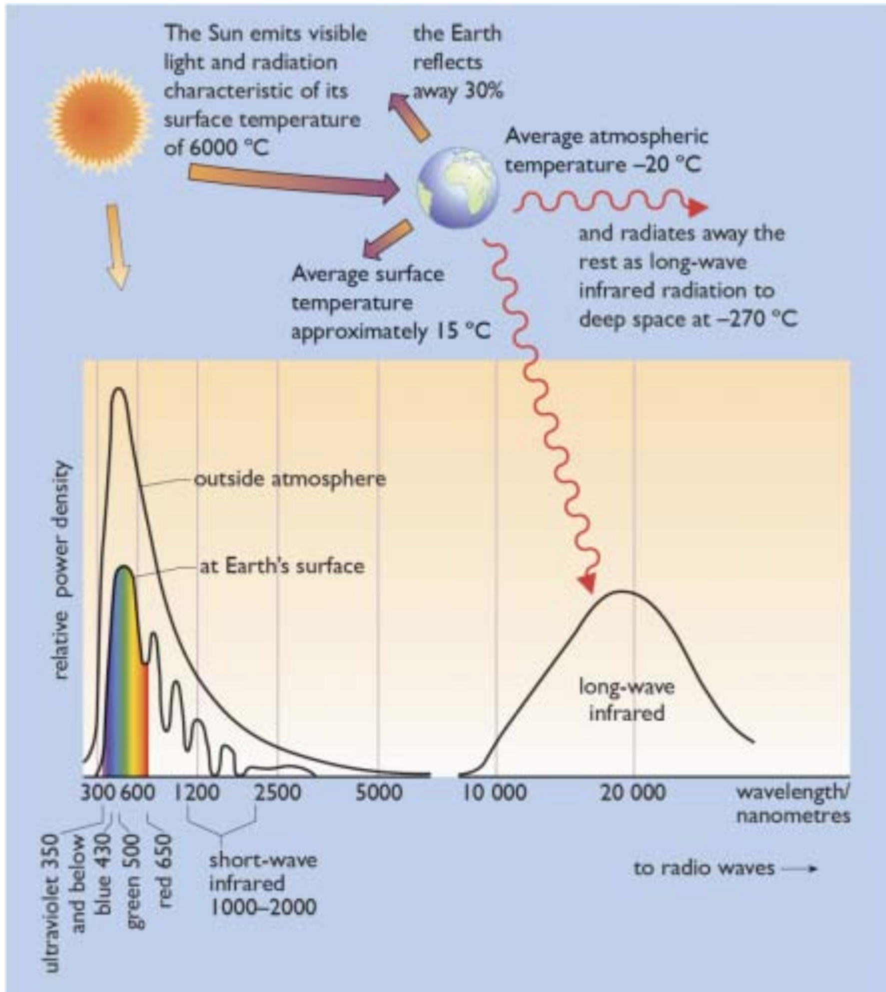
$$\text{Å} = 10^{-10}\,m$$

if $E > E_{GAP}$, excess energy → heat

if $E = E_{gap}$, absorption (max efficiency)

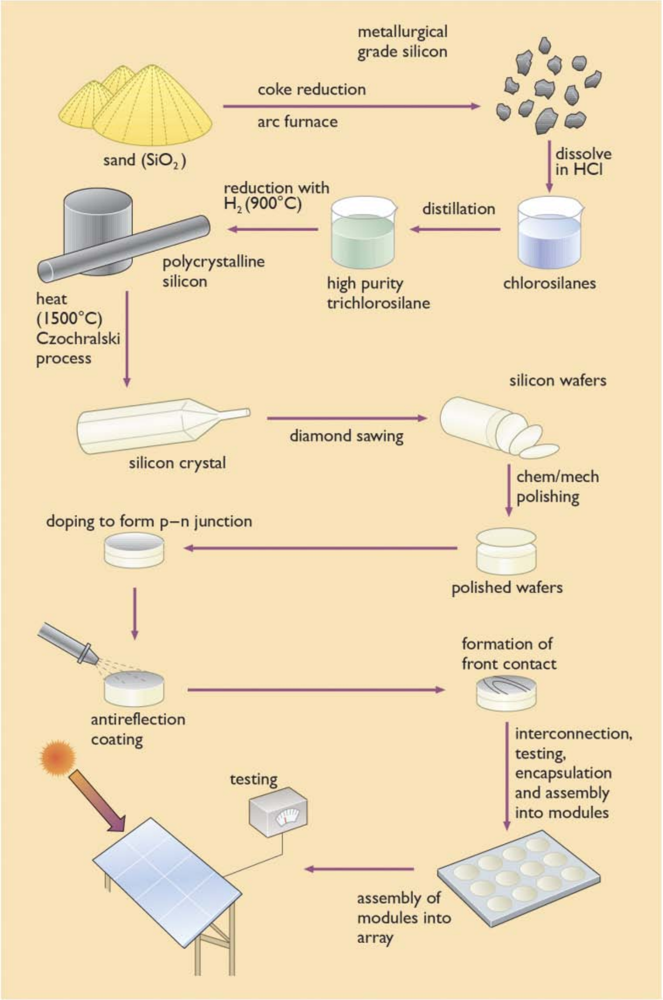
if $E < E_{gap}$, photon goes right through

Solar Spectrum



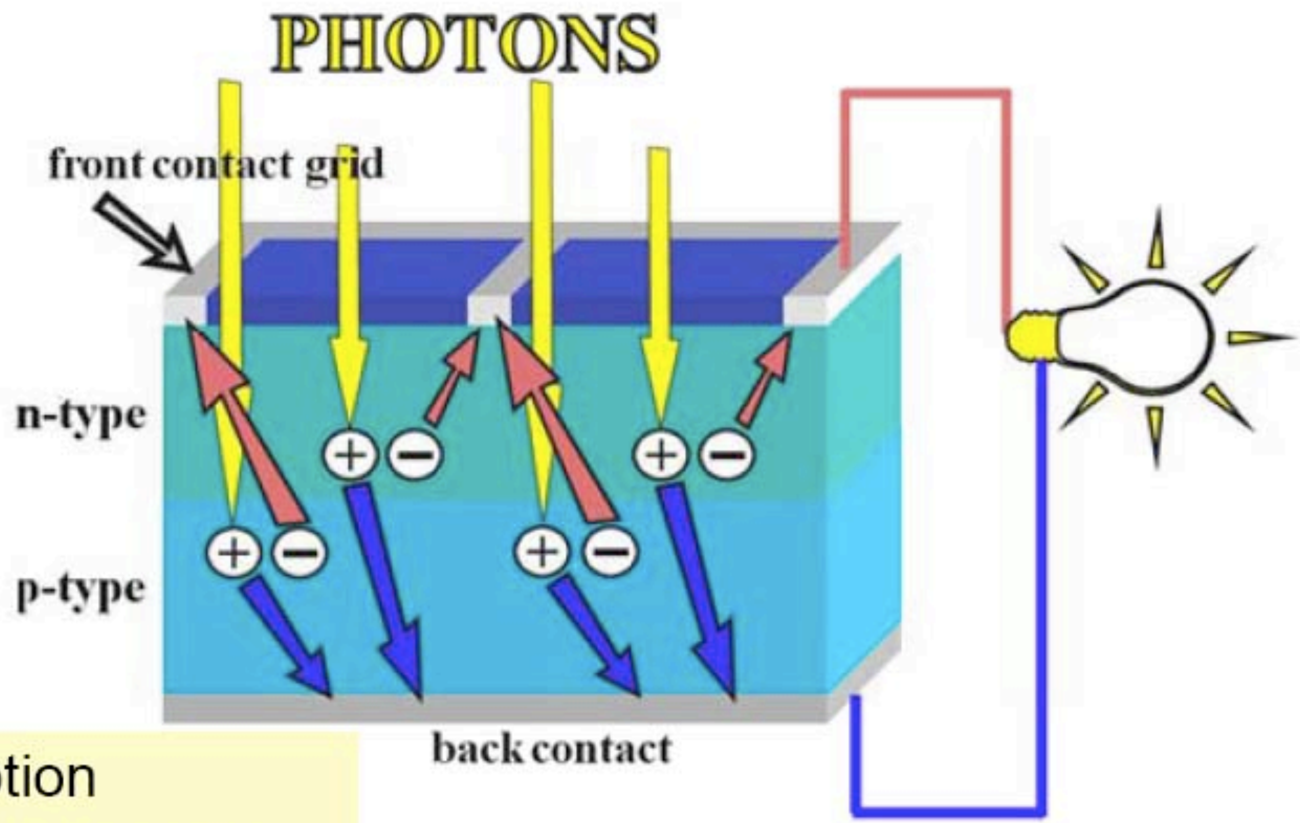
1 nm = 10 Angstroms

Figure 3.13



metallurgical grade silicon
coke reduction
arc furnace
sand (SiO_2)
dissolve in HCl
reduction with H_2 (900°C)
distillation
polycrystalline silicon
high purity trichlorosilane
chlorosilanes
heat (1500°C) Czochralski process
silicon wafers
diamond sawing
silicon crystal
chem/mech polishing
doping to form p–n junction
polished wafers
formation of front contact
antireflection coating
interconnection, testing, encapsulation and assembly into modules
testing
assembly of modules into array

Solar Cell



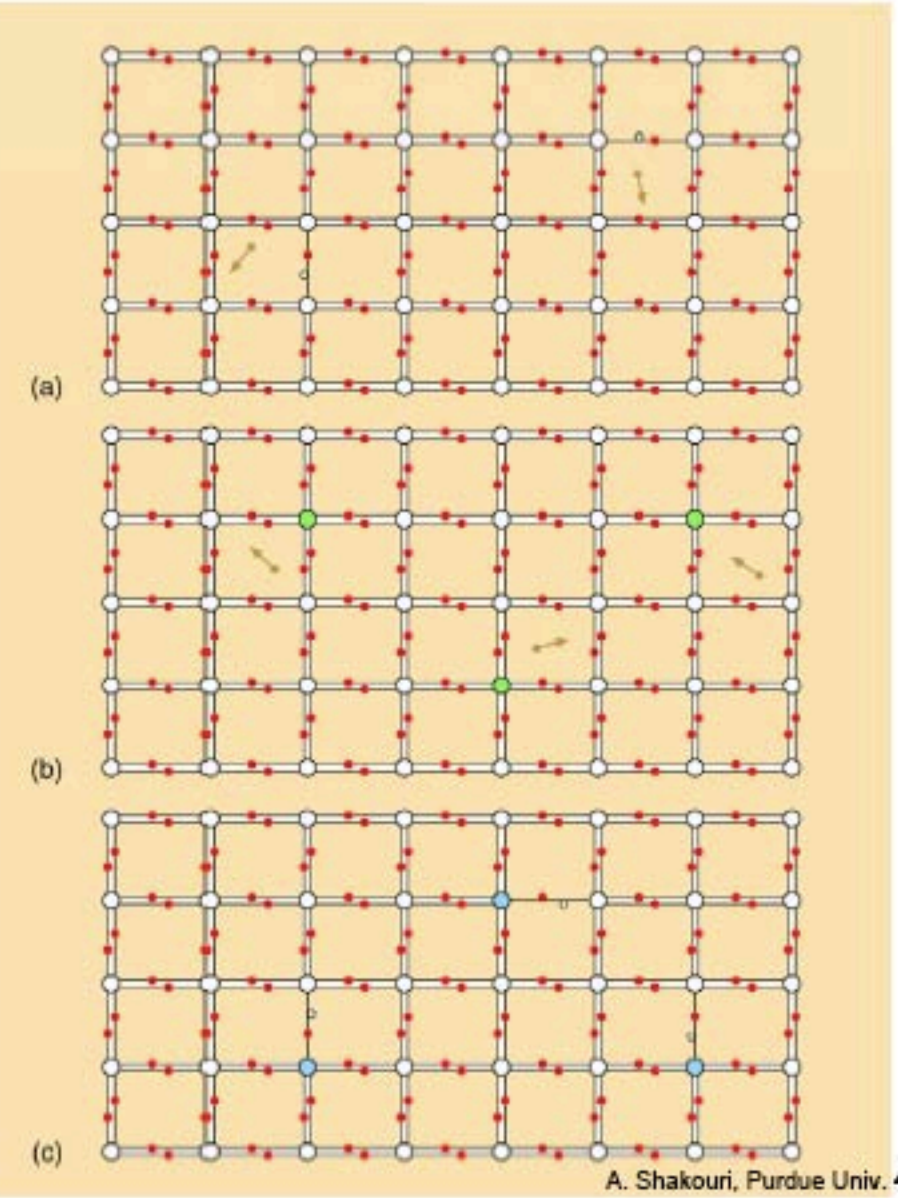
- Light absorption
- Electron/hole separation
- Charge transport

Ken Pedrotti, UCSC

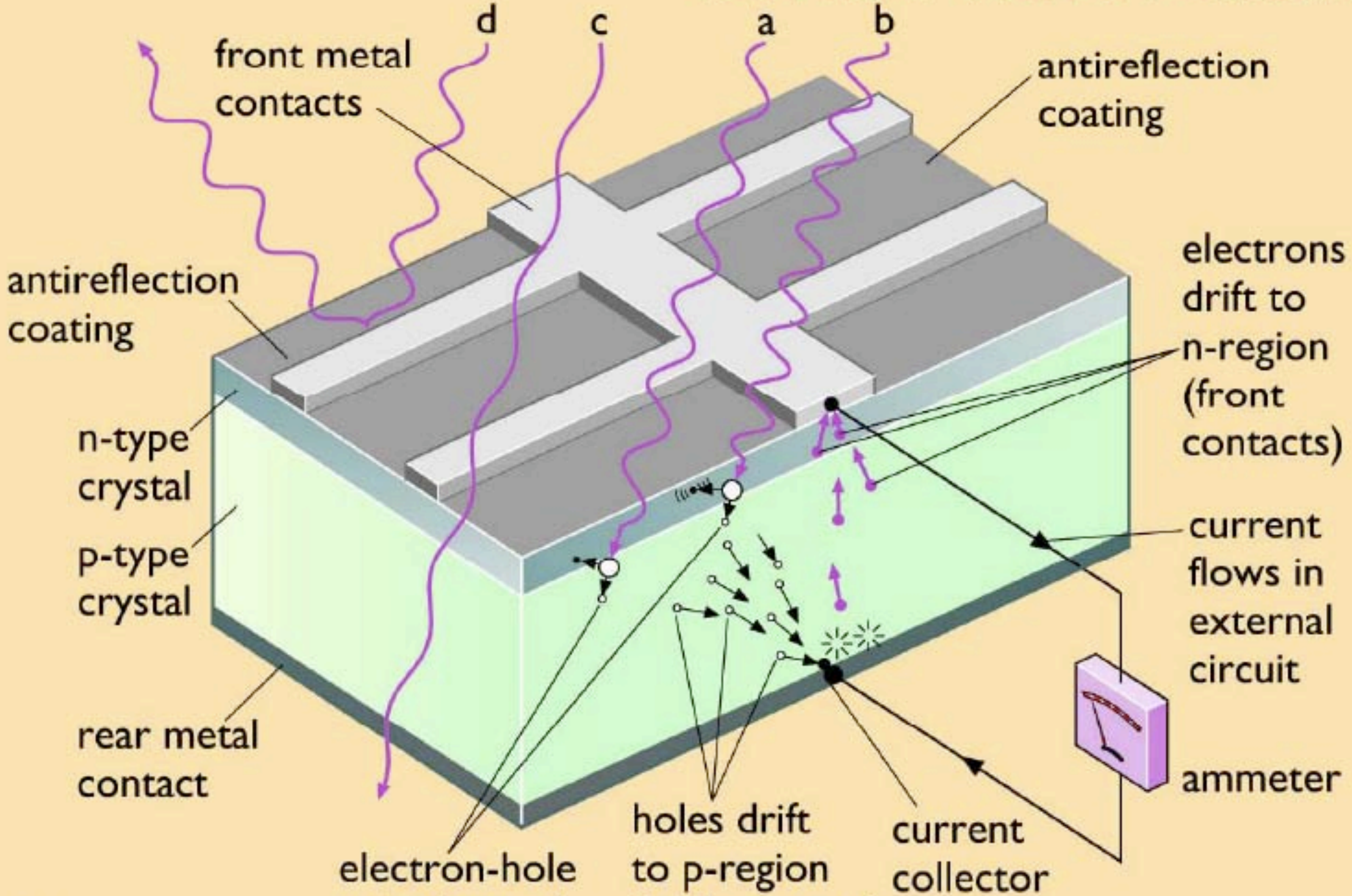
Intrinsic Semiconductor

N-type Semiconductor

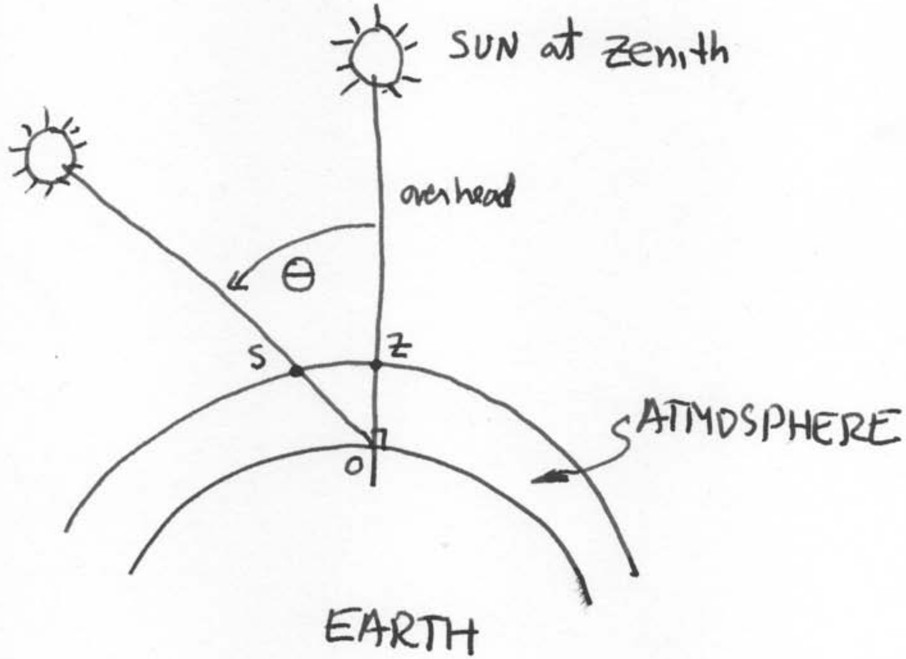
P-type Semiconductor



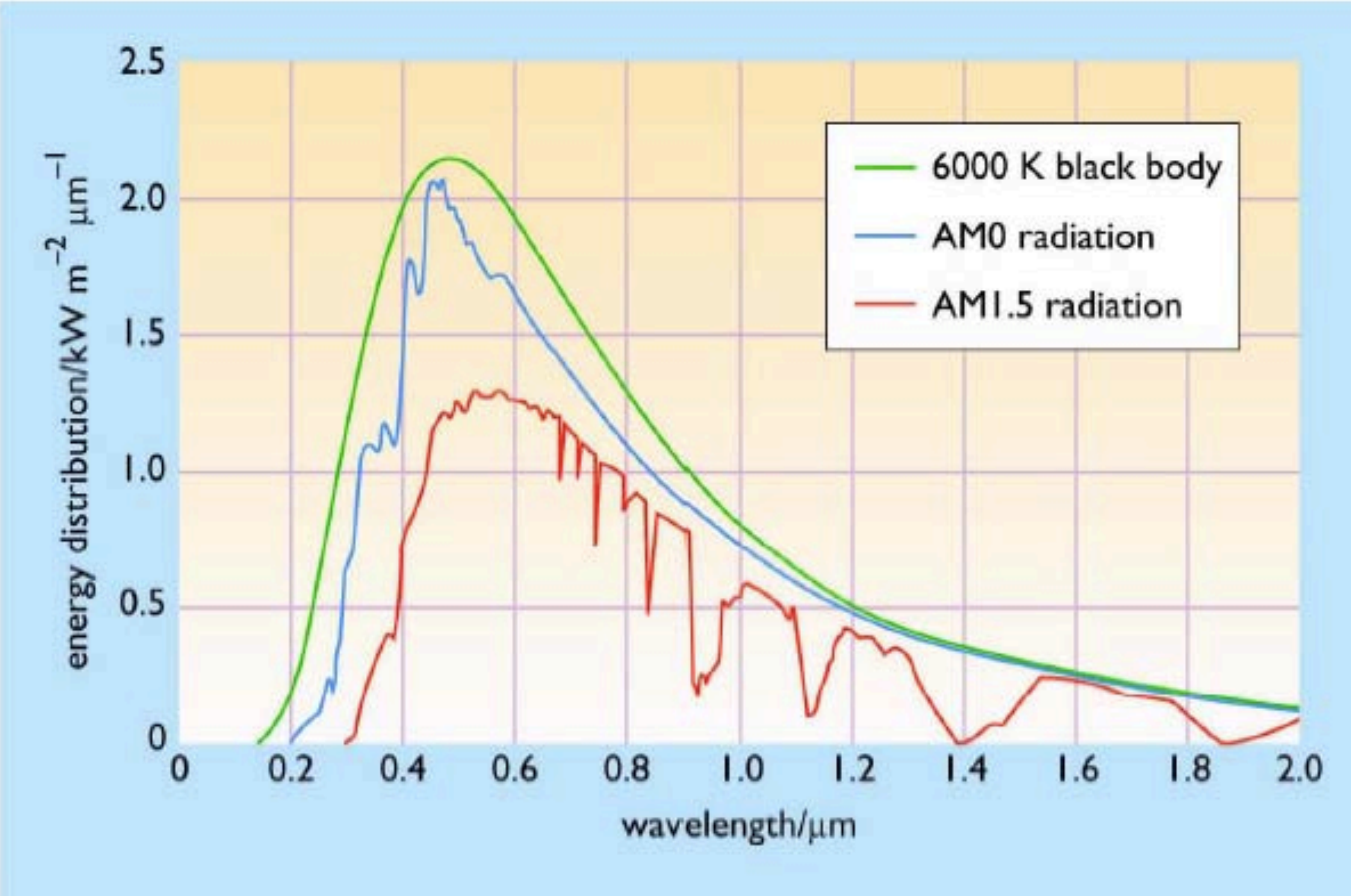
Solar Photovoltaic

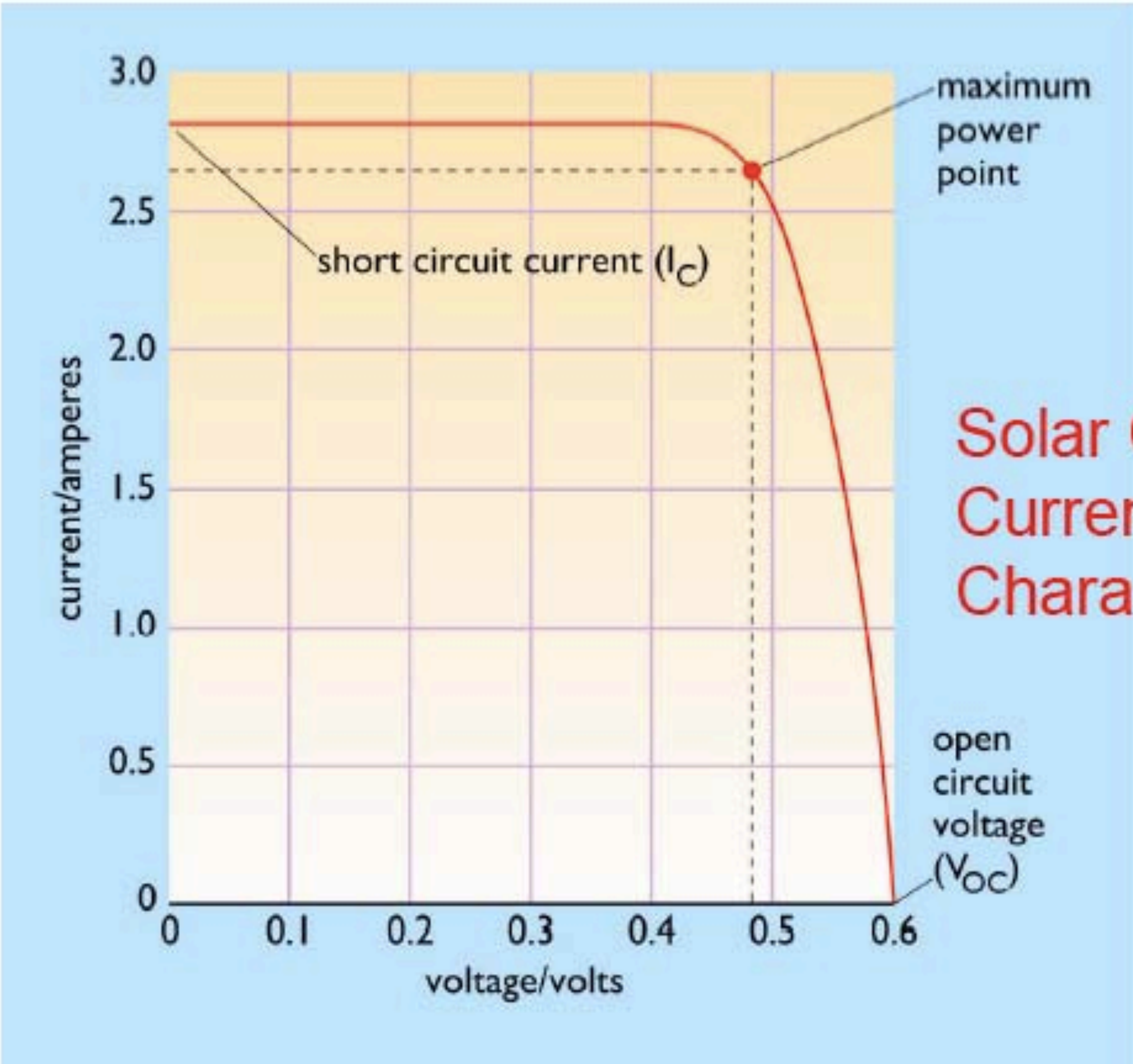


(d)



$$AM = \frac{1}{\cos\theta} = \frac{SO}{ZO}$$ air mass

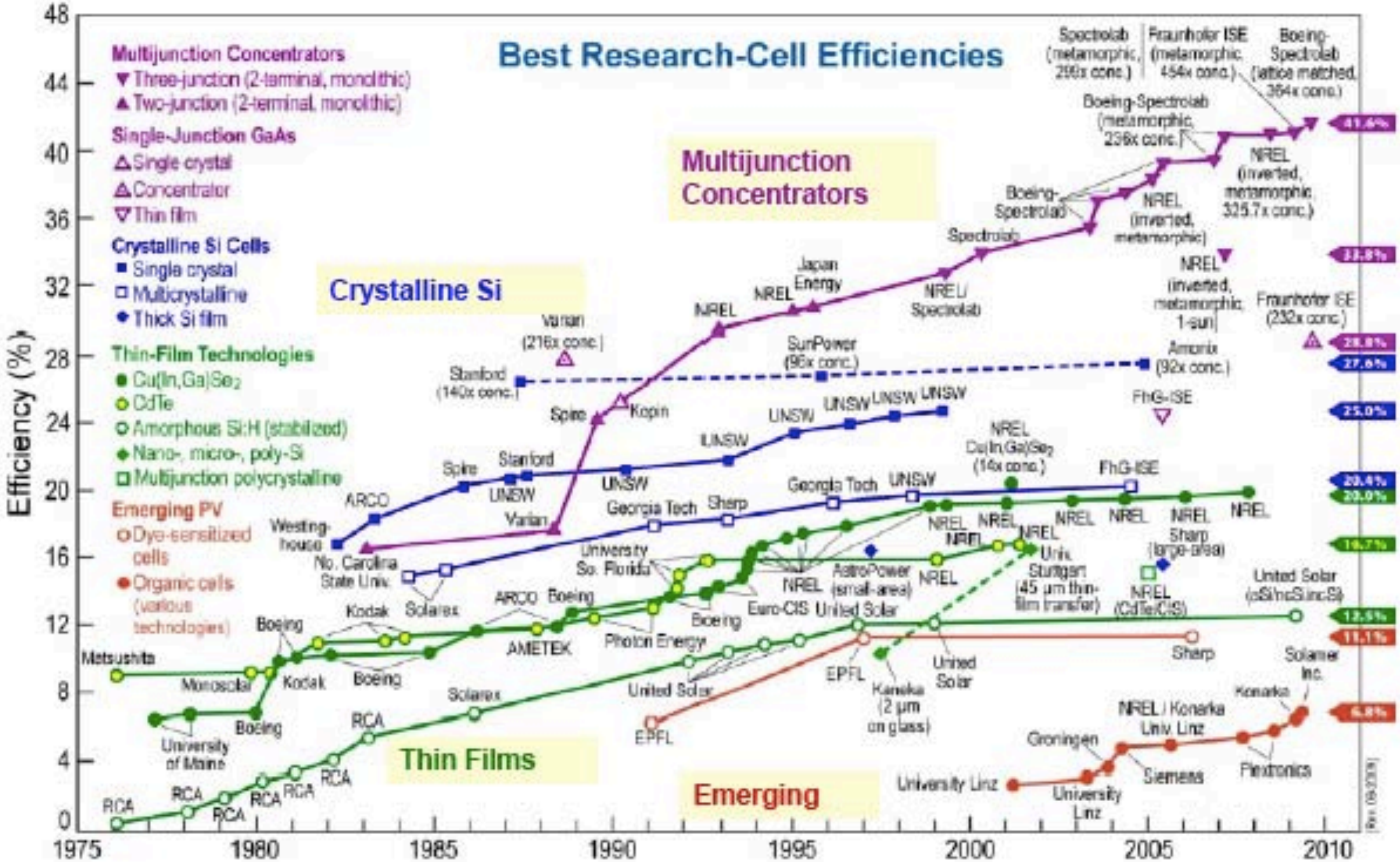

6000 K black body
AM0 radiation
AM1.5 radiation
energy distribution/kW m^{-2} µm^{-1}
2.5
2.0
1.5
1.0
0.5
0
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
wavelength/µm



Solar Cell Current-Voltage Characteristics

Silicon Solar cells

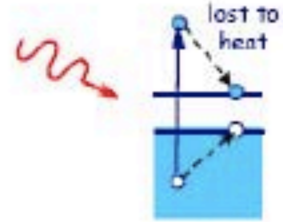
Cell Type	Efficiency
Commercial Production :	
Mono-crystalline	12 - 16 %
Poly-crystalline	10 - 12 %
Amorphous	6 - 7 %
Triple Junction Amorphous	9%
Laboratory cells:	
Mono-crystalline	> 23%
Poly-crystalline	18%
Multi layer Amorphous	Up to 16%

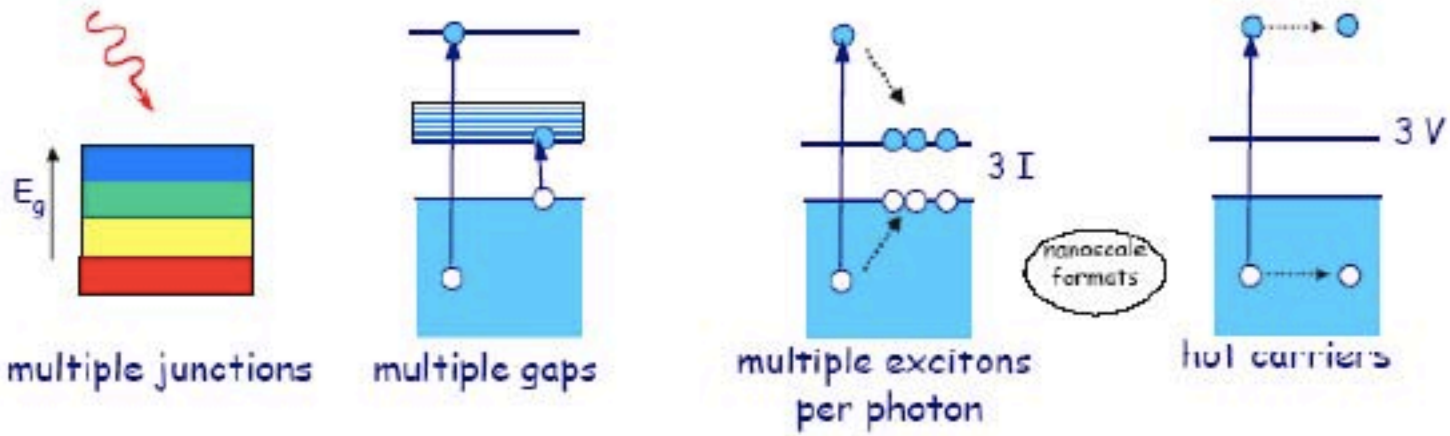


NREL Nov. 2009

Revolutionary Photovoltaics: goal of 50% Efficient Solar Cell

present technology: 32% limit for
- single junction
- one exciton per photon
- relaxation to band edge

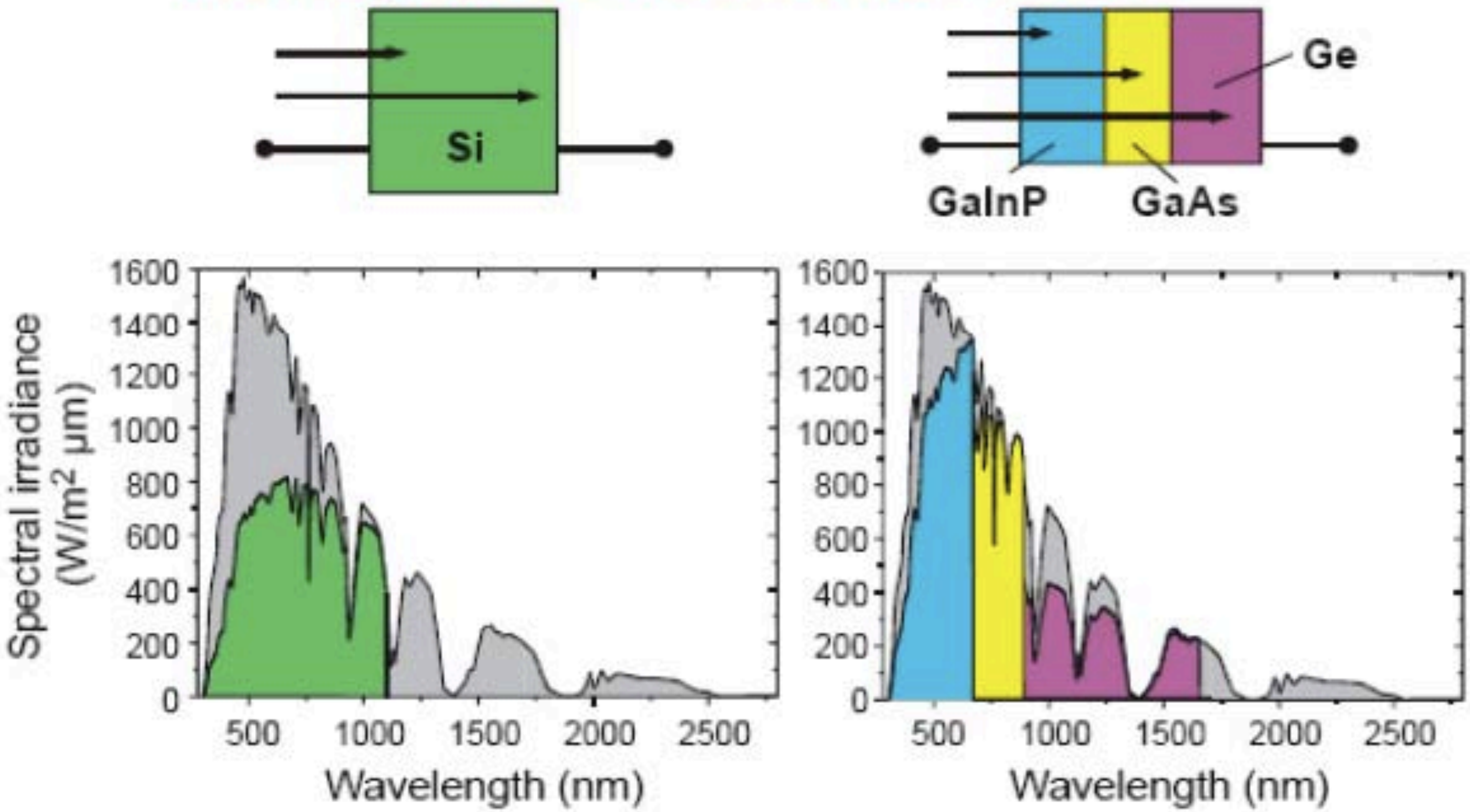




rich variety of new physical phenomena
challenge: to understand and implement

Millie Dresselhaus, MIT

Multijunction Solar Cells



Zhores Alferov, "Global Sustainability: A Nobel Cause"
Potsdam, Germany, 8-10 Oct 2007

Nanorod/Nanowire Solar Cells

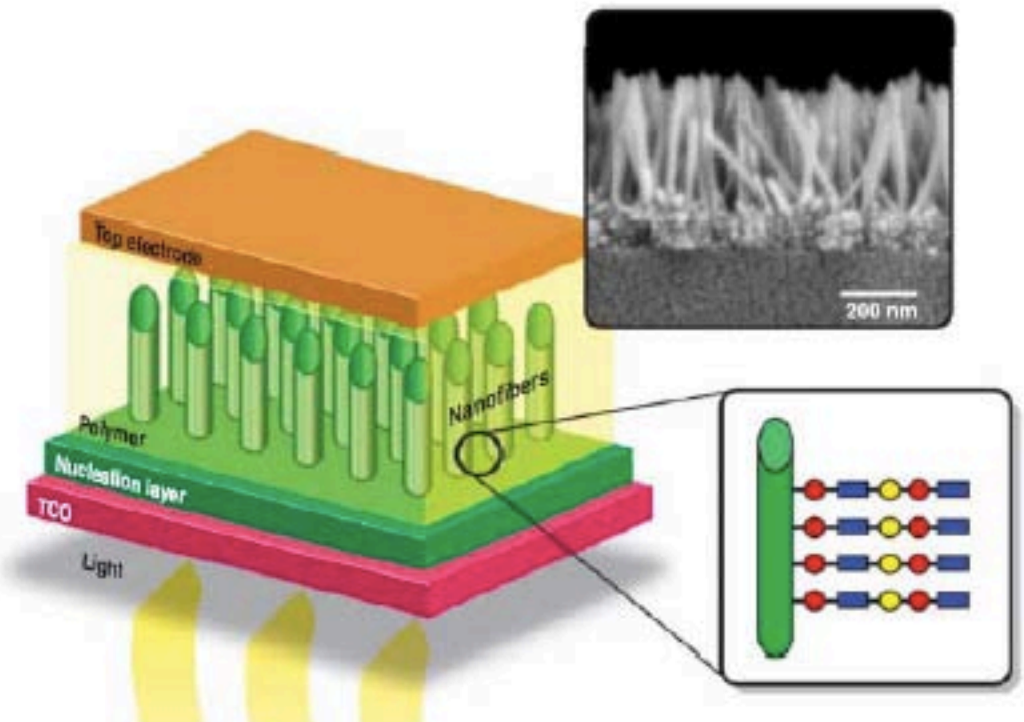
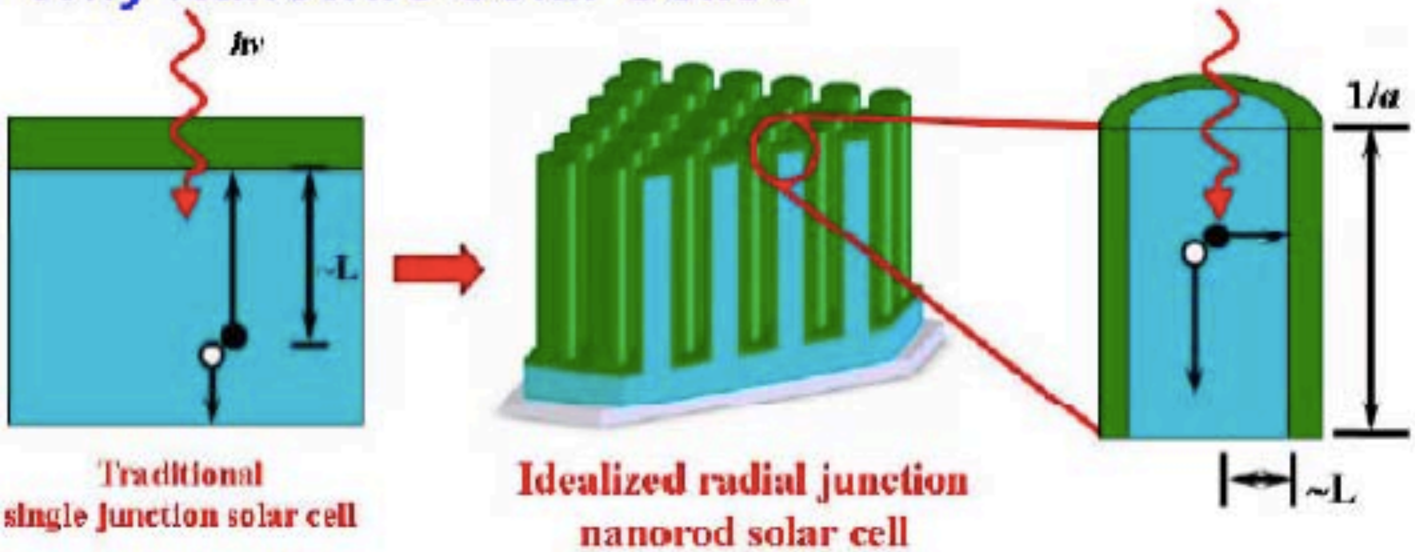


Fig. 3. Arrays of nanorods, illustrating an approach to orthogonalization of the directions of light absorption (down the length of the rods) and charge carrier collection (radially outward to the surface of the rods). [Adapted from (*2*)]

Nate Lewis
Nature, 2007

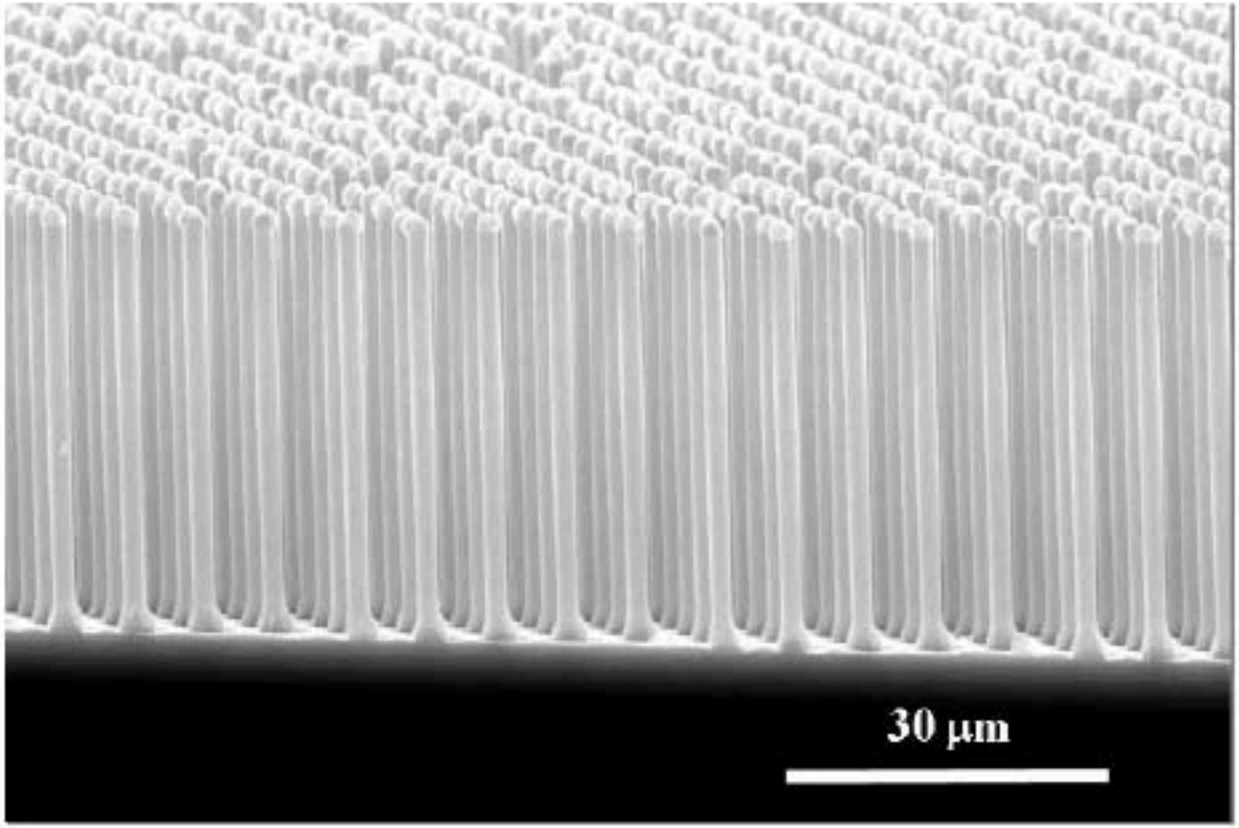
Why Nanowire Solar Cells?



- Traditional device design requires expensive, long diffusion length materials
- Nanowire device decouples light absorption and carrier extraction into orthogonal spatial directions
- Radial geometry allows for high quantum efficiency with short minority carrier diffusion lengths (i.e. inexpensive materials and processes)
- Radial or axial pn junction geometries envisioned
- Hetero- and multi-junction devices possible

H. Atwater, Caltech

Large Area Au-Catalyzed Si Arrays



3 μm array, 500 nm Au, T_{growth} = 1000°C, P_{growth} = 760 Torr, 30 min growth, 2 mole % $SiCl_4$ in H_2

Nearly 100% vertically aligned, 75 μm length microwire arrays over areas > 1 cm^2.

H. Atwater, Caltech

Dye- Sensitized Solar Cell

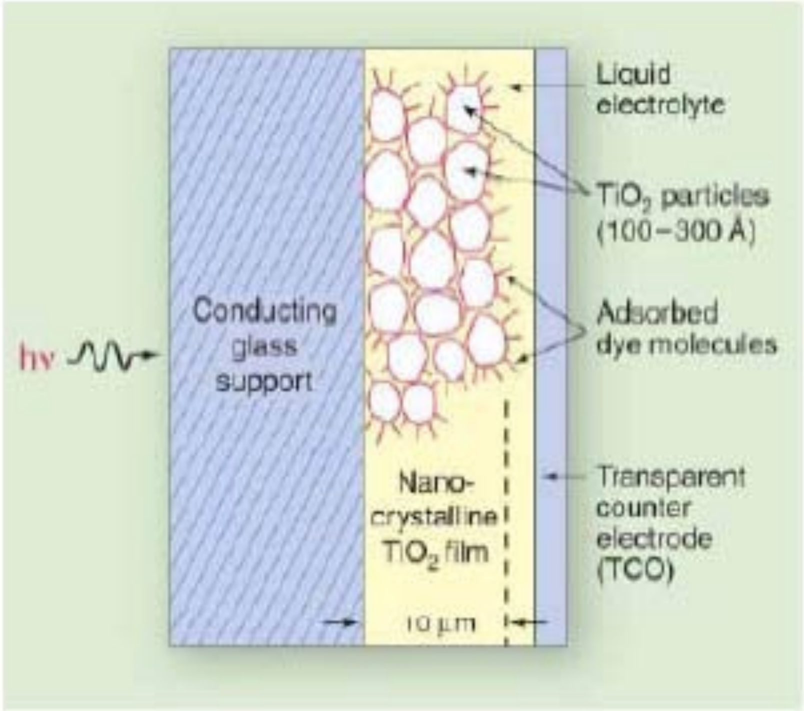


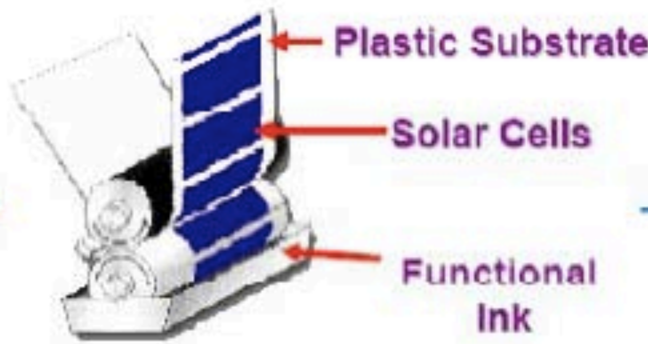
Fig. 4. Dye-sensitized solar cell, in which a nanoparticulate network provides collection of charge carriers injected into it as a result of absorption of sunlight by the adsorbed dye molecule. The oppositely charged carrier moves through the contacting liquid or polymeric phase to the counterelectrode, completing the electrical circuit in the solar cell. [Adapted from (2)]

From N. Lewis, 2007

Printing of Plastic Electronics

"inks" ---- with electronic functionality!

The Dream →

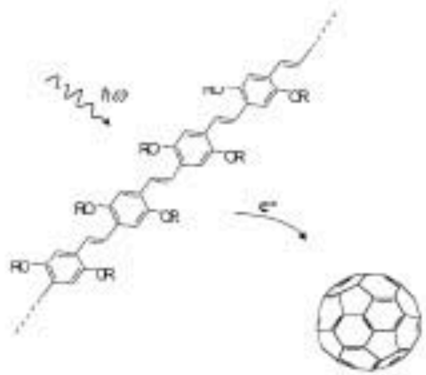


→

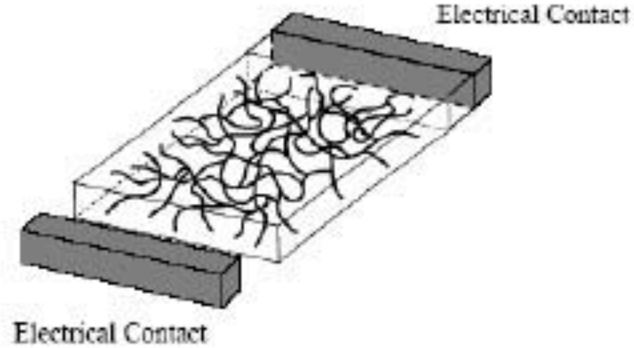
Alan Heeger, "Global Sustainability: A Nobel Cause"
Potsdam, Germany, 8-10 Oct 2007

"Plastic" Solar Cells

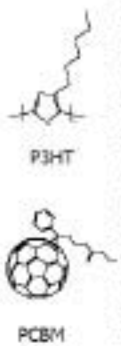
Ultrafast charge separation with quantum efficiency approaching Unity !

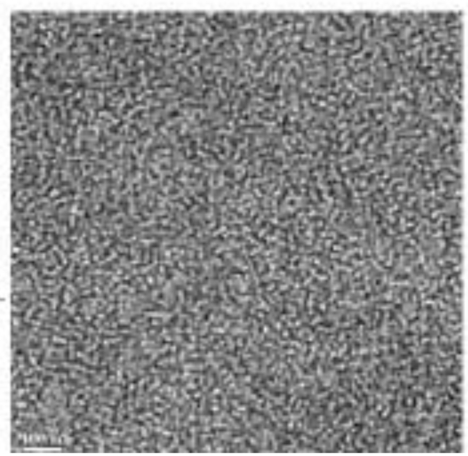


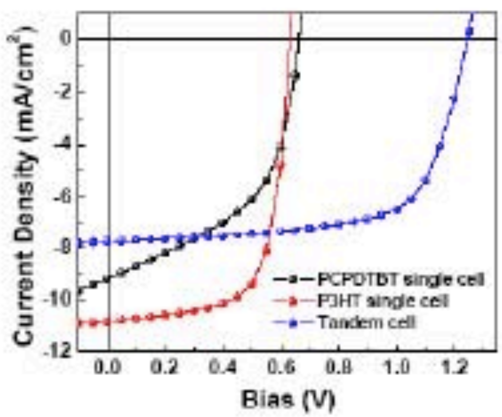
1992



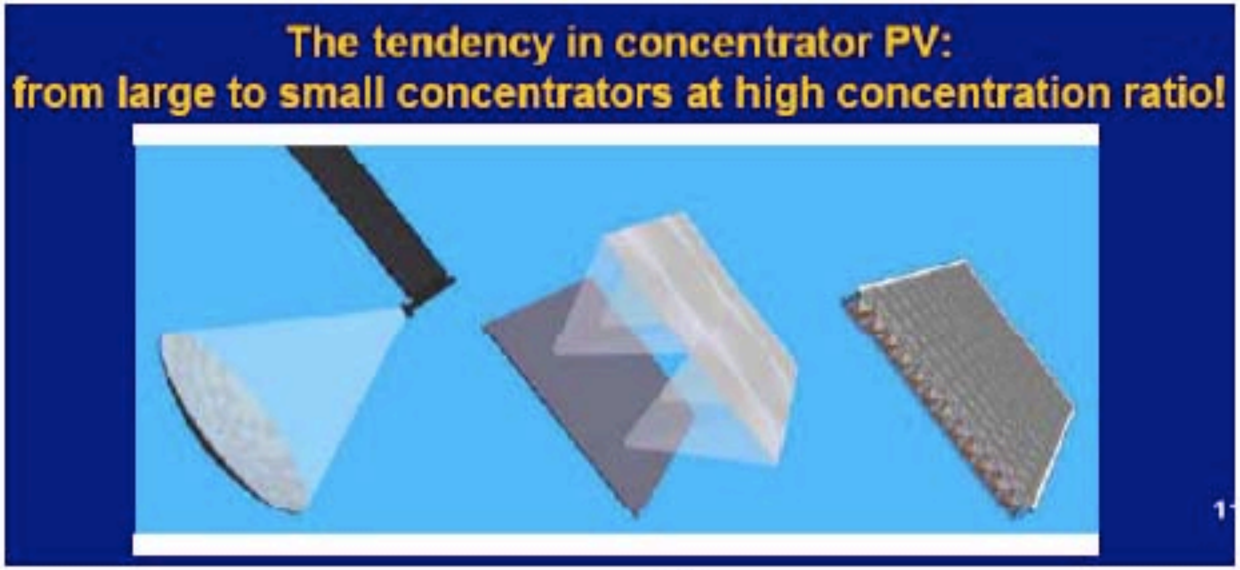
50 femtoseconds!!







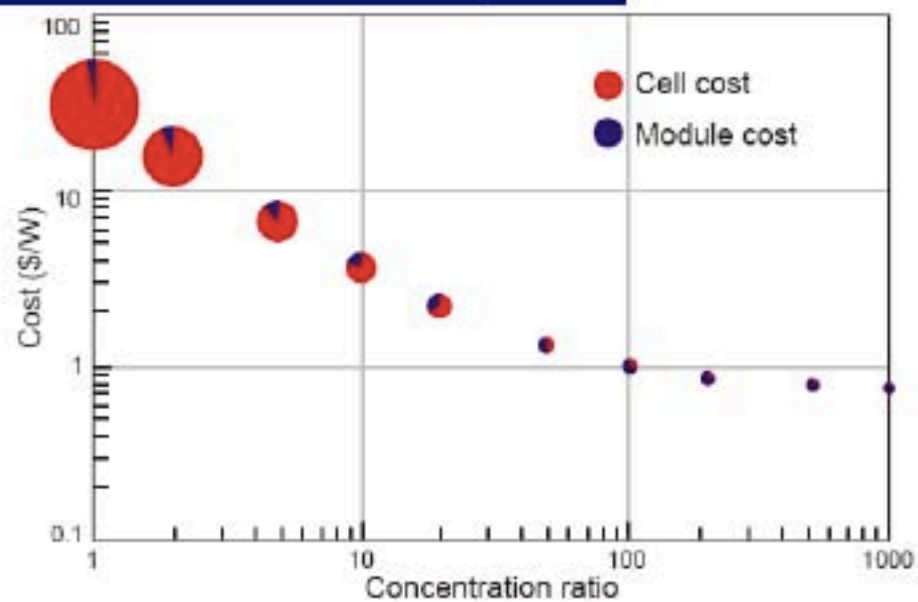
Open circuit voltage doubled; Efficiency 6.5%



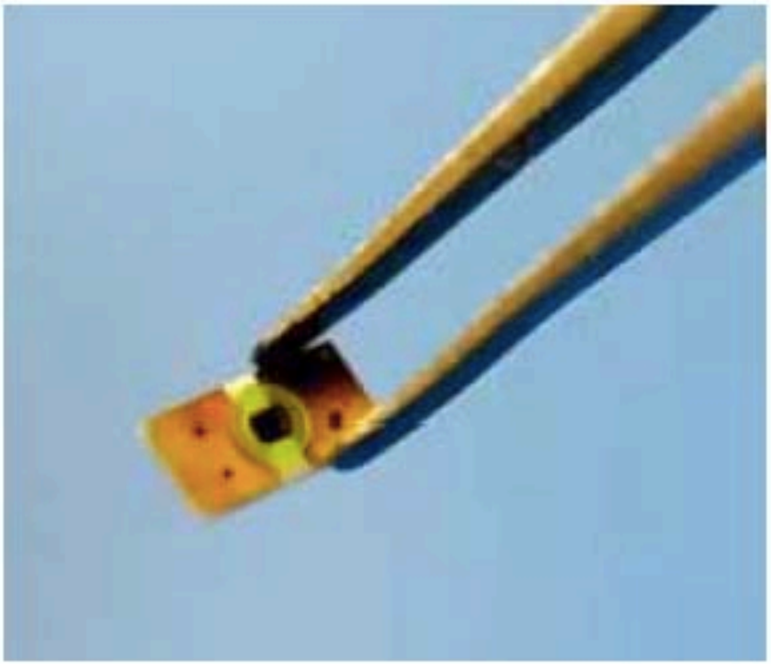
Zhores Alferov

“Global Sustainability: A Nobel Cause”

in Potsdam, Germany, 8-10 Oct 2007



Semprius' micro PV cells



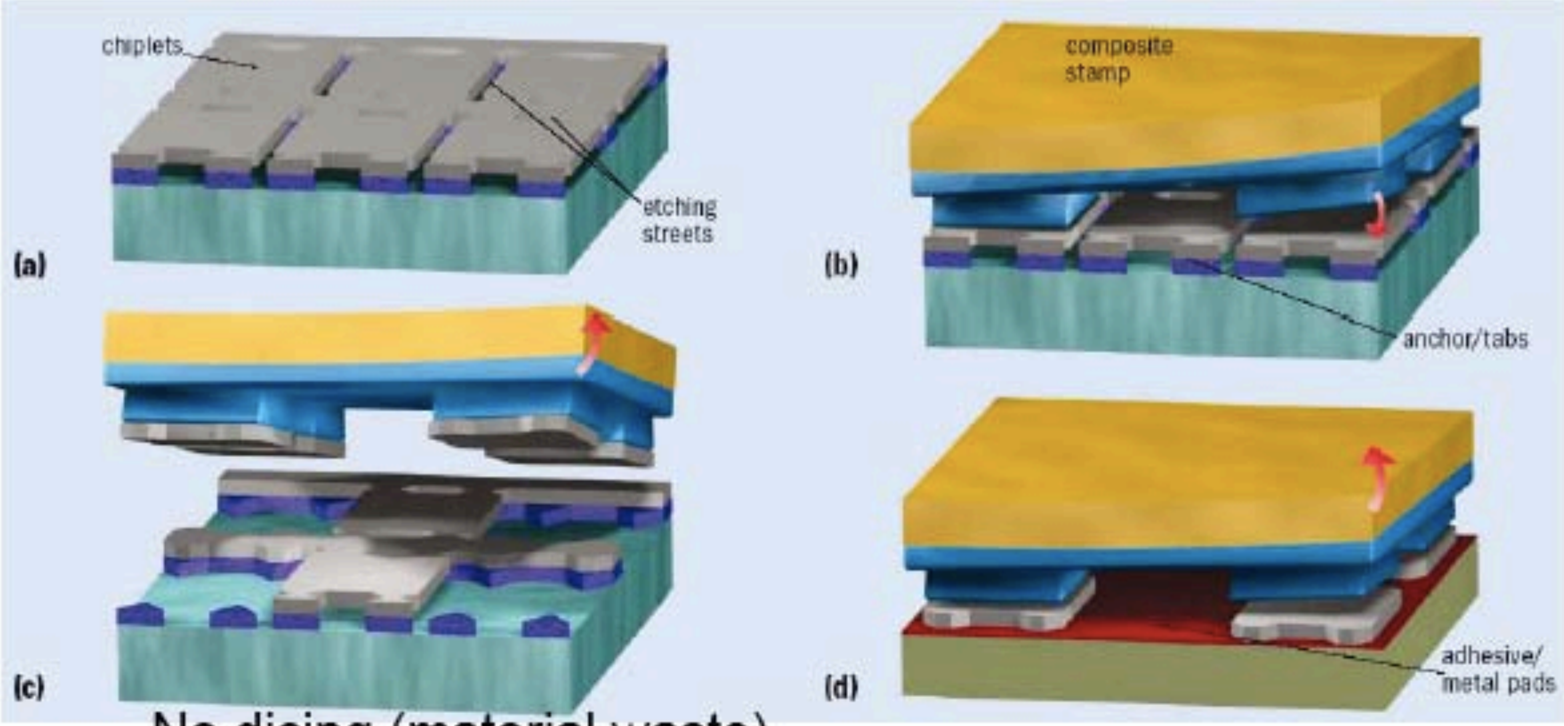
Microcell:

600 μm diameter GaAs multi junction cell

+ High-power optics

- 1000x concentration
- No cooling

•Semprius' micro printing technology



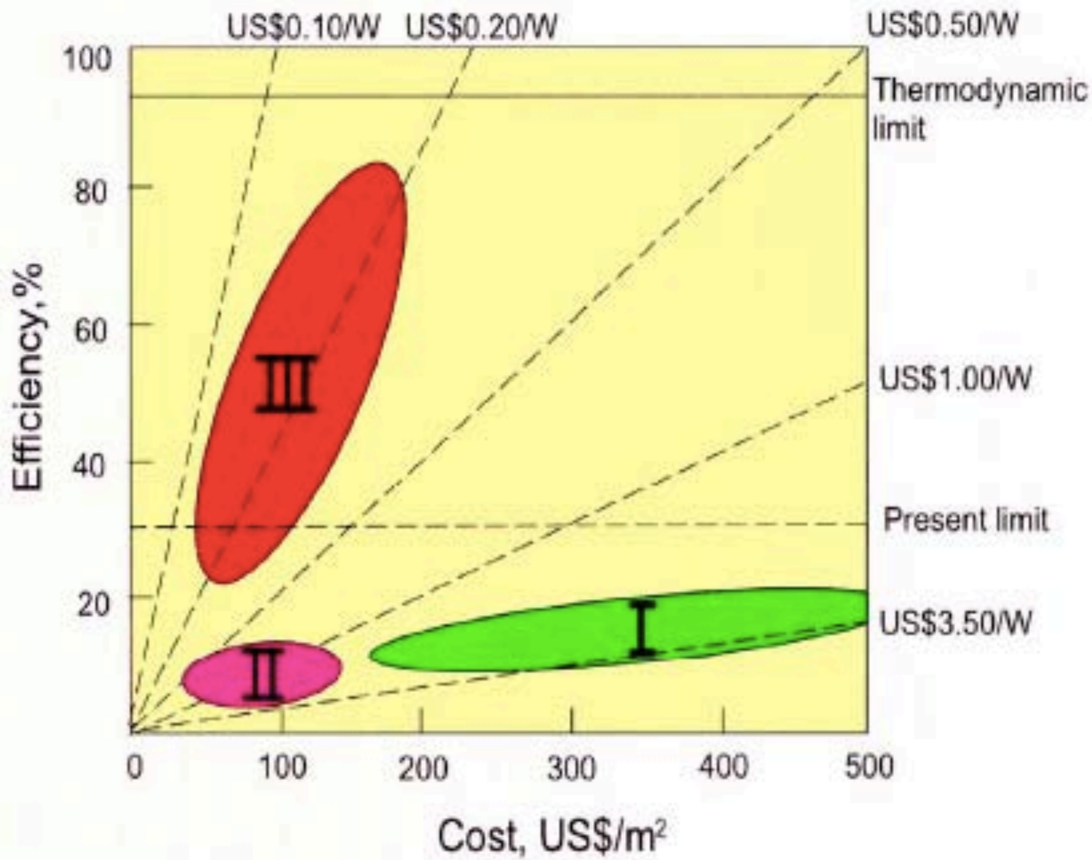
No dicing (material waste)

→ Use chemical etching and sacrificial layer

Use only a thin surface layer

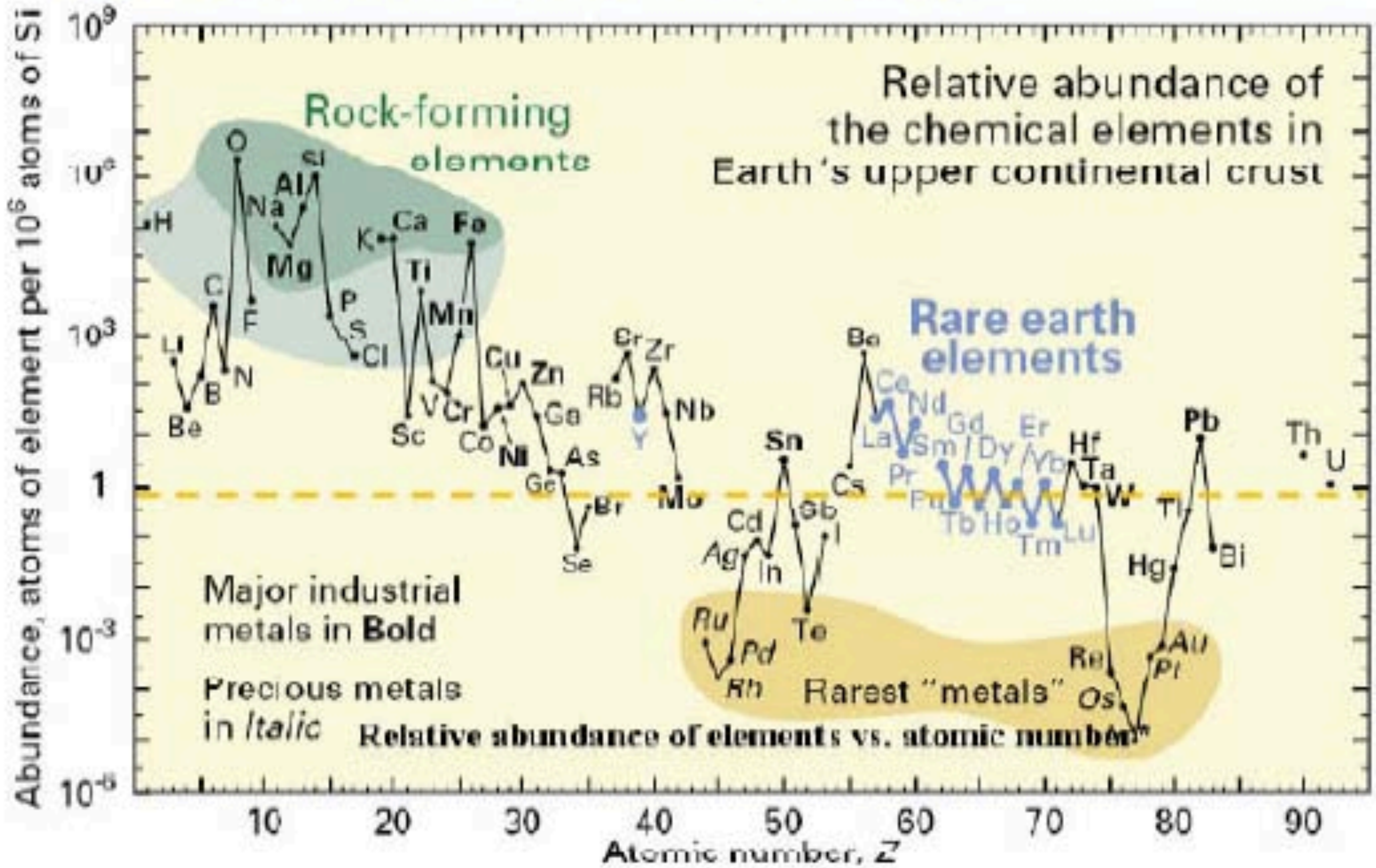
→ Wafer back to the foundry to be reused.

Cost/Efficiency of Photovoltaic Technology

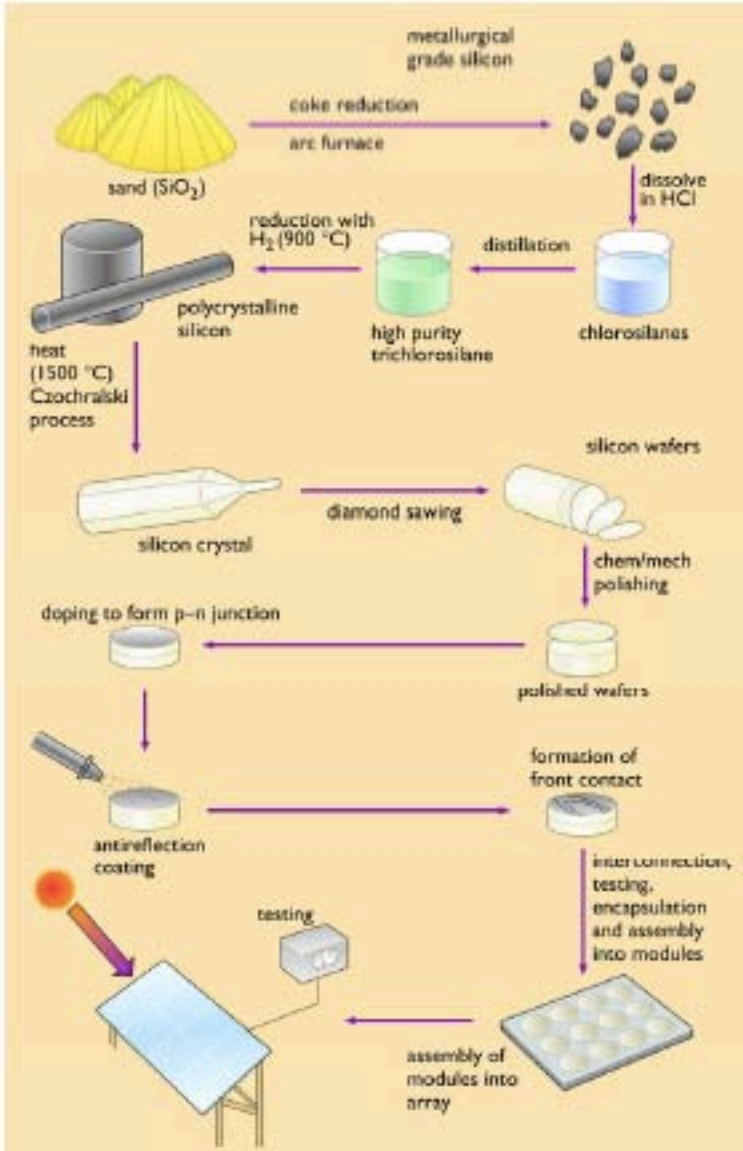


Costs are modules per peak W; installed is $5-10/W; $0.35-$1.5/kW-hr

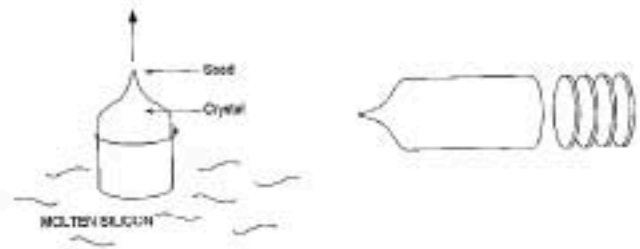
Among Conventional Thin Films ($CuIn_xGa_{1-x}Se_2$, CdTe, Si) Only Si Abundant Enough



rom P.H. Stauffer et al, Rare Earth Elements - Critical Resources for High Technology, USGS (2002)



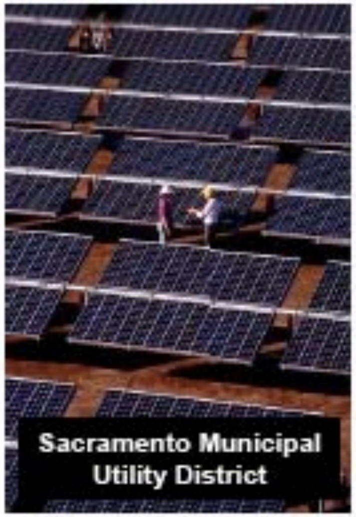
Silicon solar cell and module manufacturing



Boyle
Renewable
Energy Sources

Solar Energy - Photovoltaics

- Captures the energy in the solar radiation that reaches the Earth
- Electricity production
  - Photovoltaic (PV) cells are semiconductors that convert sunlight directly into electricity
- R&D Focus
  - Fundamental science of materials, advanced solar cells and processes, scale-up, lower cost



Sacramento Municipal Utility District

PV panels

- Generating Capacity
  - Grid-connected PV generating capacity in the U.S. ~ 25 MW (fraction of off-grid PV capacity)
- Power System Size Range
  - 1 W (single cell) – 400 kW (PV array)
- Electricity Generation Costs
  - 25¢ – $1/kWh

Sources: EIA Renewable Energy Annual 2003, EERE State Energy Alternatives Website and DOE's *Choices for a Brighter Future* brochure (1999)

Keith Wipke, NREL 2008

Table 3: TOP TEN STATES
Ranked by Grid-Connected PV Cumulative Installed Capacity through 2009

	MW_{DC}	Market Share
1. California	768	61%
2. New Jersey	128	10%
3. Colorado	59	5%
4. Arizona	46	4%
5. Florida	39	3%
6. Nevada	36	3%
7. New York	34	3%
8. Hawaii	26	2%
9. Connecticut	20	2%
10. Massachusetts	18	1%
All Other States	83	7%
Total	**1,256**	--

Table 4: TOP TEN STATES
Ranked by Cumulative Installed PV Capacity per Capita (W_{DC}/person) through 2009

	Cumulative through 2009 (W_{DC}/person)	2009 Installations (W_{DC}/person)
1. California	20.8	5.7
2. Hawaii	20.2	9.8
3. New Jersey	14.6	6.6
4. Nevada	13.8	1.0
5. Colorado	11.8	4.7
6. Arizona	7.0	3.2
7. Connecticut	5.6	2.5
8. Delaware	3.7	1.6
9. Oregon	3.7	1.7
10. Vermont	2.7	1.0
National Average	**4.2**	**1.4**

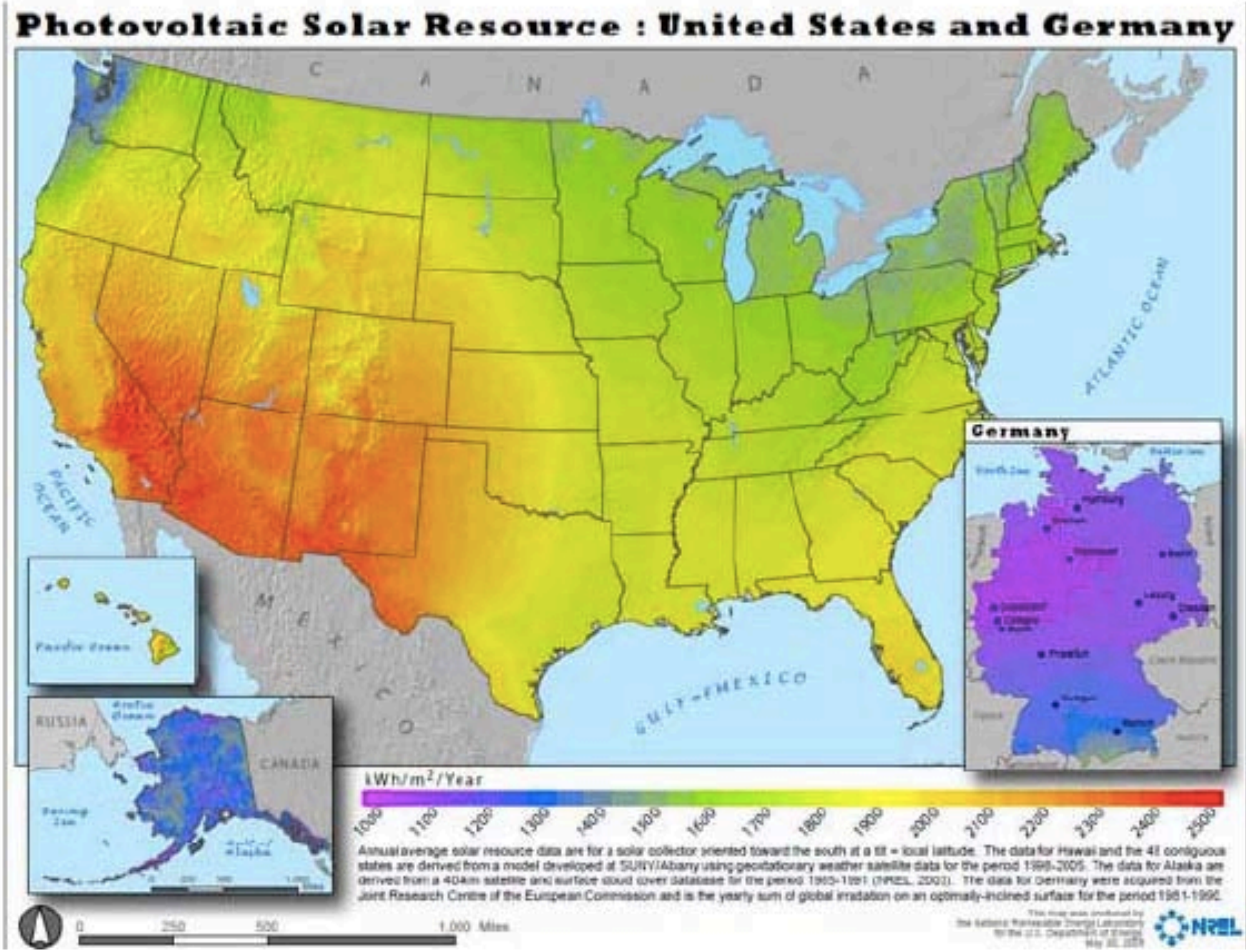
IREC's 2009 edition of U.S. Solar Market Trends

Table 2: TOP TEN STATES
Ranked by Grid-Connected PV Capacity Installed in 2009

2009 Rank by State	2009 (MW_{DC})	2008 (MW_{DC})	08-09 % change	2009 Market Share	2008 Rank
1. California	212.1	197.6	7%	49%	1
2. New Jersey	57.3	22.5	155%	13%	2
3. Florida	35.7	0.9	3668%	8%	16
4. Colorado	23.4	21.7	8%	5%	4
5. Arizona	21.1	6.2	243%	5%	8
6. Hawaii	12.7	8.6	48%	3%	5
7. New York	12.1	7.0	72%	3%	7
8. Massachusetts	9.5	3.5	174%	2%	11
9. Connecticut	8.7	7.5	16%	2%	6
10. North Carolina	7.8	4.0	96%	2%	10
All Other States	34.2	24.6	41%	7%	--
Total	**434.6**	**311.3**	**40%**	--	--

2008 and 2009 columns include installations completed in those years.
"2009 Market Share" means share of 2009 installations. "2008 Rank" is the state ranking for installations completed in 2008.

IREC's 2009 edition of U.S. Solar Market Trends

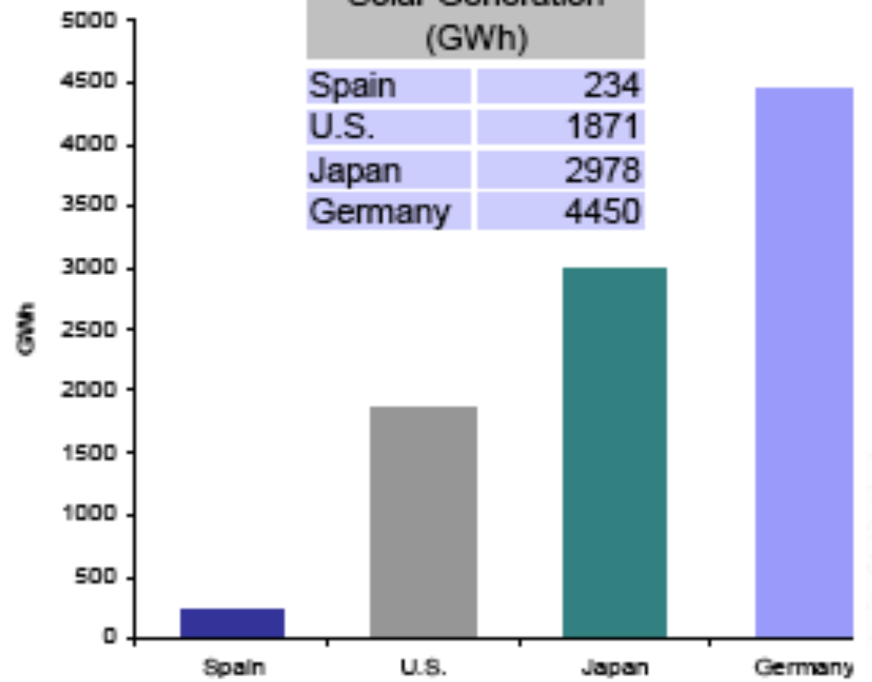


Photovoltaic Solar Resource : United States and Germany
CANADA
ATLANTIC OCEAN
PACIFIC OCEAN
MEXICO
GULF of MEXICO
Germany
RUSSIA
CANADA
kWh/m²/Year
1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100 2200 2300 2400 2500
Annual average solar resource data are for a solar collector oriented toward the south at a tilt = local latitude. The data for Hawaii and the 48 contiguous states are derived from a model developed at SUNY/Albany using geostationary weather satellite data for the period 1998-2005. The data for Alaska are derived from a 40km satellite and surface cloud cover database for the period 1985-1991 (NREL, 2003). The data for Germany were acquired from the Joint Research Centre of the European Commission and is the yearly sum of global irradiation on an optimally-inclined surface for the period 1981-1990.
0 250 500 1,000 Miles
NREL

California Solar Initiative

- The program is funded at $3.35 billion over 11 years.
- 10 percent of the program is set aside for low income homes.
- Expands the net metering cap to 2.5 percent, allowing approximately 500,000 new solar systems into the net metering program.
- Mandates that solar systems are a standard option for all new homeowners.
- Requires the state's municipal utilities to create their own solar rebate programs, totaling $800 million in rebates.
- Directs the California State Licensing Board to review current licensing requirements for solar installers.

Germany leads world
In Solar Power Generation



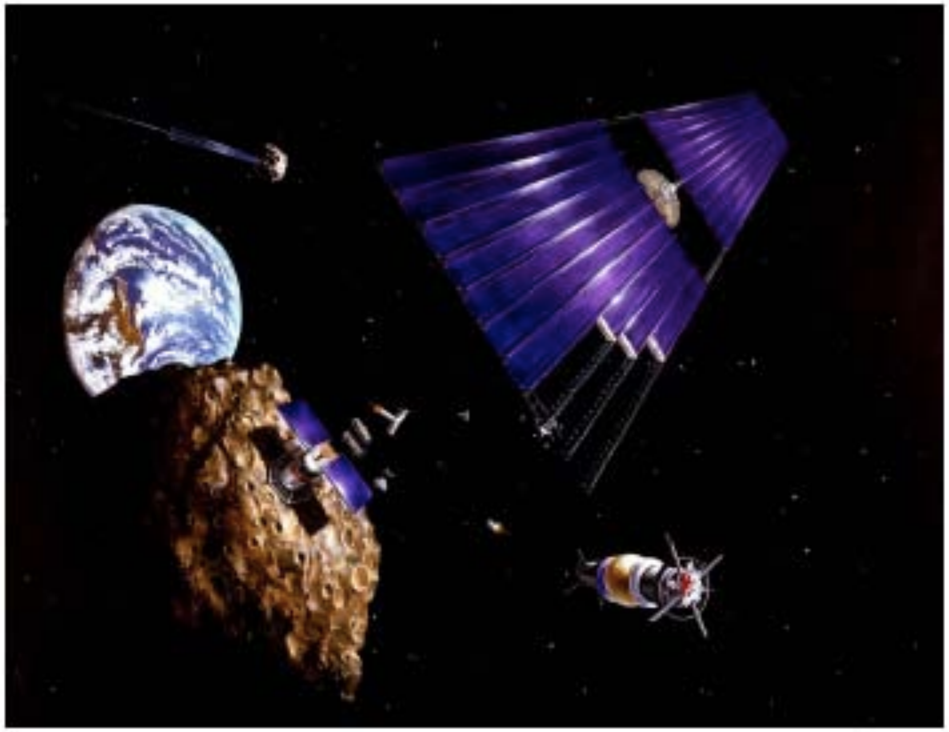
Solar Generation (GWh)	
Spain	234
U.S.	1871
Japan	2978
Germany	4450

Source: IEA PVPS; La Generacion del Sol

* Numbers calculated using capacity factors of 20% for PV and 25% for CSP

Keith Wipke, NREL 2008 (2006 Data)

Solar Powered Satellites



Picture credit: Space Studies Institute

Photonic design principles for ultrahigh-efficiency photovoltaics

Albert Polman and Harry A. Atwater

For decades, solar-cell efficiencies have remained below the thermodynamic limits. However, new approaches to light management that systematically minimize thermodynamic losses will enable ultrahigh efficiencies previously considered impossible.

NATURE MATERIALS | VOL 11 | MARCH 2012 | www.nature.com/naturematerials

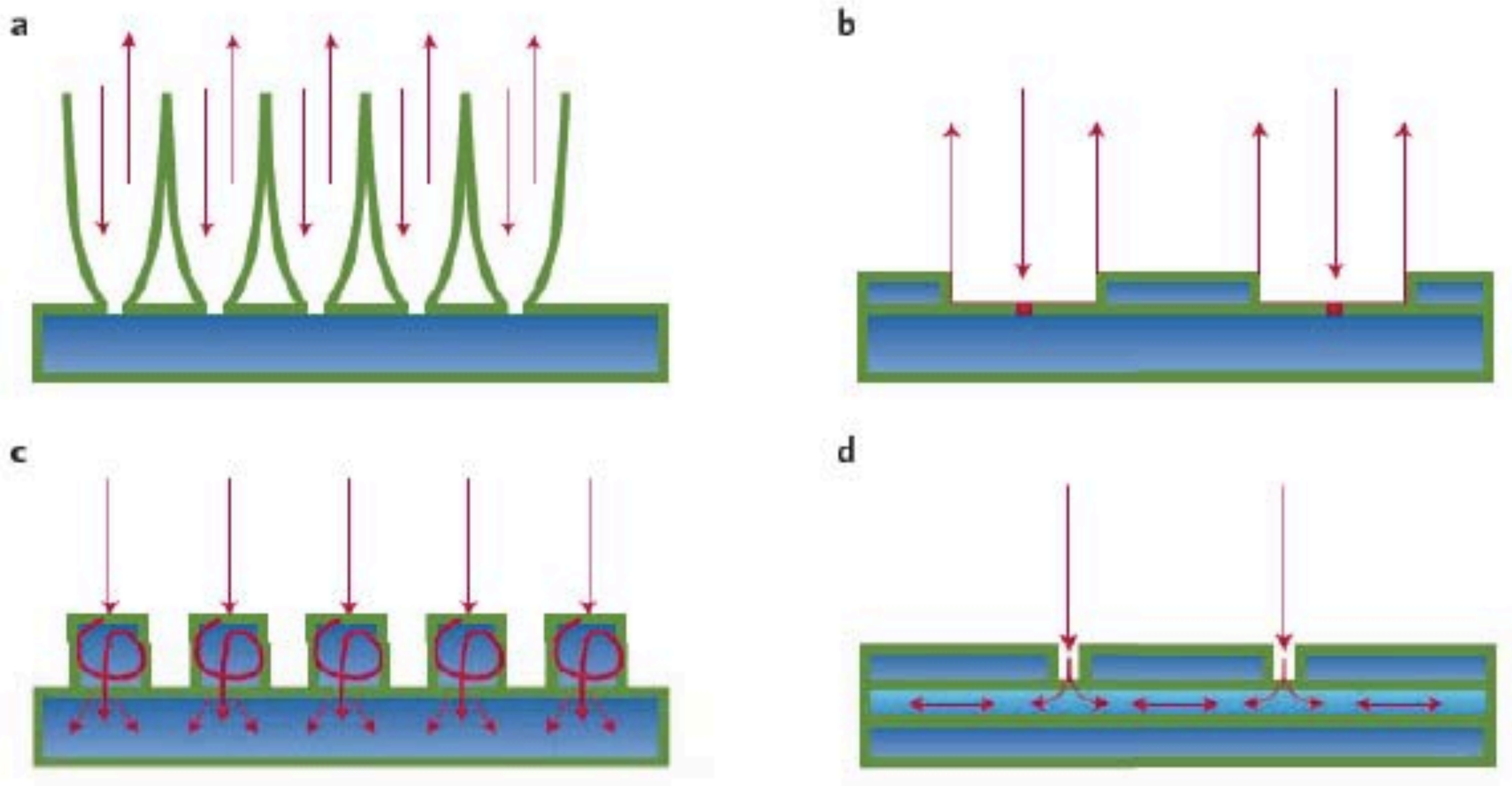


Figure 2 | Light-management architectures for reaching ultrahigh efficiency. **a**, Three-dimensional parabolic light reflectors direct spontaneous emission back to the disk of the Sun. **b**, Planar metamaterial light-director structures. **c**, Mie-scattering surface nanostructure for light trapping. **d**, Metal–dielectric–metal waveguide or semiconductor–dielectric–semiconductor slot waveguide with enhanced optical density of states to increase the spontaneous emission rate.

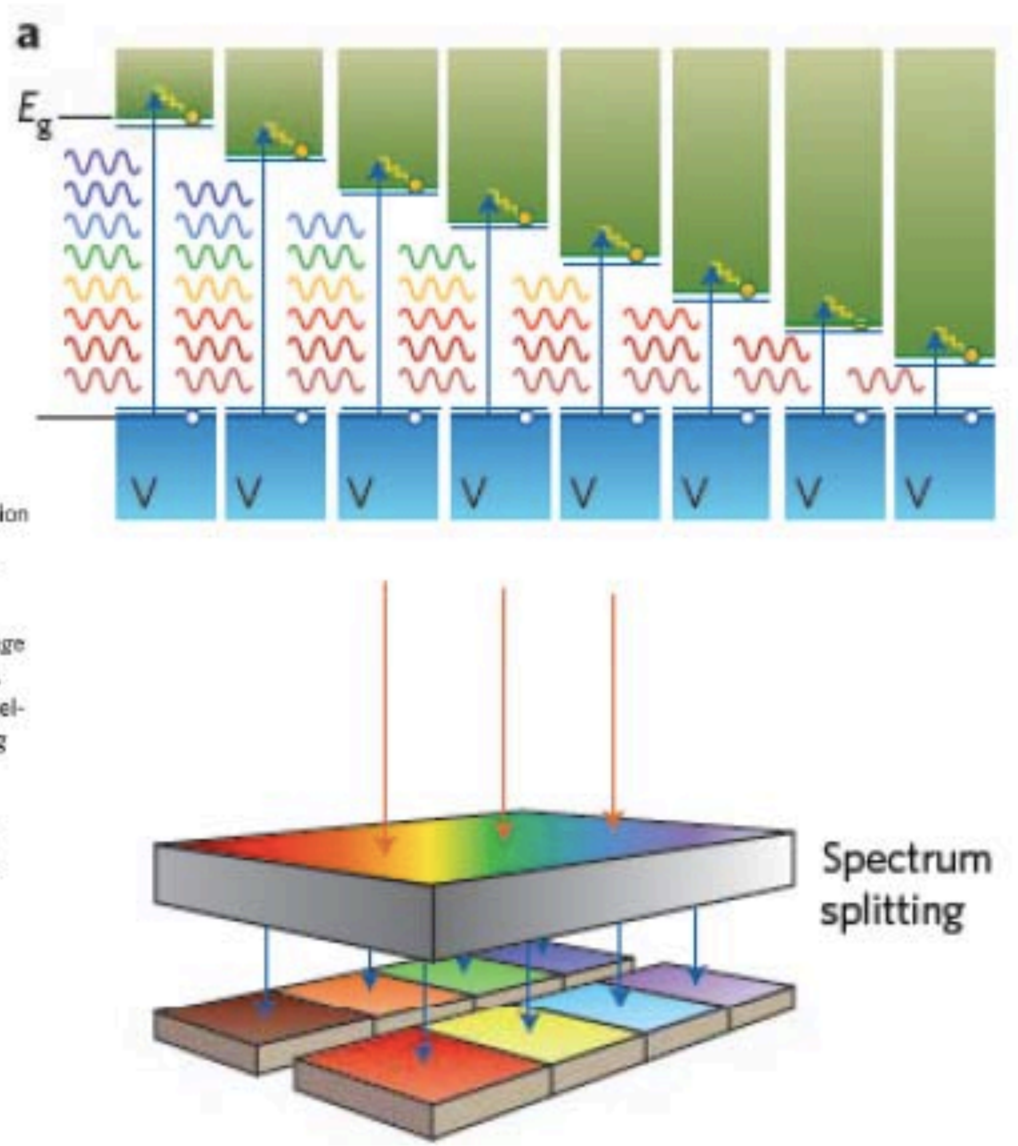
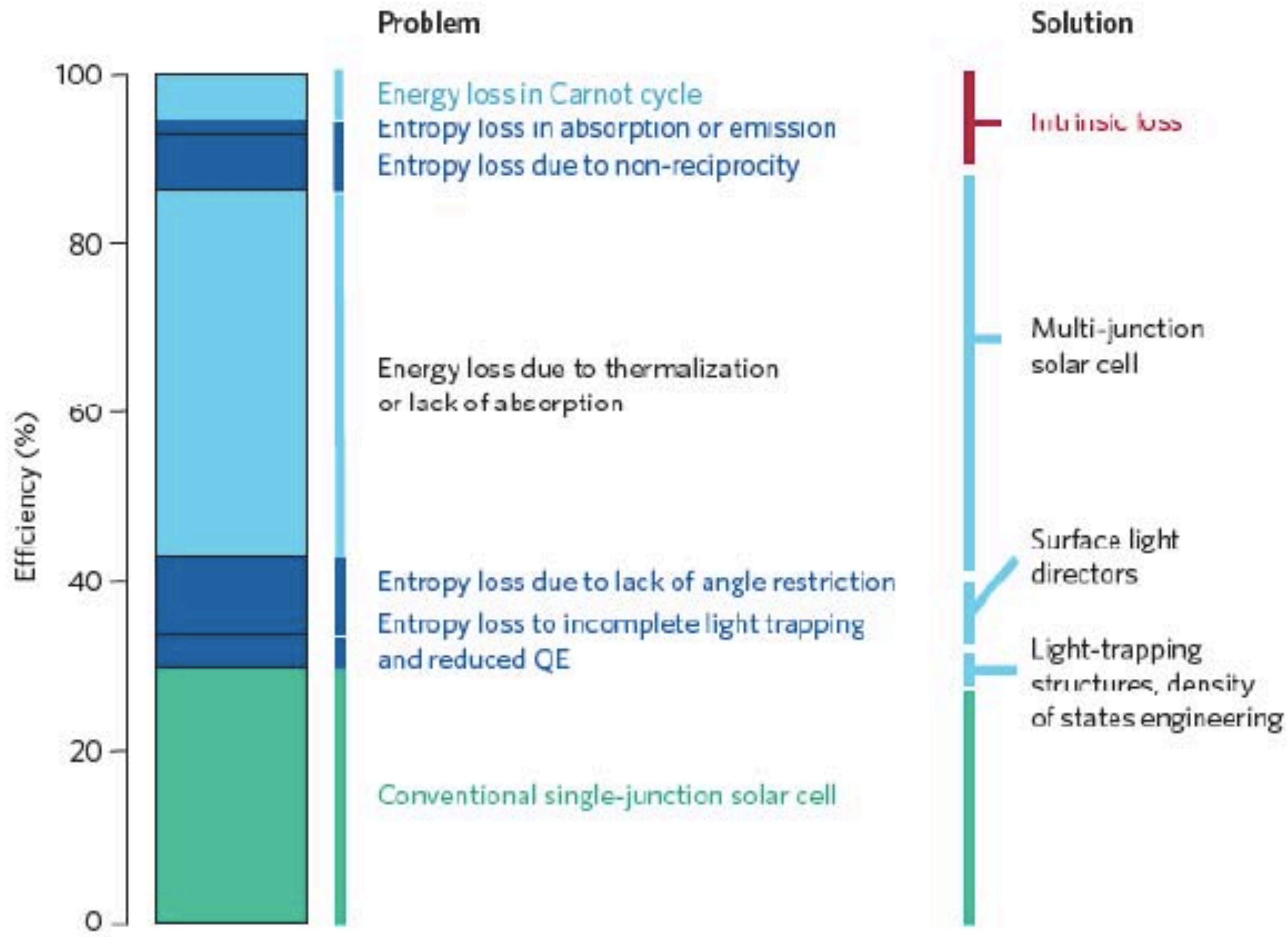


Figure 3 | Multi-junction solar cells. a, Multi-junction energy diagram. Semiconductors with different bandgaps convert different portions of the solar spectrum to reduce thermalization losses. The quasi-Fermi levels defining the open-circuit voltage are indicated by the horizontal blue dashed lines. The yellow dots represent the electrons. **b,** Parallel-connected architecture that can be realized using epitaxial liftoff and printing techniques of the semiconductor layers, followed by printing of a micro- or nanophotonic spectrum splitting layer. Each semiconductor layer can be combined with one of the structures in Fig. 2 to reduce entropy losses and these structures can be separately optimized for each semiconductor.


Problem
Solution
Efficiency (%)
100
80
60
40
20
0
Energy loss in Carnot cycle
Entropy loss in absorption or emission
Entropy loss due to non-reciprocity
Intrinsic loss
Energy loss due to thermalization
or lack of absorption
Multi-junction
solar cell
Entropy loss due to lack of angle restriction
Surface light
directors
Entropy loss to incomplete light trapping
and reduced QE
Light-trapping
structures, density
of states engineering
Conventional single-junction solar cell