Photovoltaic Basics:
Overview and Materials Options

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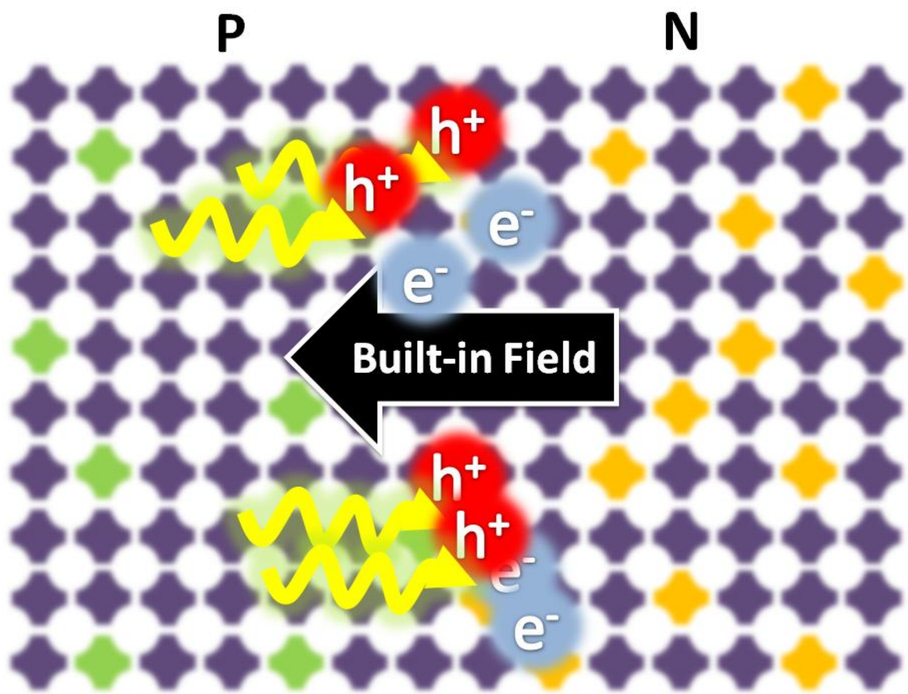


Outline

- The sun as a source of energy
  - What are the scale and usefulness of solar energy?
- Fundamental physics behind photovoltaic solar cells
  - What is a solar cell made from?
  - How does a solar cell work on the level of atoms and electrons?
  - What are the current voltage characteristics of a single cell?
- Types of solar cells, challenges, and the future
  - How do types of solar cells differ?
  - What are the challenges in materials science to making solar cells more efficient and economical?
  - What did I just read in the news about a new discovery in solar cells and is it actually promising?

The sun as a source of energy

What are the scale and usefulness of solar energy?

Scale of Energy Consumption

- U.S. Energy consumption = **10^{20} Joules / year**
- Spread out evenly over time = **3 Trillion Watts (3 TW)**
- Per person = **10,000 Watts / person**

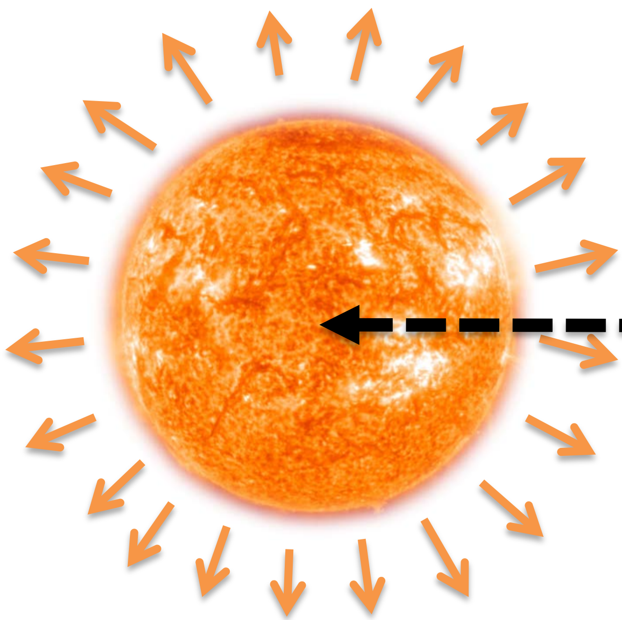
QUESTION: When you curl a 20 lb. dumb-bell and lift it about 3 feet, how much energy are you expending to lift it?

ANSWER: About 100 Joules.

Per Person

- You would need to lift this 20 lb. dumb-bell 380,000 times an hour in order to supply your own energy (assuming your efforts could be harnessed with 100% efficiency).

Energy from Sun



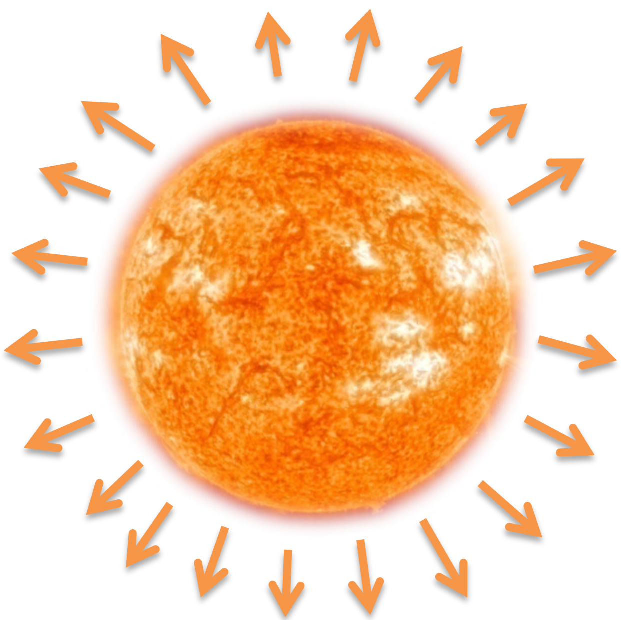
P_{EARTH} =
one-billionth P_{SUN}
= 3×10^{17} Watts

T = 6000 K
$P_{SUN} = 3.9 \times 10^{26}$ Watts

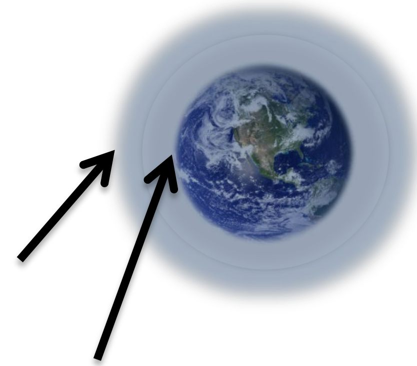
http://nssdc.gsfc.nasa.gov/planetary/factsheet/sunfact.html

How much energy reaches the surface?

- Most of the solar radiation penetrates the outer atmosphere.



Peak intensities:



1,366 W/m^2

~1,000 W/m^2

Average intensities?

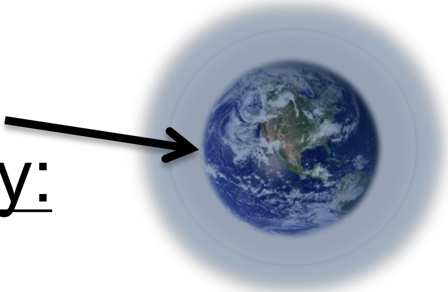
- **Geography and climate-dependent**: considering clouds, four seasons, day and night

Peak intensity:

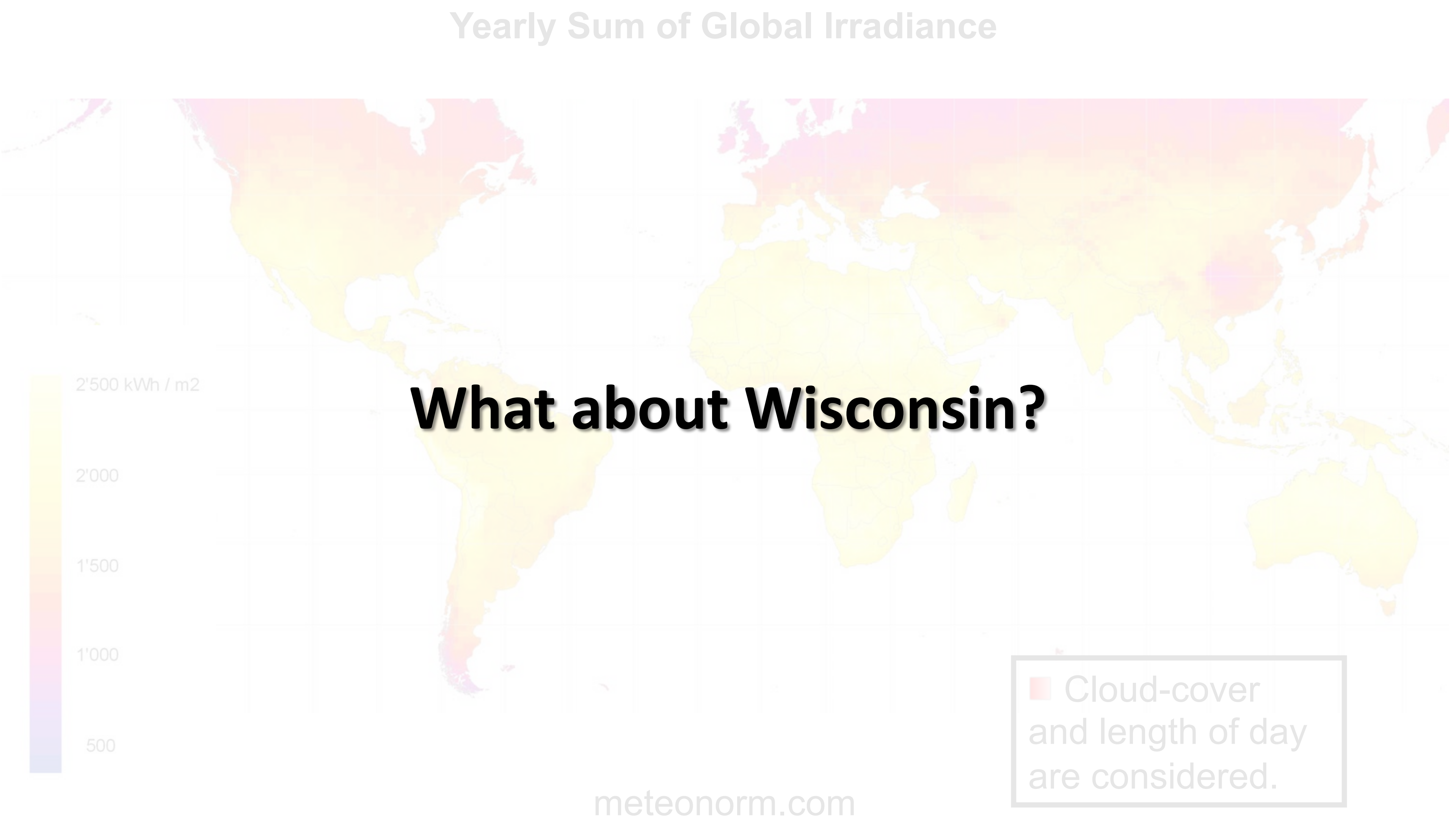
~1,000 W/m^2

Average intensity:

~100-300 W/m^2

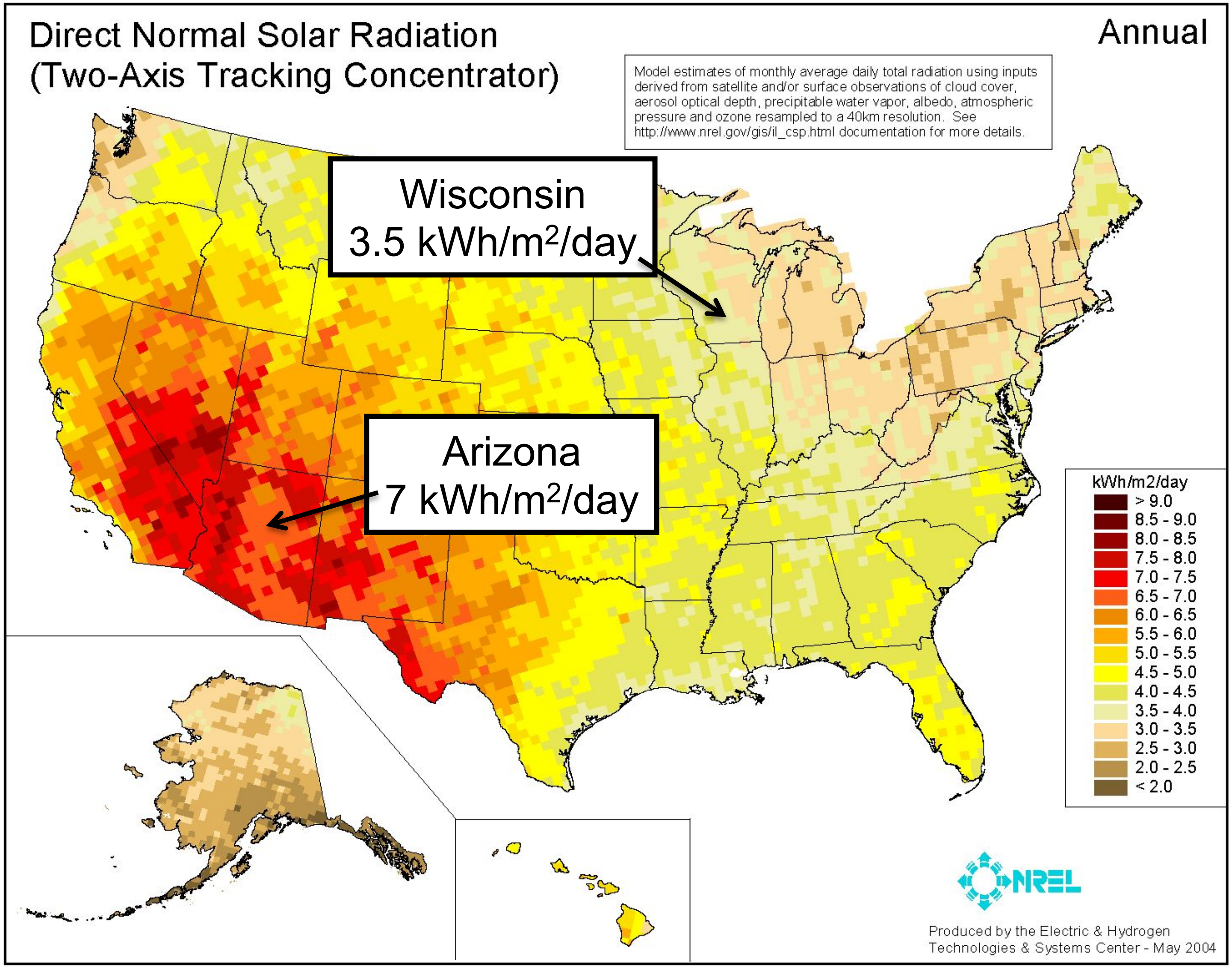


How much energy reaches us?

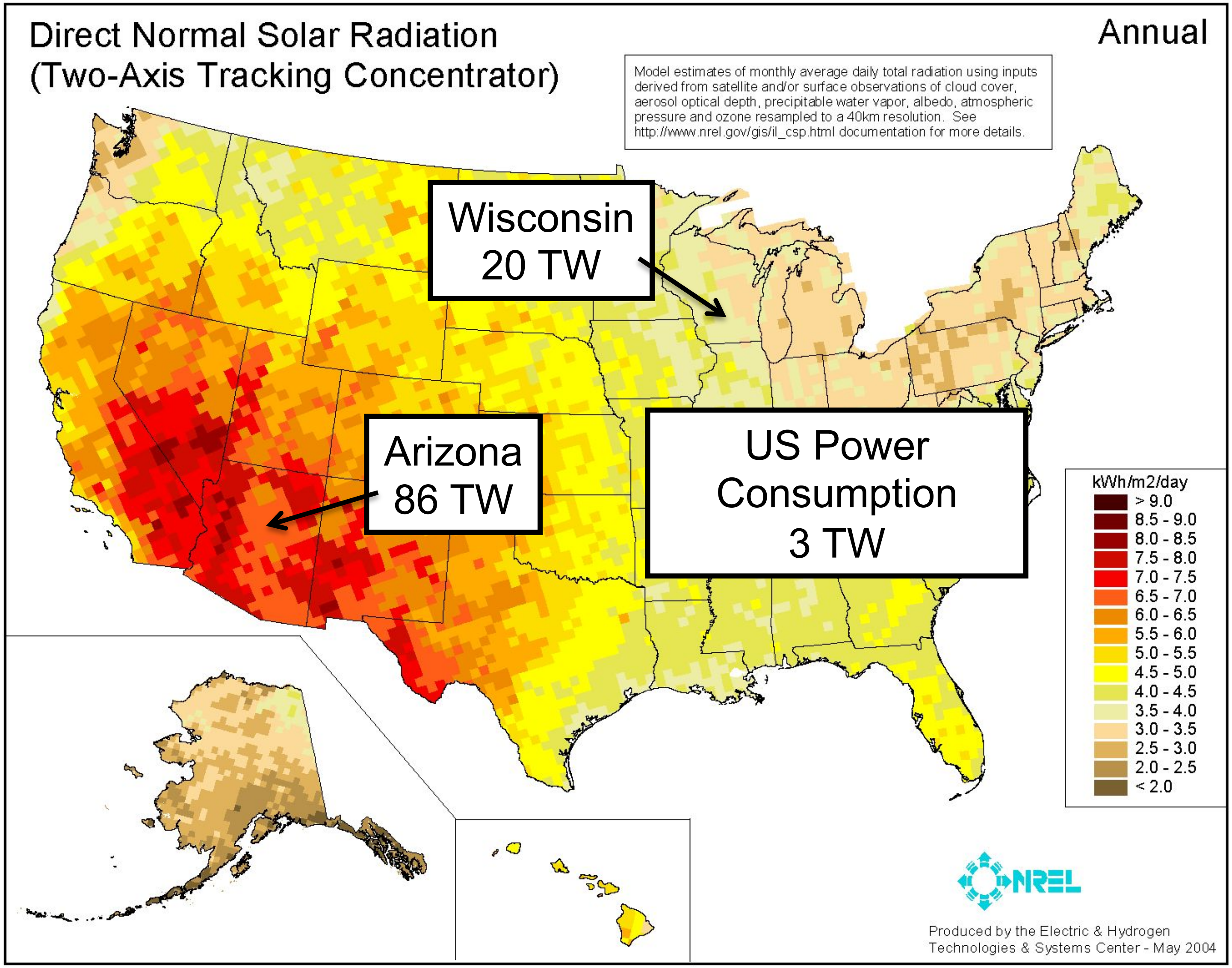


What about Wisconsin?

US?


Direct Normal Solar Radiation
(Two-Axis Tracking Concentrator)
Annual
Model estimates of monthly average daily total radiation using inputs derived from satellite and/or surface observations of cloud cover, aerosol optical depth, precipitable water vapor, albedo, atmospheric pressure and ozone resampled to a 40km resolution. See http://www.nrel.gov/gis/il_csp.html documentation for more details.
Wisconsin
3.5 kWh/m2/day
Arizona
7 kWh/m2/day
kWh/m2/day
> 9.0
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2.0
NREL
Produced by the Electric & Hydrogen Technologies & Systems Center - May 2004

US?



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Wisconsin
20 TW
Arizona
86 TW
US Power
Consumption
3 TW
kWh/m2/day
> 9.0
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2.0
NREL
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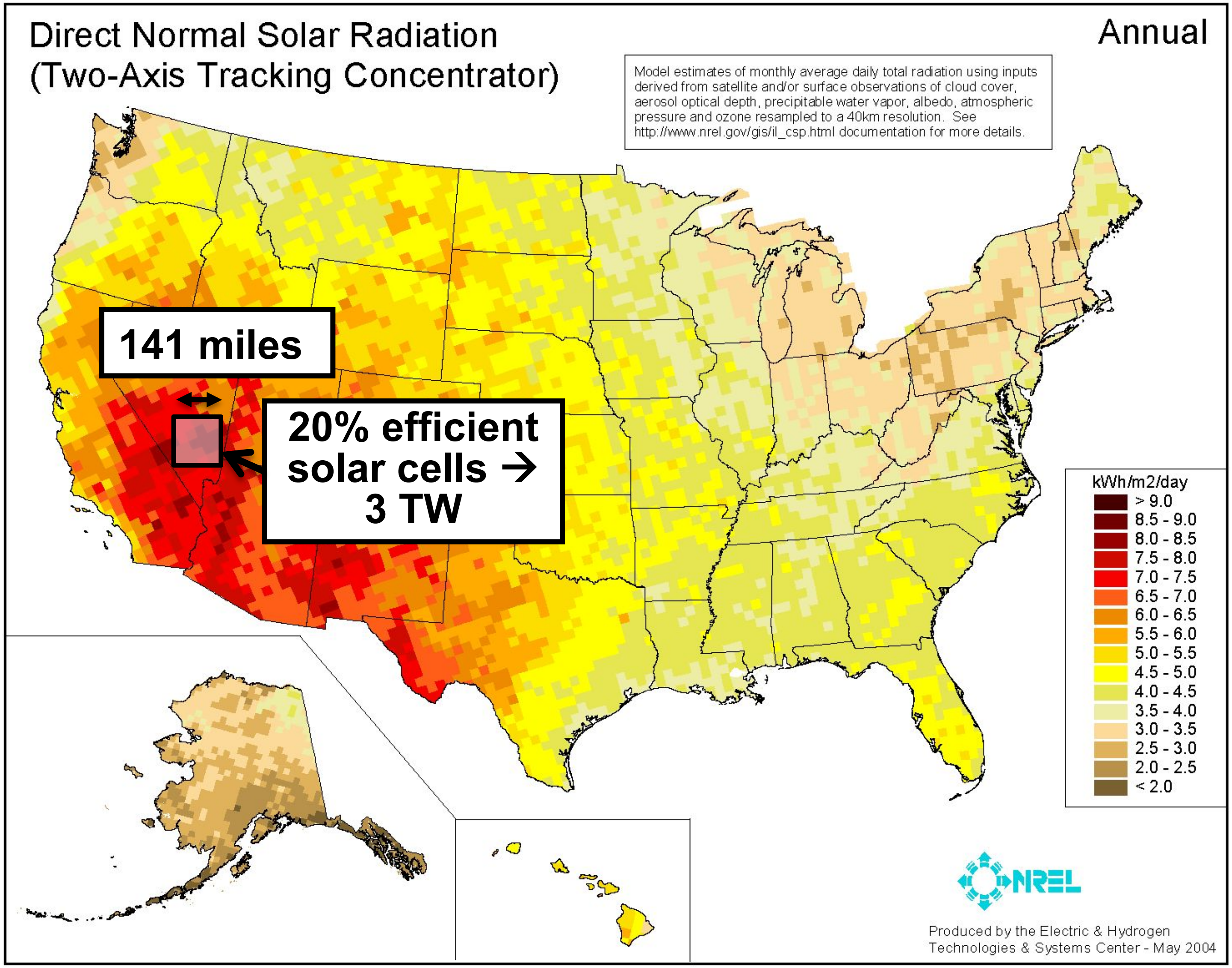
US?



Direct Normal Solar Radiation
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141 miles
20% efficient solar cells → 3 TW
kWh/m2/day
> 9.0
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2.0
NREL
Produced by the Electric & Hydrogen Technologies & Systems Center - May 2004

Conclusions about solar resources

- Humankind's energy needs are enormous.
- The energy we receive from the sun is more enormous.
- Sunlight could power our society if the proper technology were available and affordable.

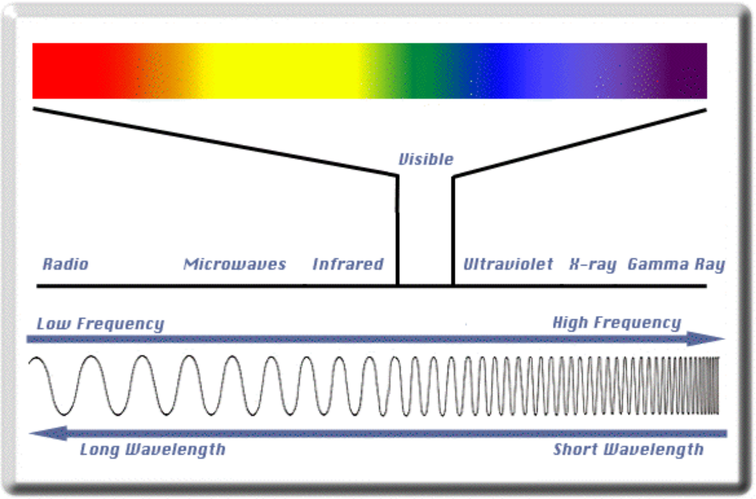
If we run out of coal and oil, the sun could save your arms from a lot of unnecessary exertion:

Fundamental Physics Behind Photovoltaic Solar Cells

What is a solar cell made from?

How does a solar cell work on the level of atoms and electrons?

What is a Solar Cell Made From?

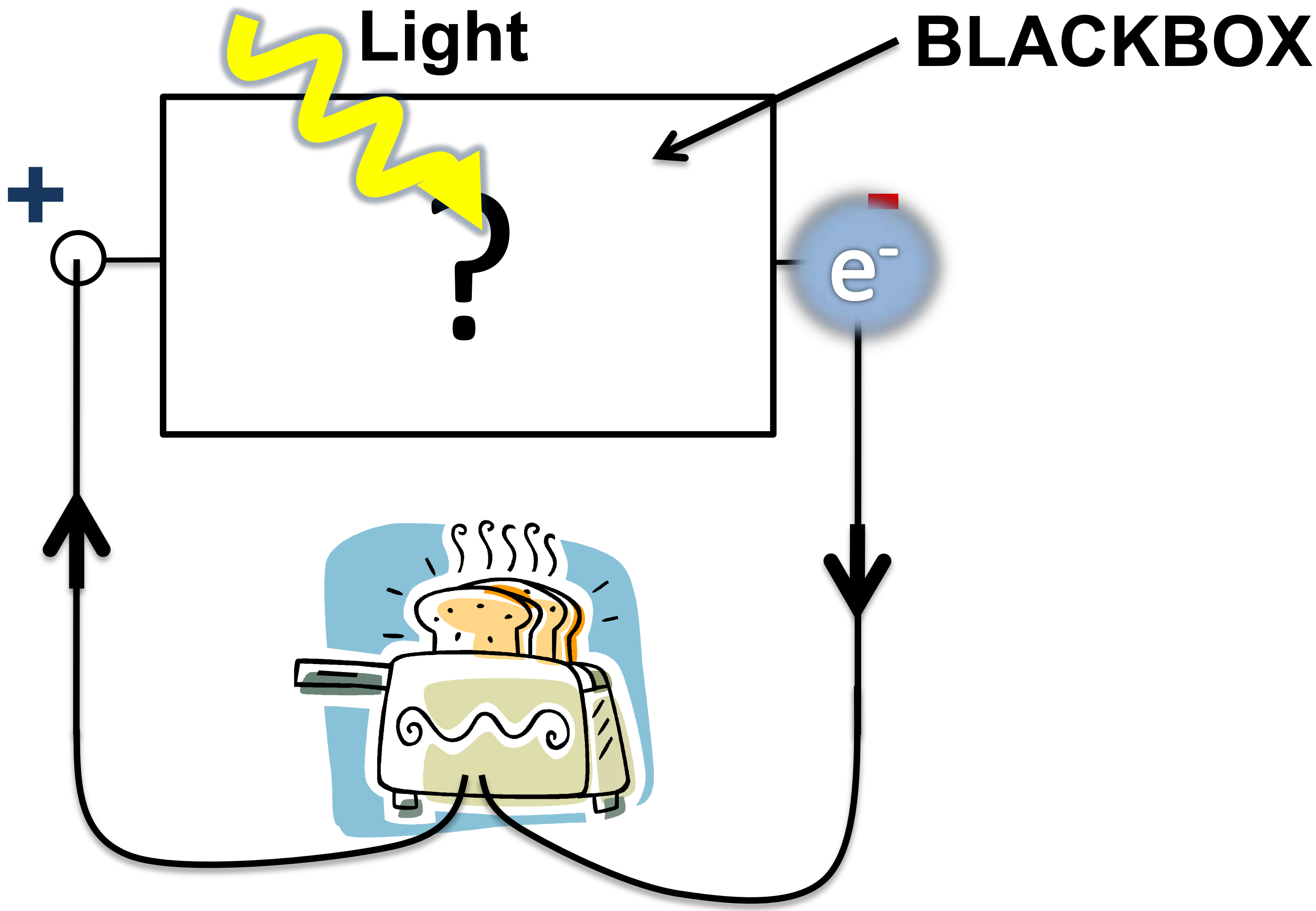


Light

Electricity

www.freefoto.com

What is a Solar Cell Made From?



What is a Solar Cell Made From?

- At heart: **a semiconductor**
- Silicon is most common
- (also: inactive components such as metal, glass, structural materials, etc.)

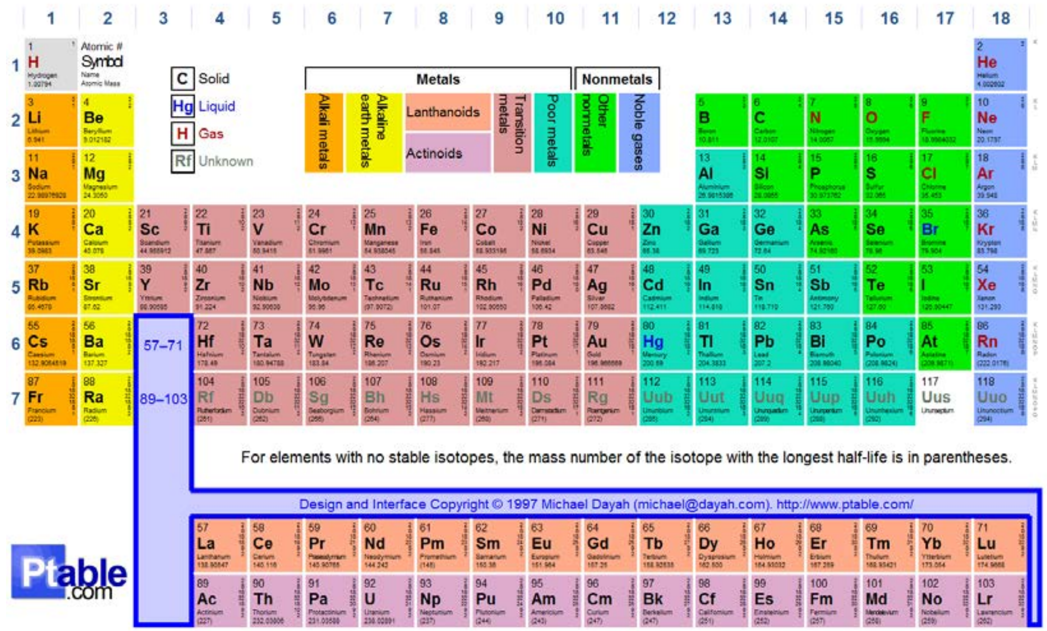
A computer chip and a solar cell are both made from semiconductors.

Oxidized Silicon

http://www.dailygalaxy.com/.a/6a00d8341bf7f753ef0168eafb3053970c-pi

Other Semiconductors

- GaAs
- CdTe
- CuInGaSe (CIGS)
- Organic molecules (C)
- PbI2 + Organic molecules (Organic-inorganic hybrid perovskite)



Many elements and compounds are semiconductors.

What Makes a Semiconductor a Semiconductor?

- It can act like both a conductor or an insulator.
- It can be doped to conduct negative charge (electrons) or positive charge (holes).
- It has an “energy gap” or “band gap”.

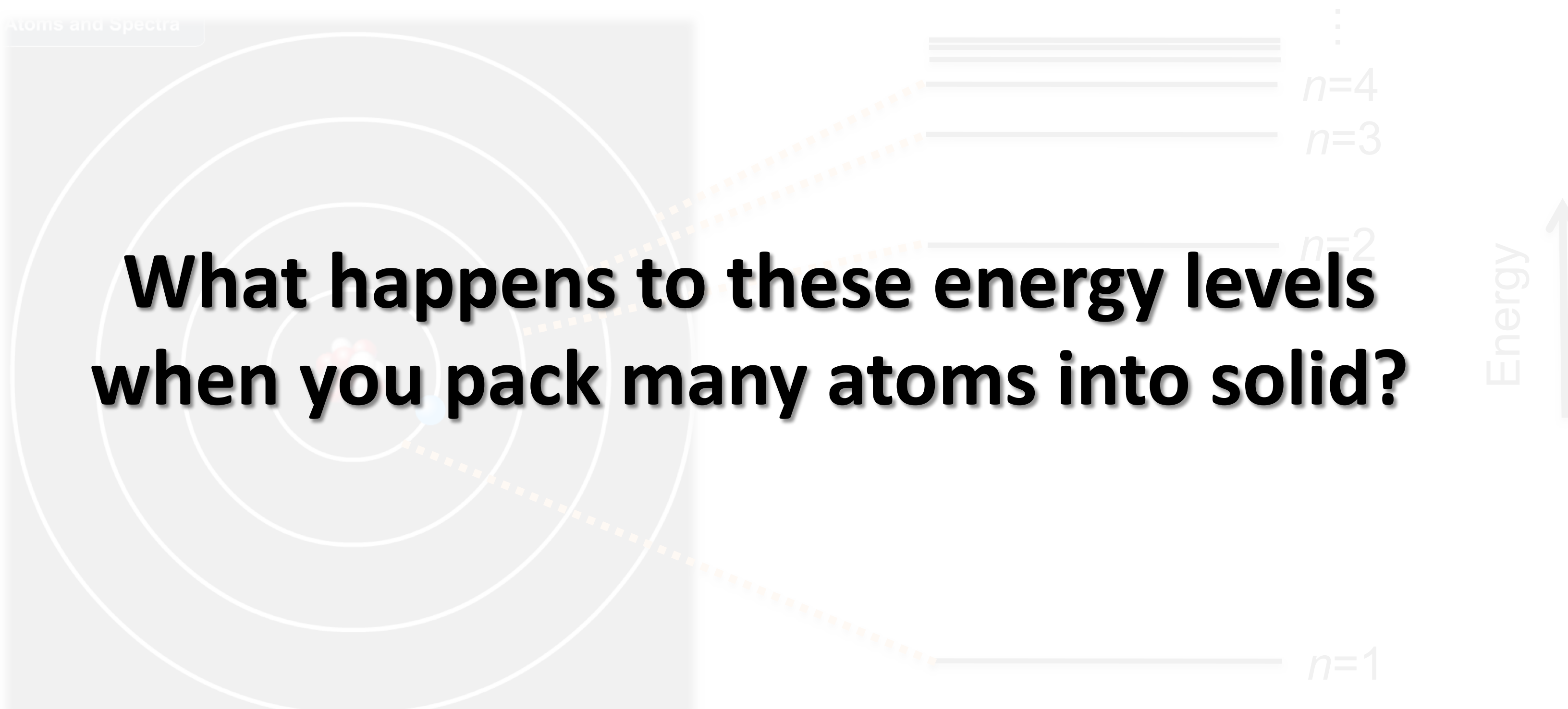
Conductor

Insulator

What Makes a Semiconductor a Good Semiconductor?

- Proper bandgap
  - Determines energies of photons absorbed and PV voltage
- Abundance of materials
- Economics of processing / scale-up / toxicity / cost of disposal
- “Speed” of charges
- Thermal and chemical stability / lifetime / reliability
- Electronic nature of atomic-scale defects and imperfections in semiconductors

Concepts of Bandgap and Energy Levels of Isolated Atoms and Materials

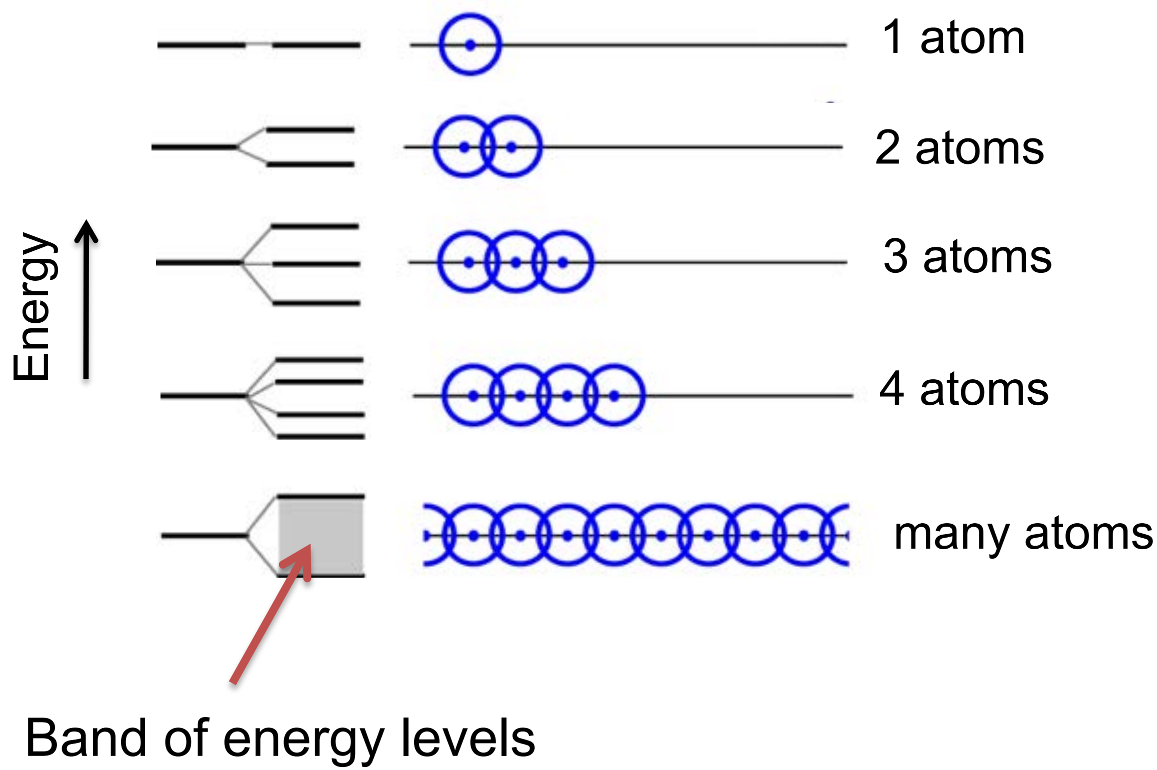


What happens to these energy levels when you pack many atoms into solid?

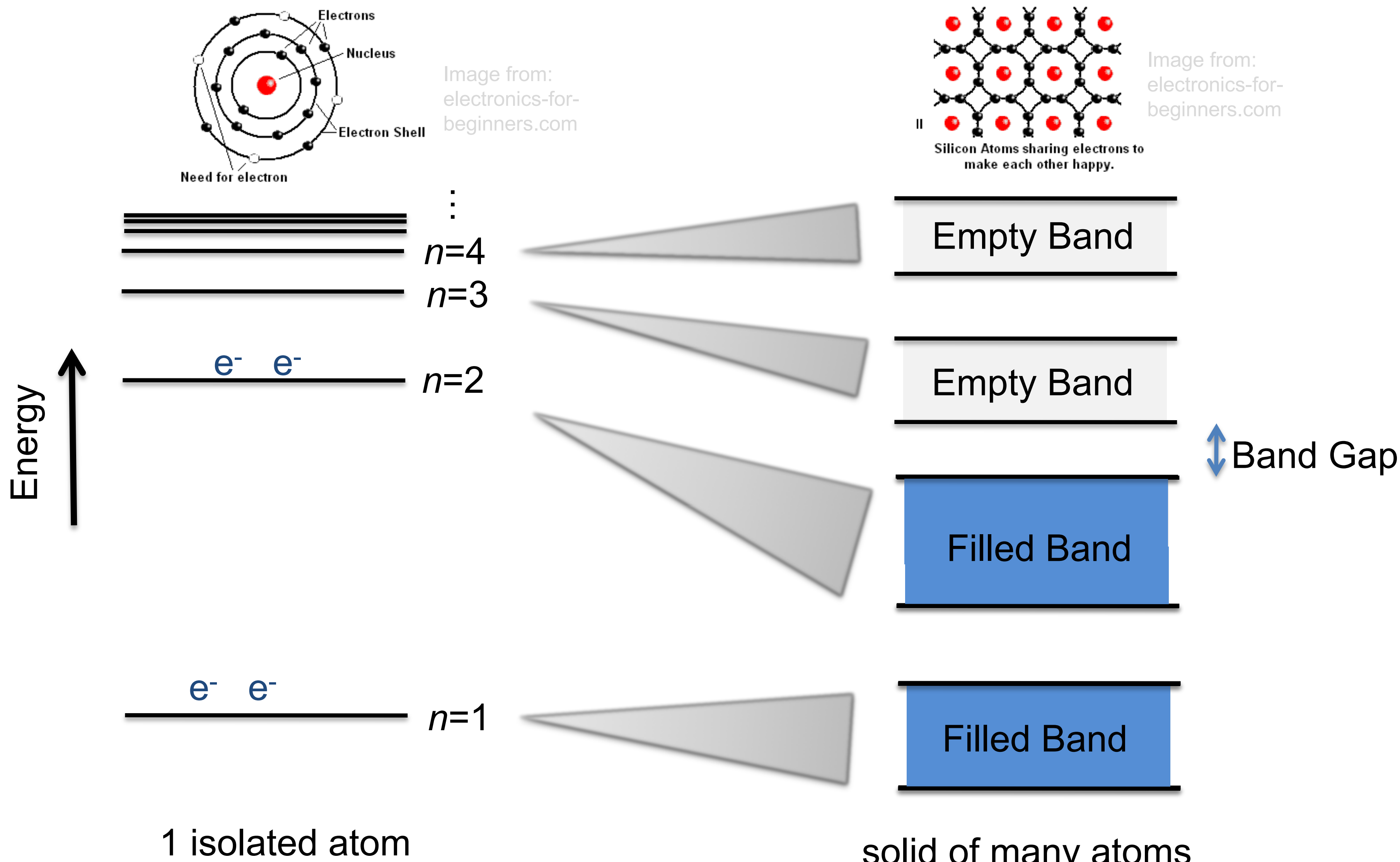
Image from: http://spiff.rit.edu/classes/phys301/lectures/spec_lines/Atoms_Nav.swf

Energy Levels Split in a Solid to Form Bands

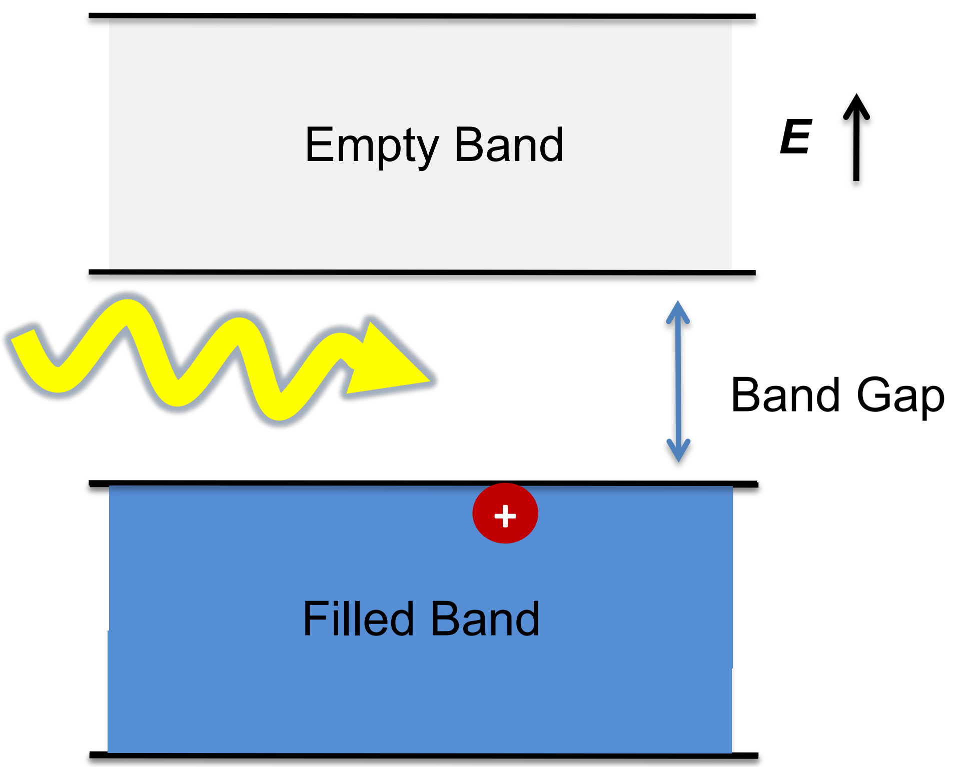
Look at effect on lowest n=1 orbital.



Semiconductor Has Gap Between Bands

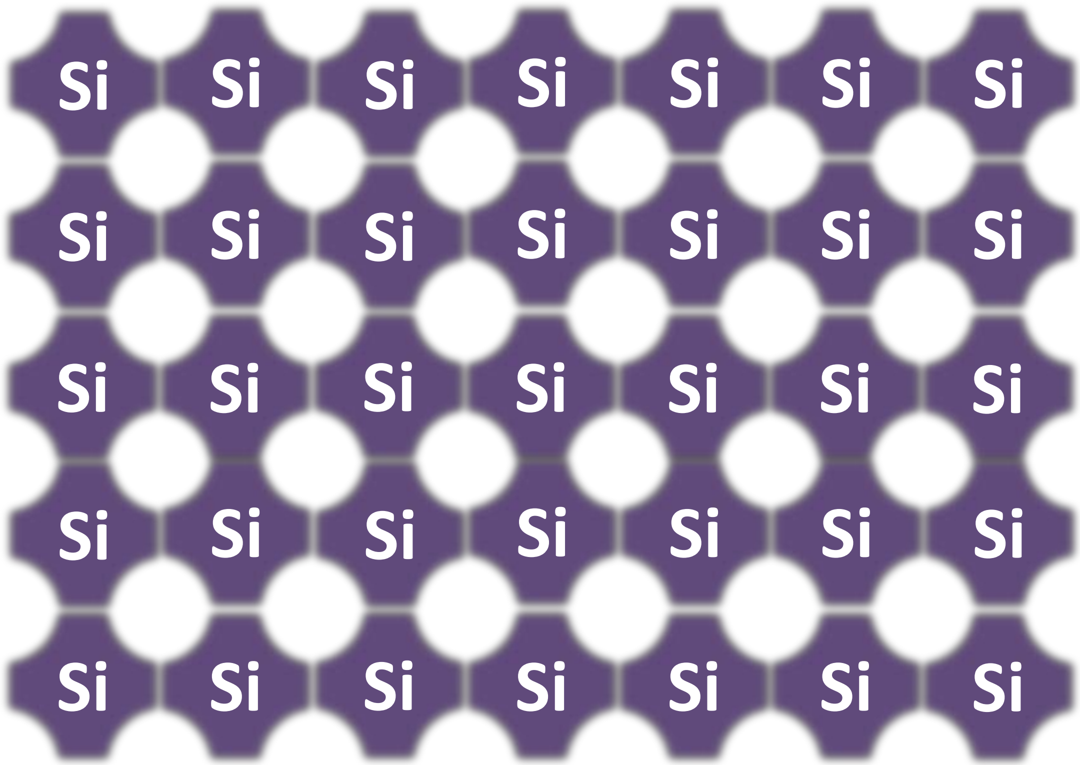


Light Excites Electrons Across Bandgap



Challenge is to next separate negative and positive charge to opposite sides of a solar cell before the electron falls back down to the filled band and turns into heat!

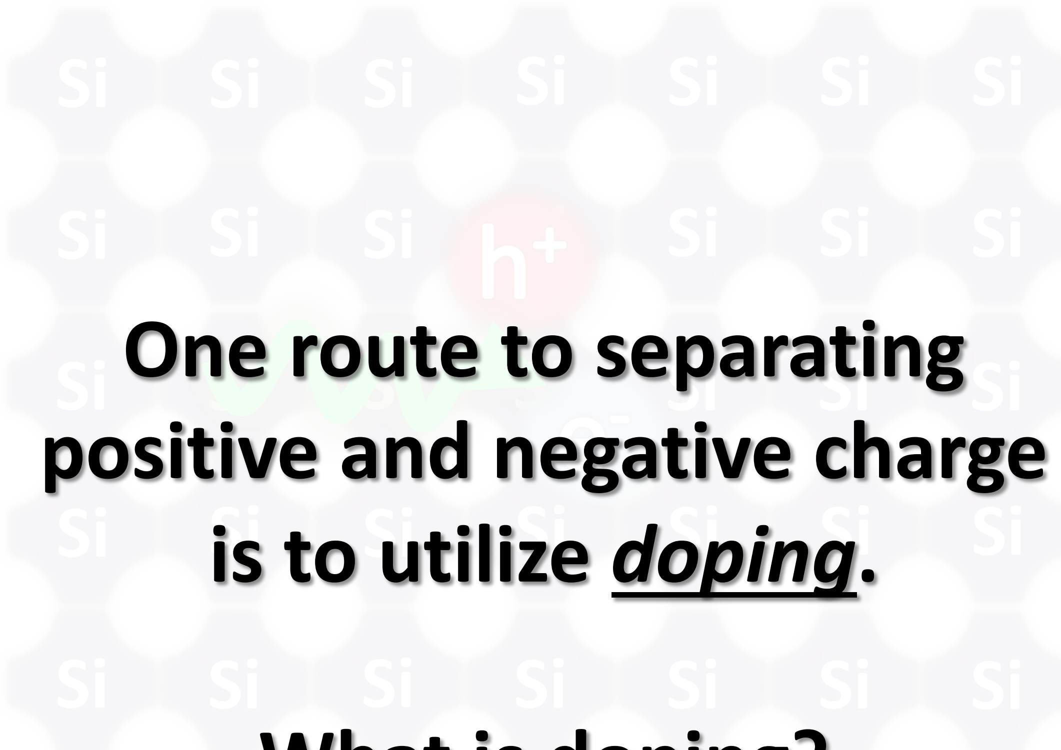
How Can Charge Be Spatially Separated?



Example 2D Representation of Si:

- Each Si atom is covalently bonded to 4 other Si atoms.
- All 4 electrons in the outer-shell are in covalent bonds.
- **No free charges to move around – low conductivity.**

Absorption of Light

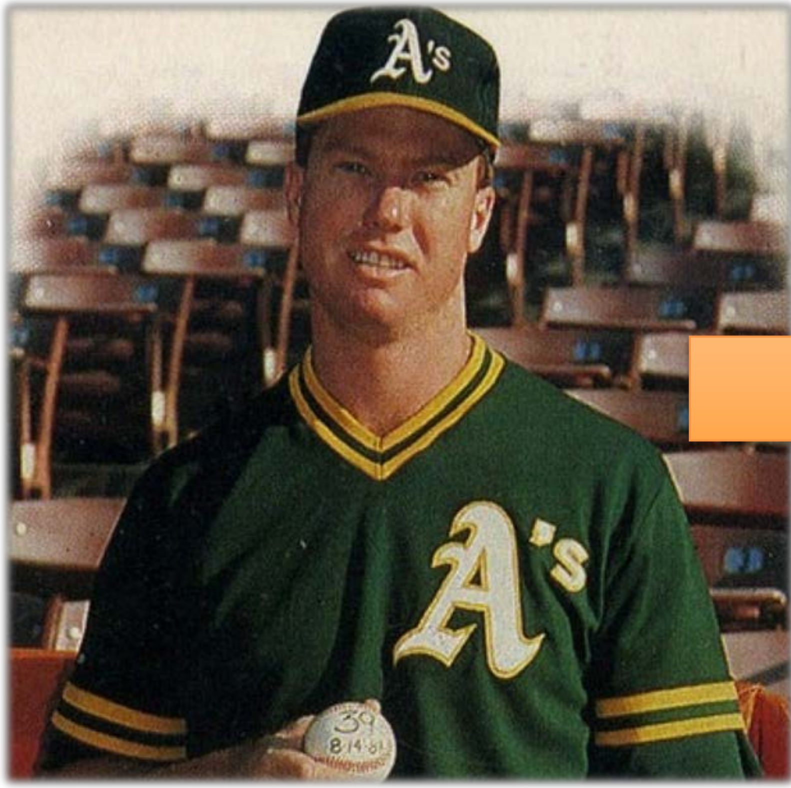


One route to separating positive and negative charge is to utilize *doping*.

What is doping?

- When a semiconductor absorbs light → positive (holes) and negative (electrons) charges are created.
- But, how can you induce their spontaneous separation?

Not the Kind of Doping I Am Talking About.

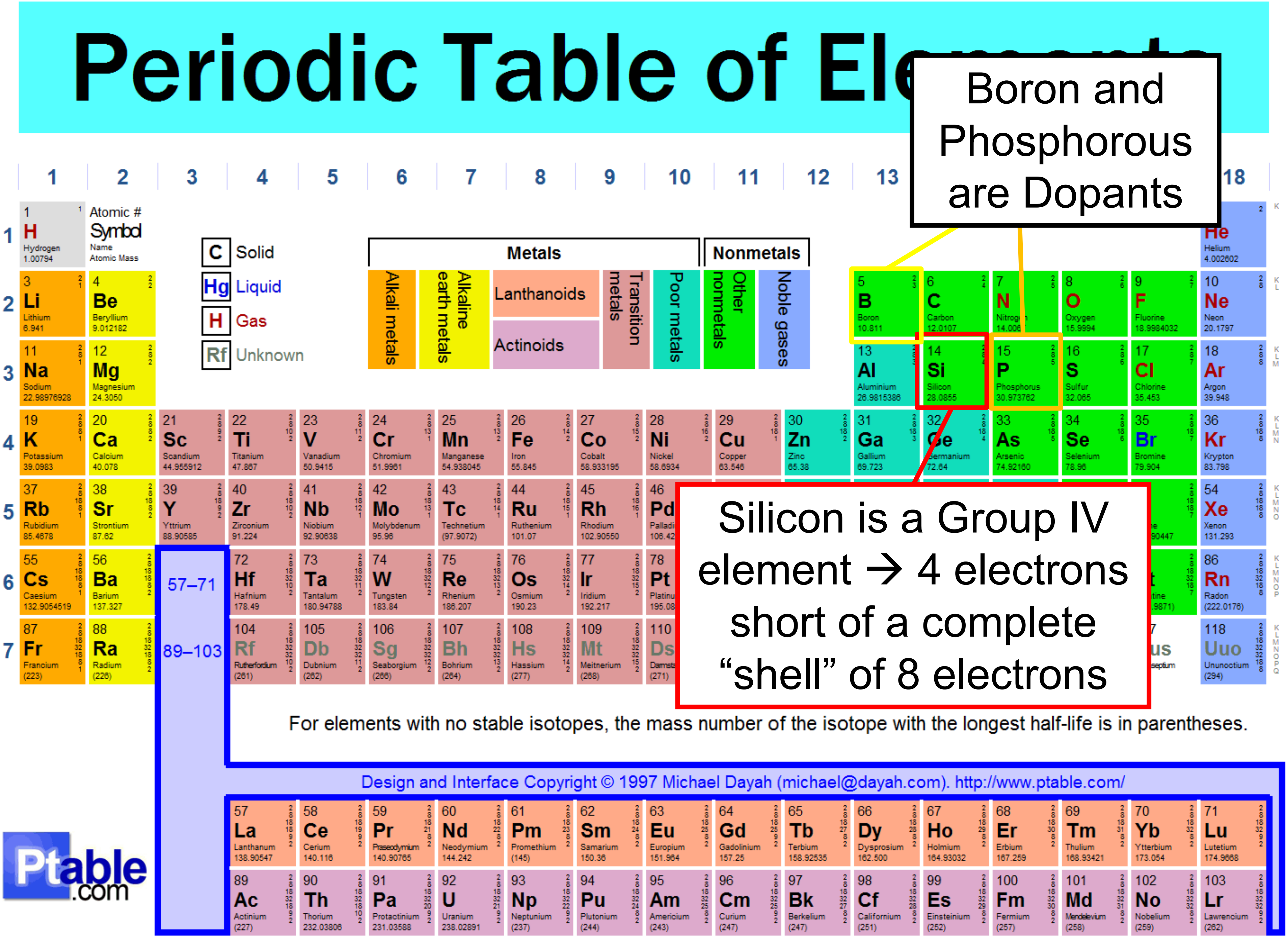


?

<u>380,000 times / hour?</u>

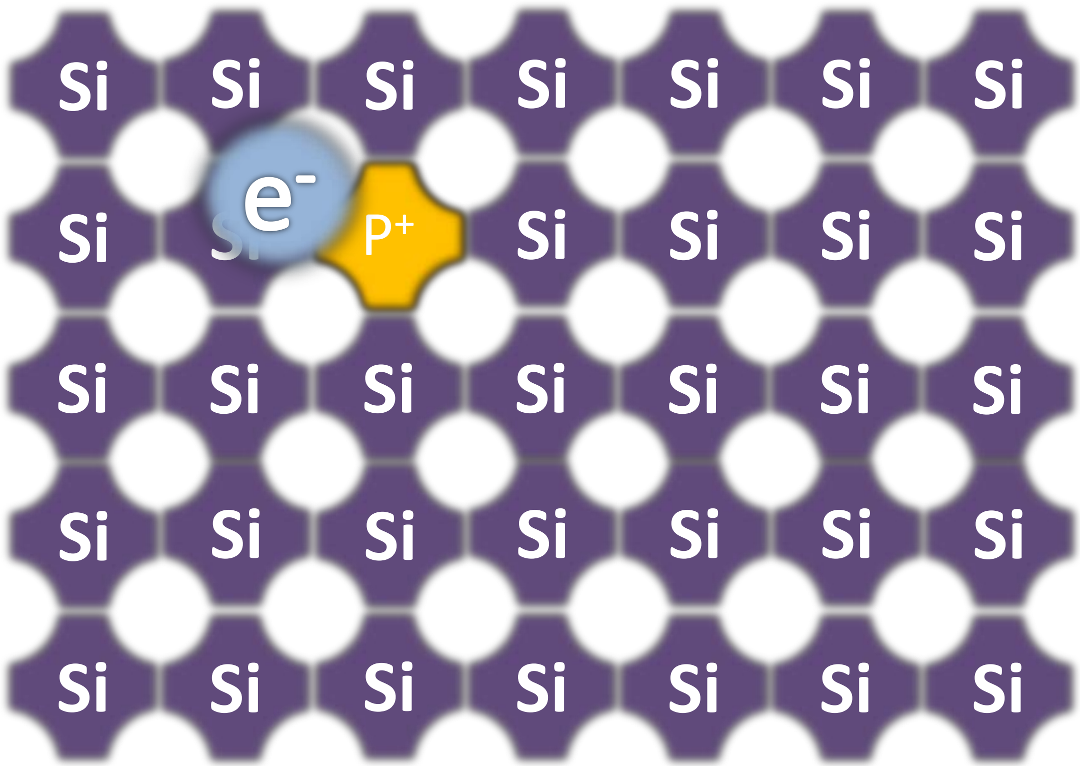
What is Doping?

- Doping results from the ***intentional*** or ***unintentional*** addition of impurities to a semiconductor.



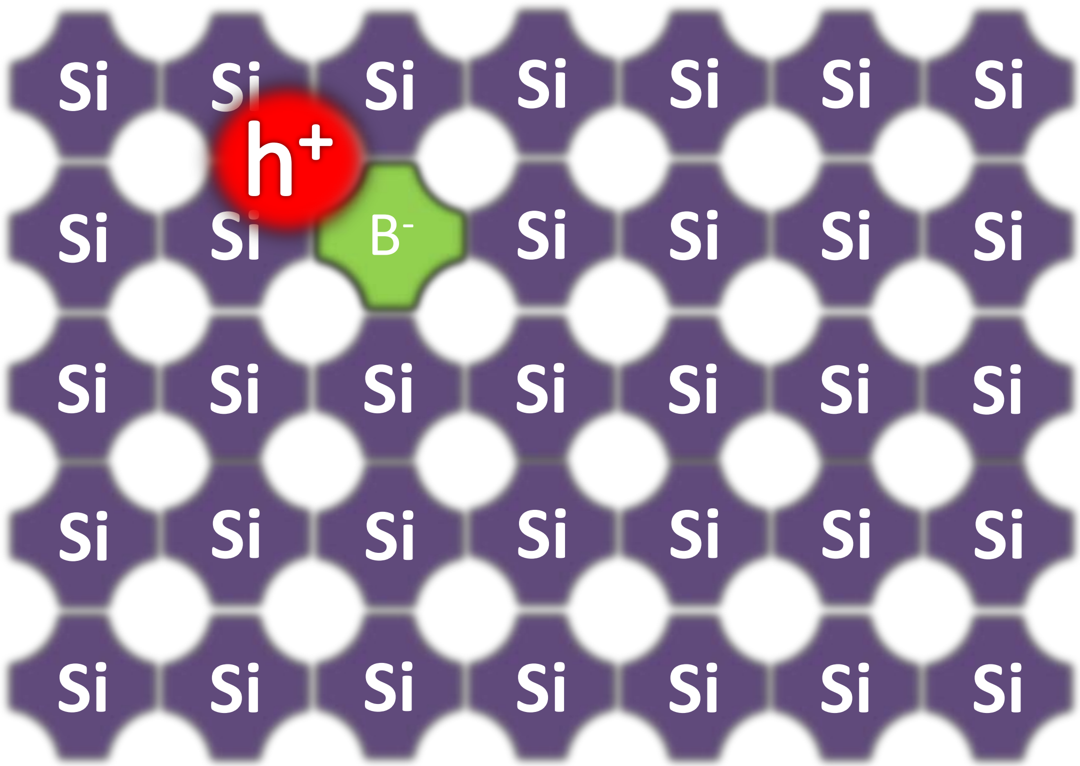
Periodic Table of Elements
Boron and Phosphorous are Dopants
Silicon is a Group IV element → 4 electrons short of a complete “shell” of 8 electrons
Metals
Nonmetals
Alkali metals
Alkaline earth metals
Lanthanoids
Actinoids
Transition metals
Poor metals
Other nonmetals
Noble gases
Solid
Liquid
Gas
Unknown
For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.
Design and Interface Copyright © 1997 Michael Dayah (michael@dayah.com). http://www.ptable.com/
Ptable.com

N-type (Electron Doped) Silicon (Si)



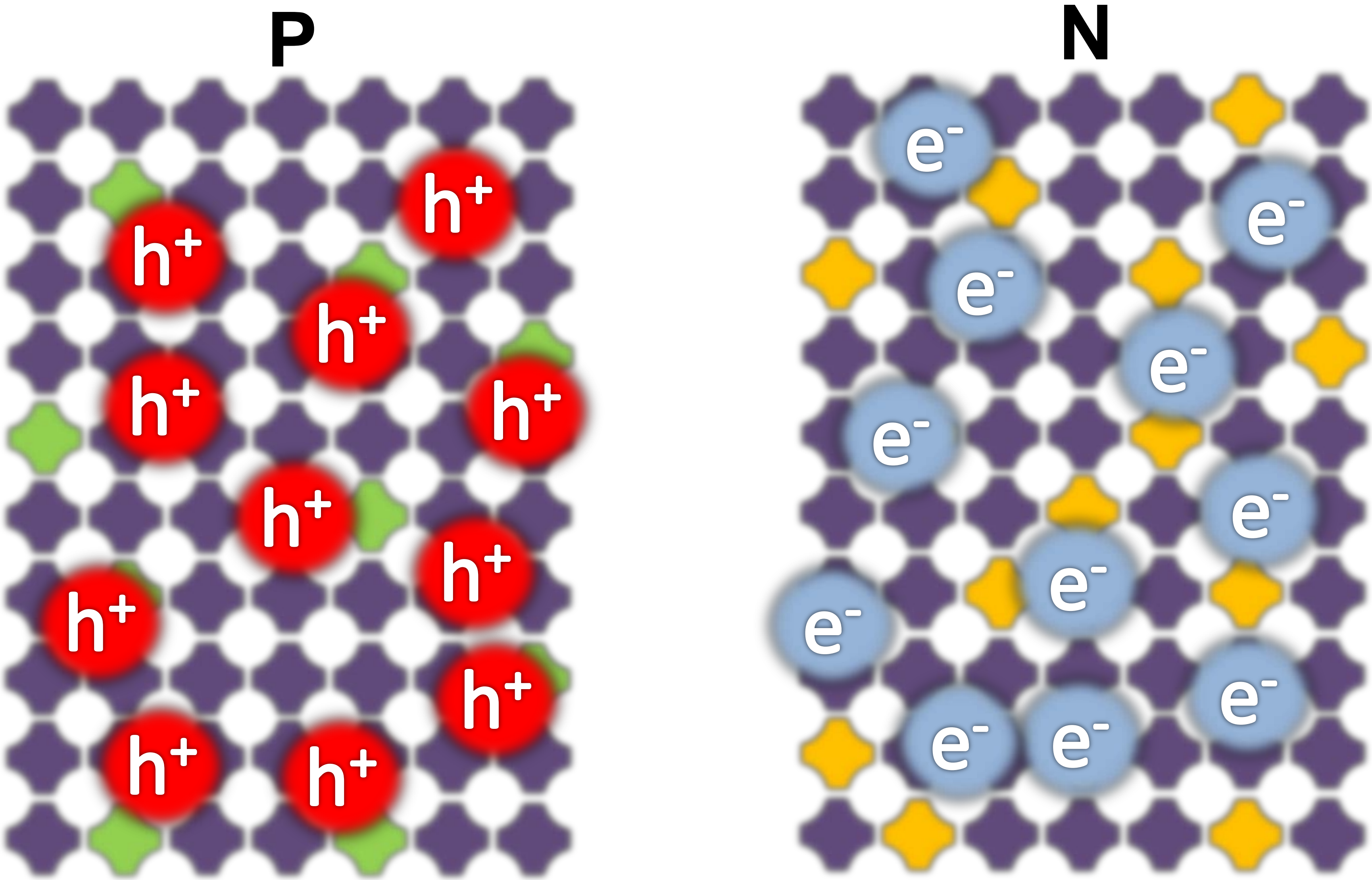
- Replacement of Group IV Si atom with Group V P atom
- P atom becomes positively ionized, releasing free electron that can move and conduct.

P-type ("Hole" Doped) Silicon (Si)

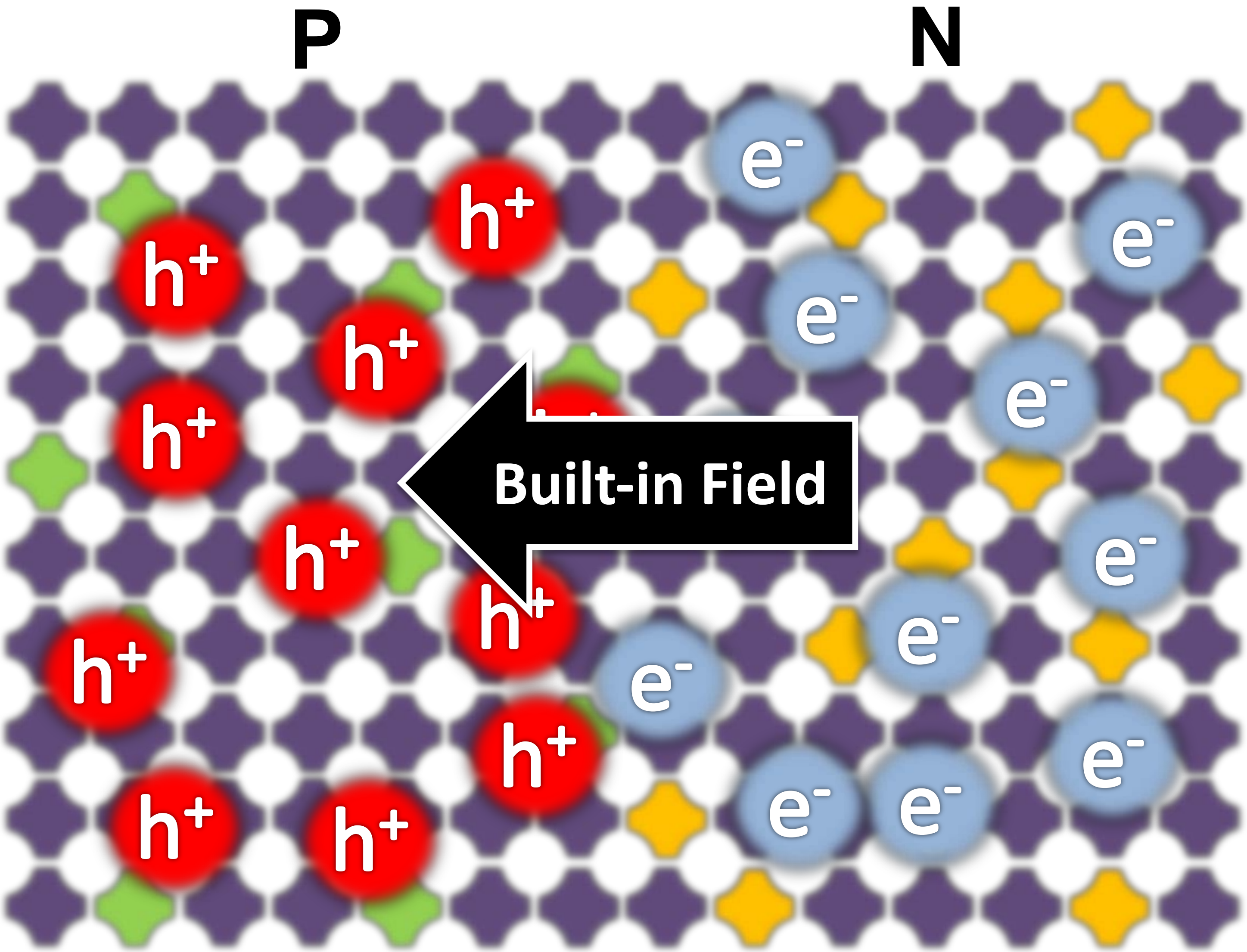


- Replacement of Group IV Si atom with Group III B atom
- B atom becomes negatively ionized, effectively releasing positive charge called a hole that can move and conduct.

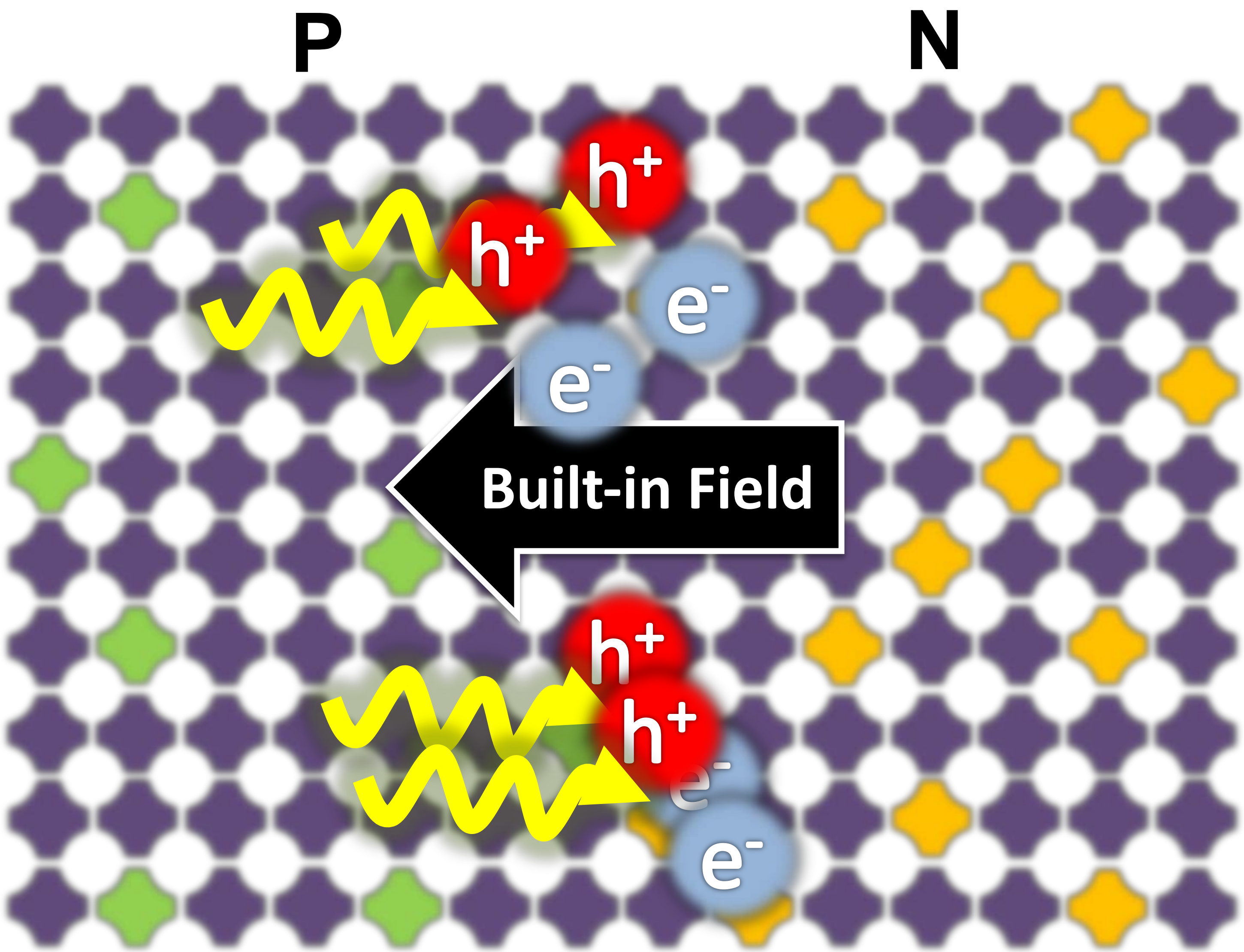
A Common Device is: P-N Junction



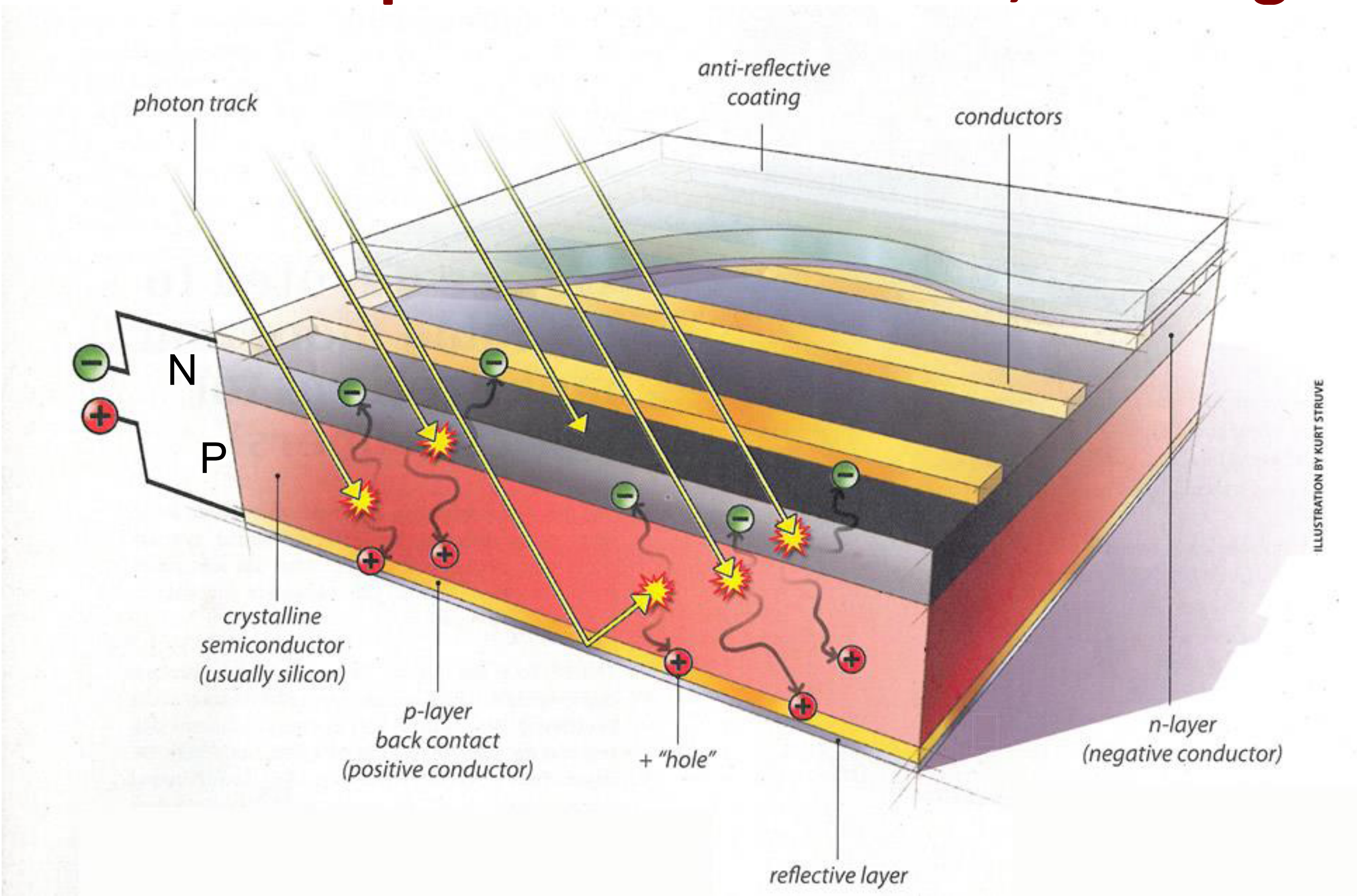
P-N Junction



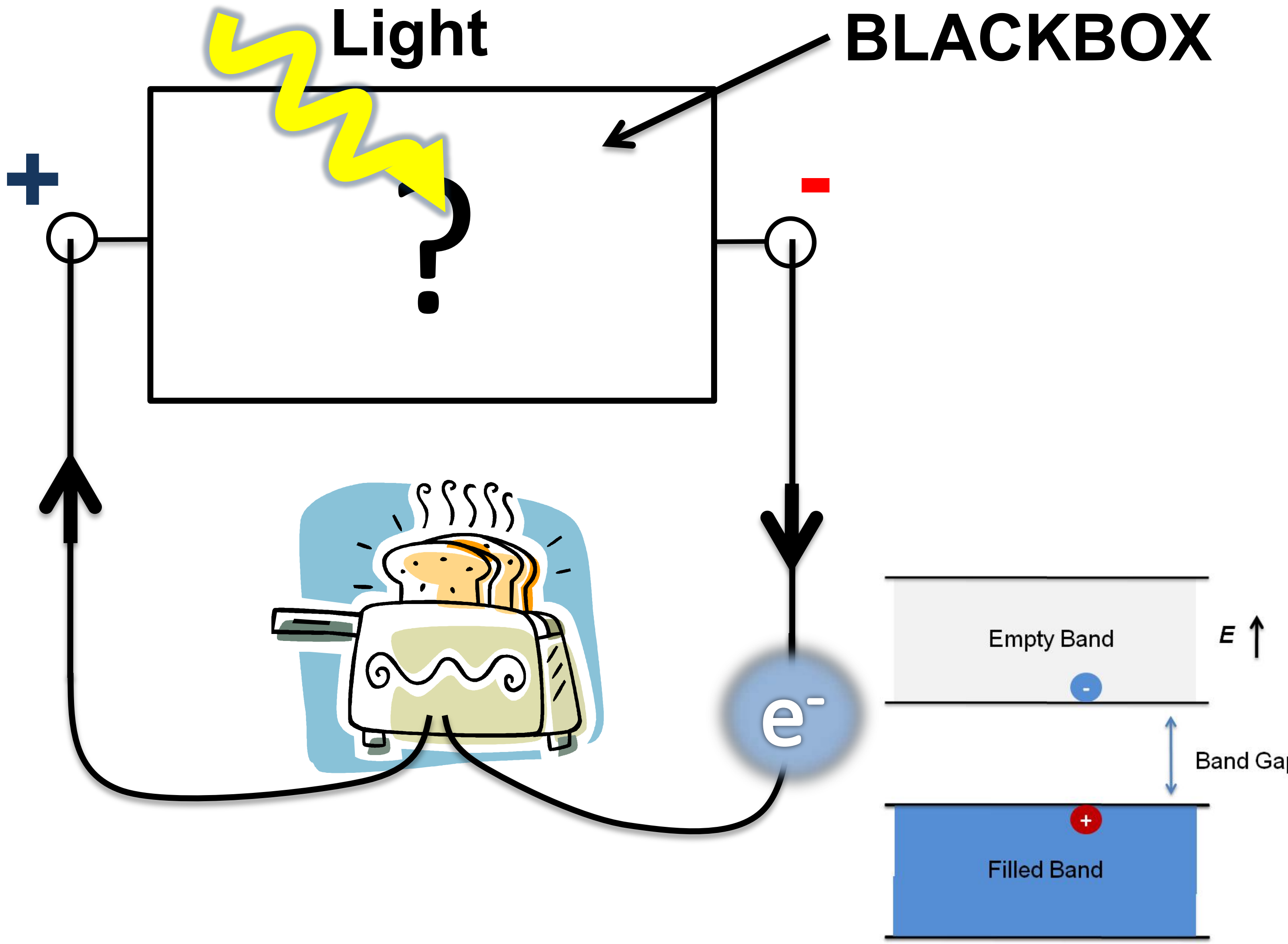
P-N Junction



Other Components: Electrodes, Coatings



Our Blackbox



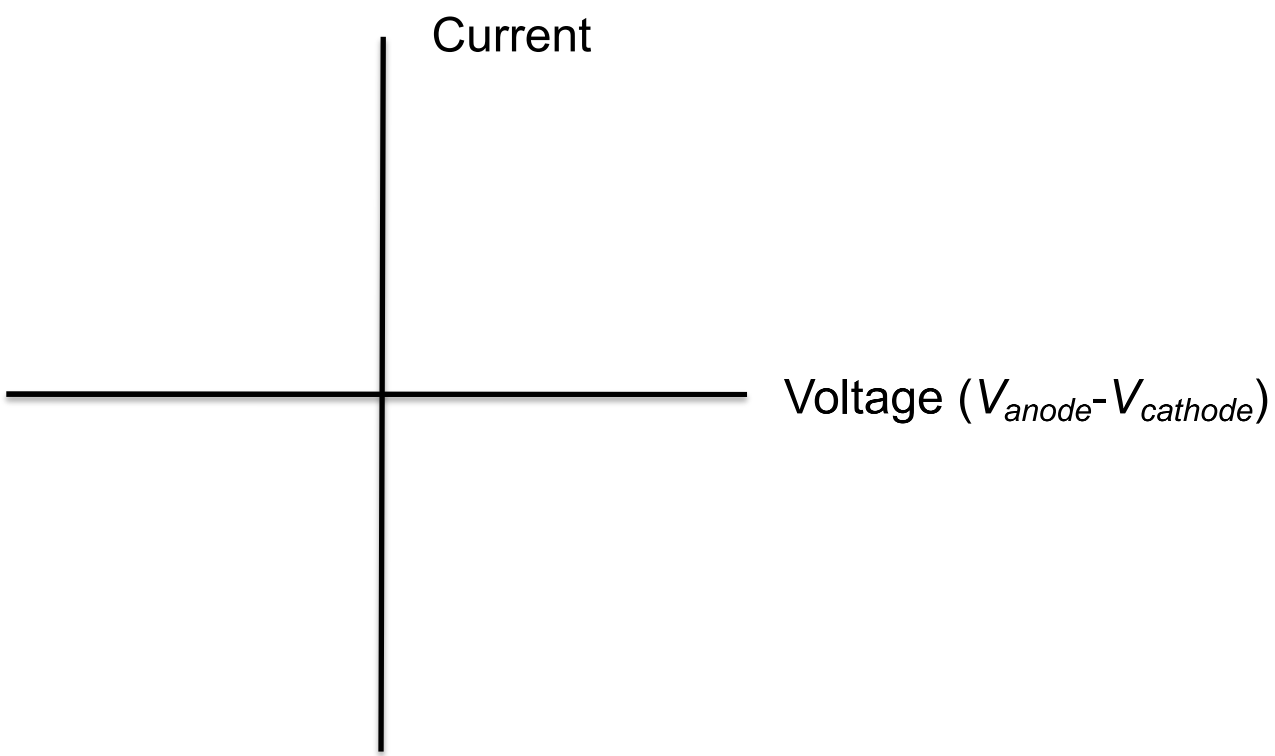
Conclusions About How a Solar Cell Works on the Level of Electrons and Atoms

- The active materials in a photovoltaic solar cell are semiconductors.
- Light excites negative charge (electrons) higher in energy across the band gap.
- A junction between P-doped and N-doped semiconductors (PN junction) is used to separate the positive and negative charges → electricity.

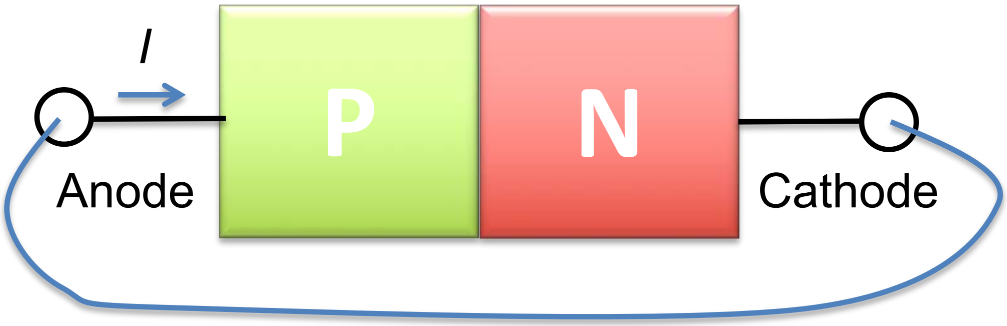
Fundamental Physics Behind Photovoltaic Solar Cells

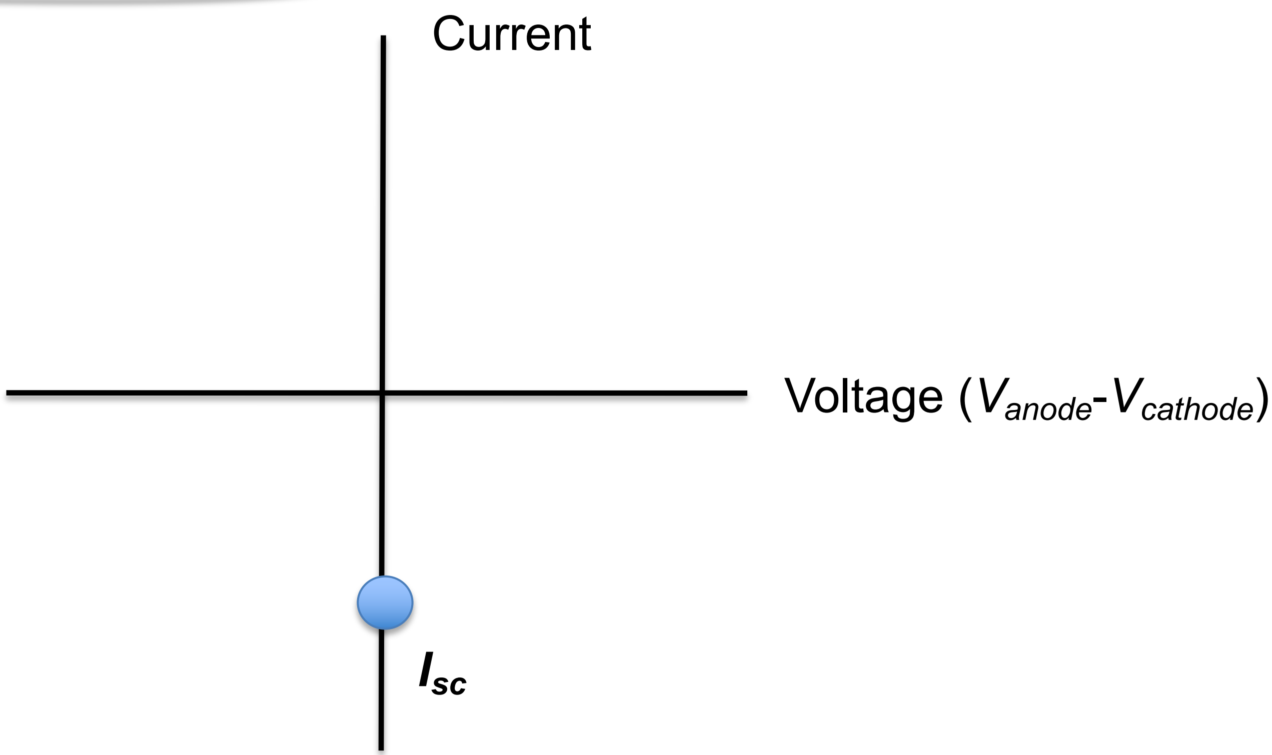
What are the current voltage characteristics of a single cell?

Current-Voltage Characteristics



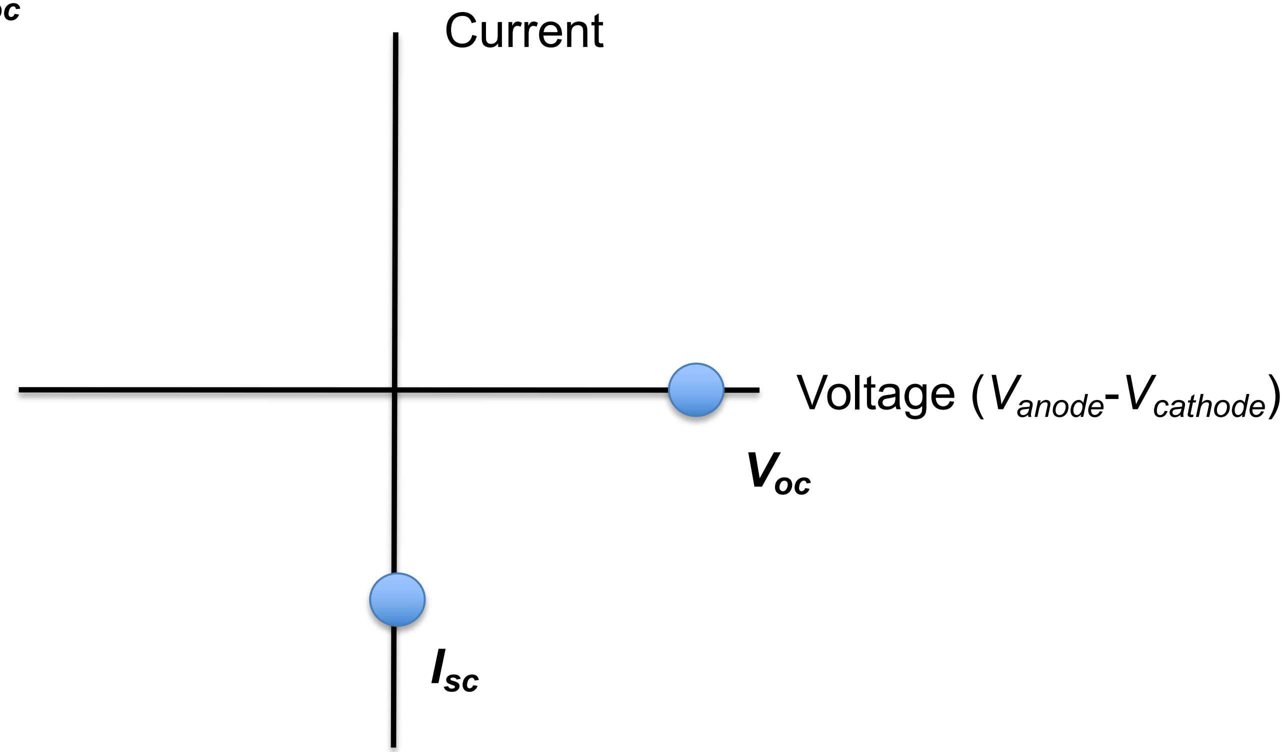
Short-Circuit Current (I_{sc})





Open-Circuit Voltage (V_{oc})

V_{oc}



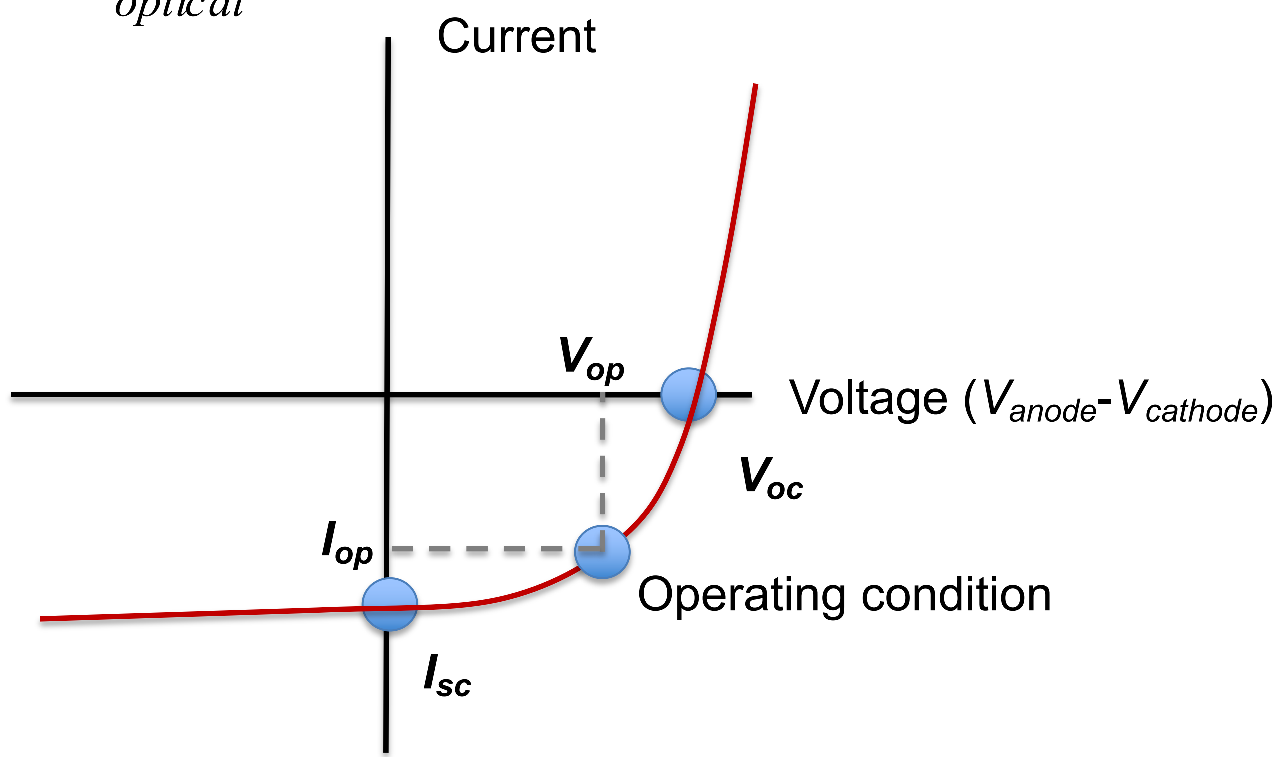
P=IV

FF = “Fill Factor”

Electrical power = $I_{op} * V_{op} = V_{oc} * I_{sc} * FF$

$$FF = \frac{I_{op} V_{op}}{V_{oc} I_{sc}}$$

Efficiency $\eta_P = \frac{I_{oc} V_{sc} FF}{P_{optical}}$



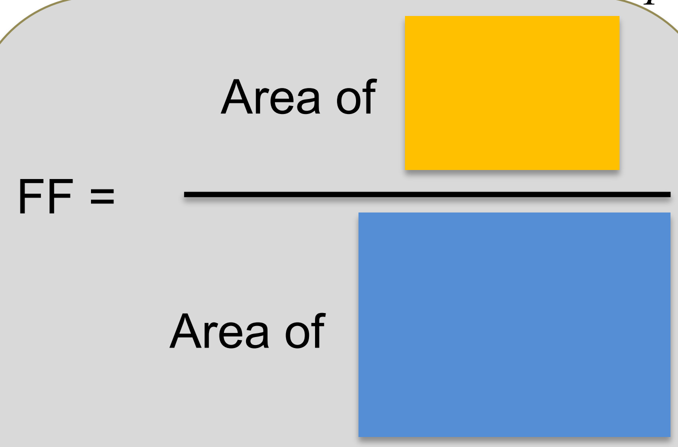
What is the *FF*?

FF = “Fill Factor”

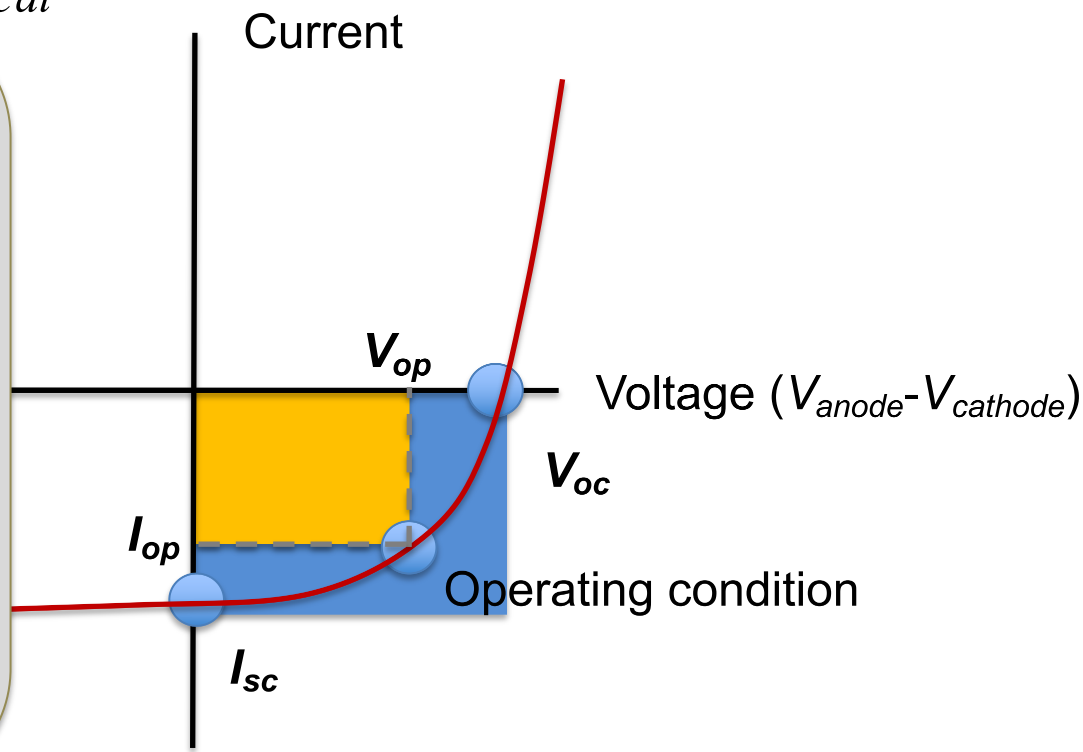
Electrical power = I_{op}*V_{op} = V_{oc}*I_{sc}*FF

$$FF = \frac{I_{op} V_{op}}{V_{oc} I_{sc}}$$

Efficiency $\eta_P = \frac{I_{oc} V_{sc} FF}{P_{optical}}$



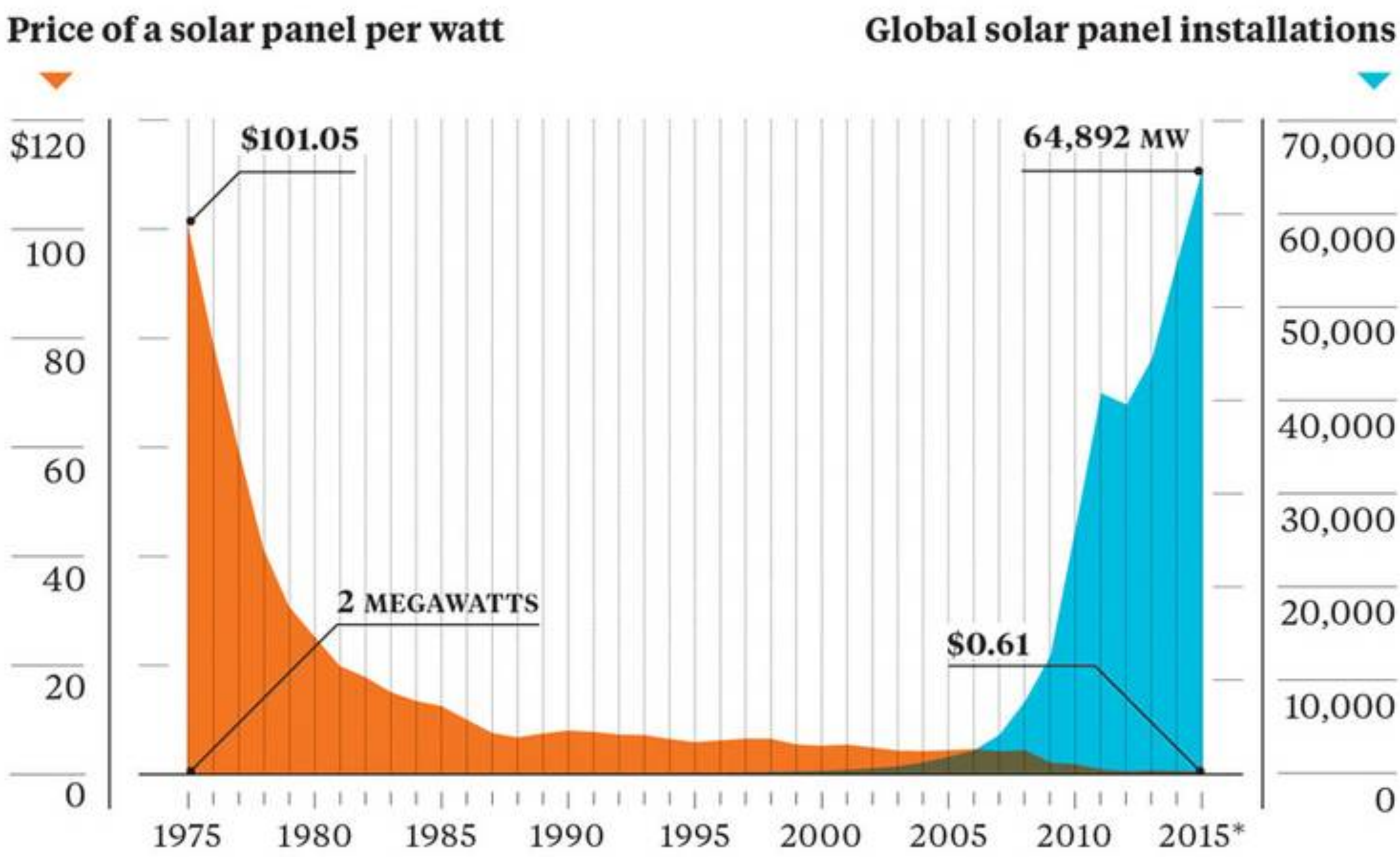
FF measures squareness of the curve and how close operating voltage and current come to the V_{oc} and I_{sc}.



Trends

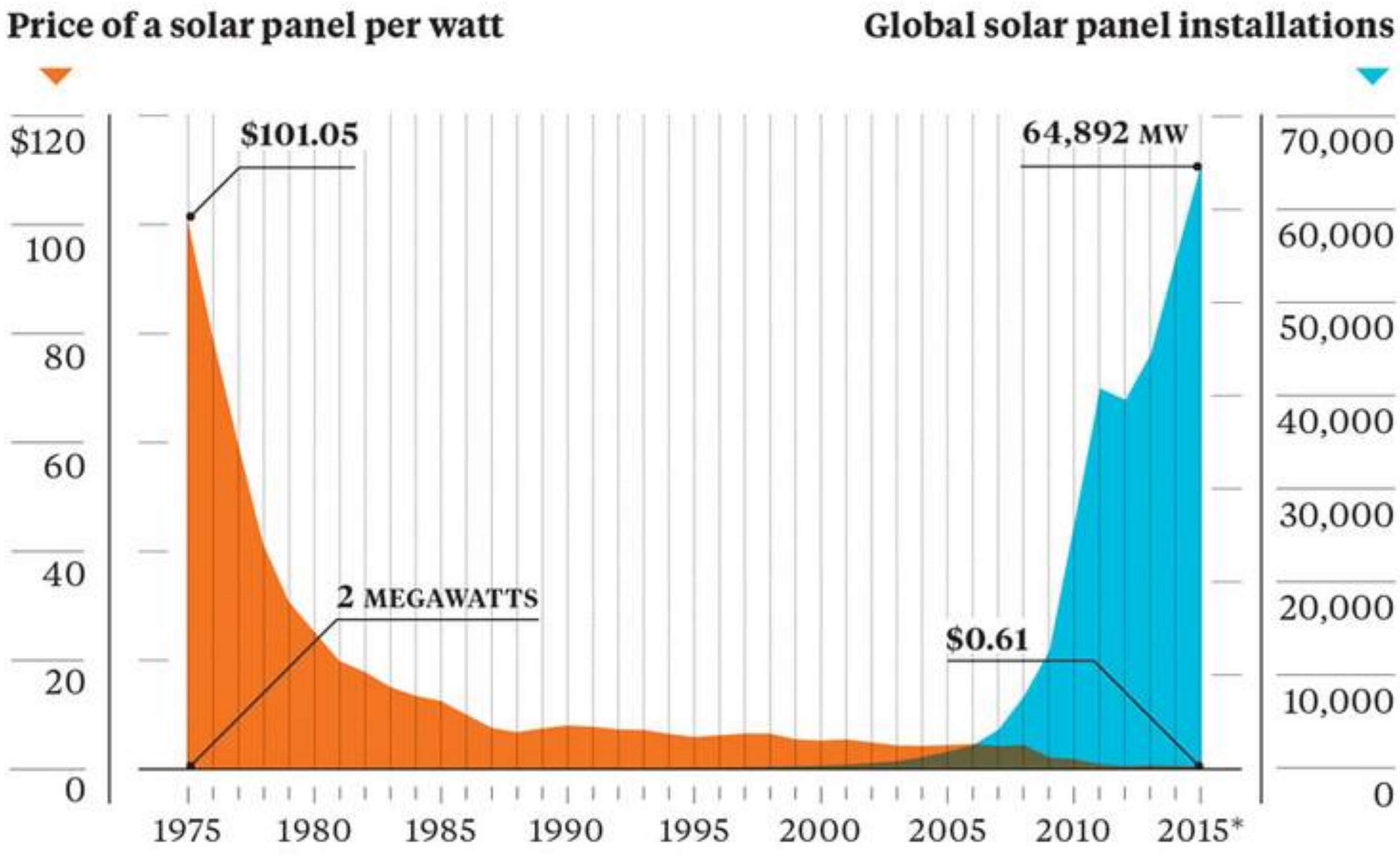
Dramatic changes in solar installations and cost over the last several decades.

The PV market has been growing rapidly over the last two decades.



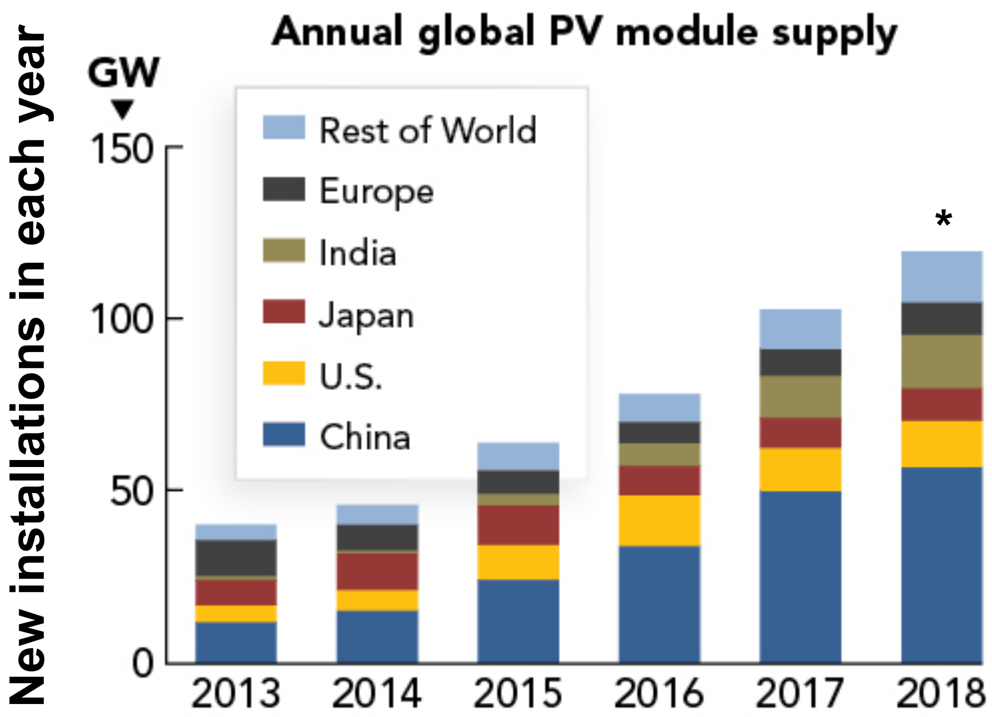
Data/image source: Earth Policy Institute/Bloomberg

Meanwhile, price has plummeted.



Data/image source: Earth Policy Institute/Bloomberg

The growth has been world-wide and especially in China.



2018 is projection from March, has since been revised downward

"Annual solar PV installations reached 100 GW in 2017, with China consuming half of the global demand."

Data source:

INDUSTRIAL LASER SOLUTIONS FOR MANUFACTURING

Types of Solar Cells

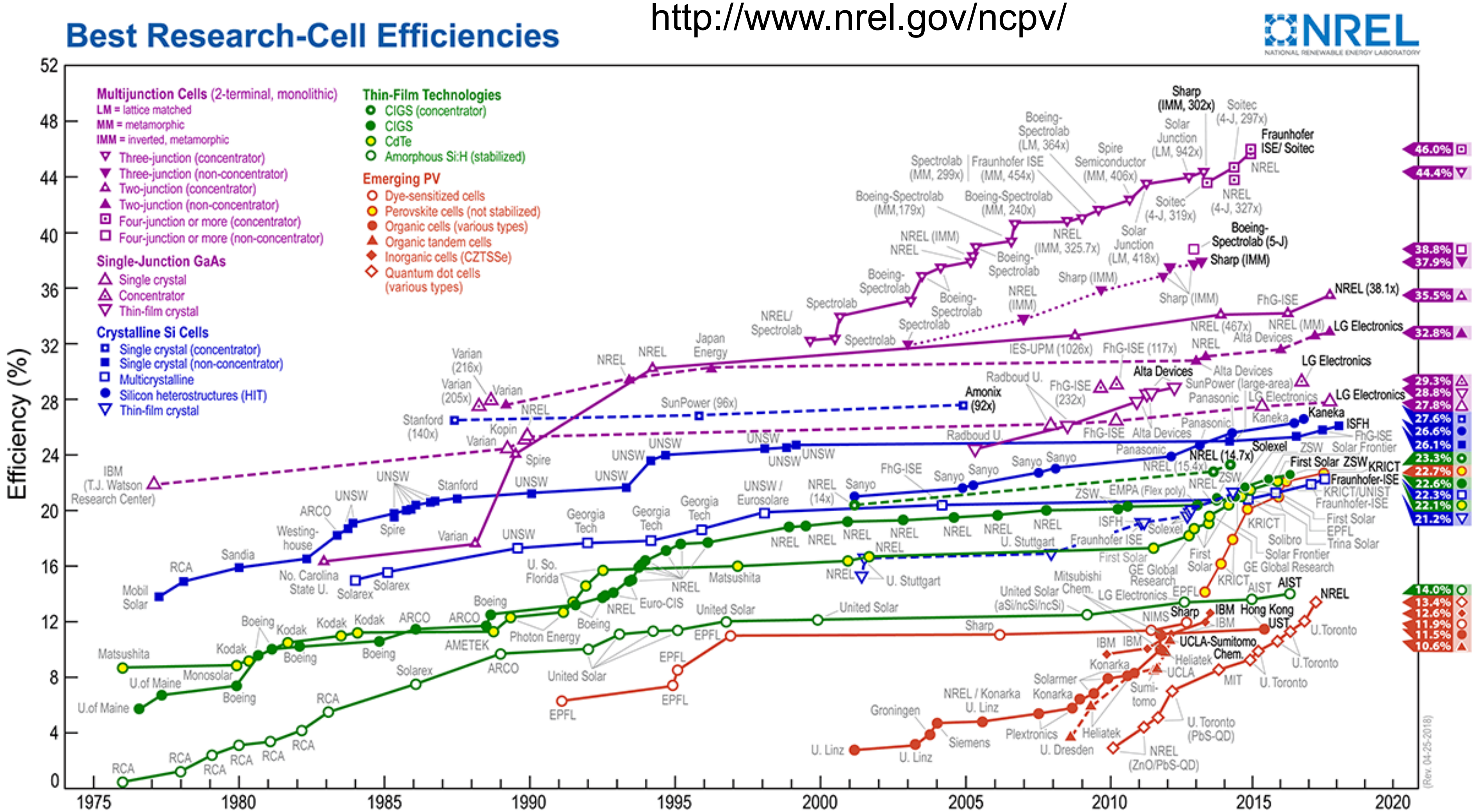
How do types of solar cells differ?

How efficient are they?

What are the challenges in materials science to making solar cells more efficient and economical?

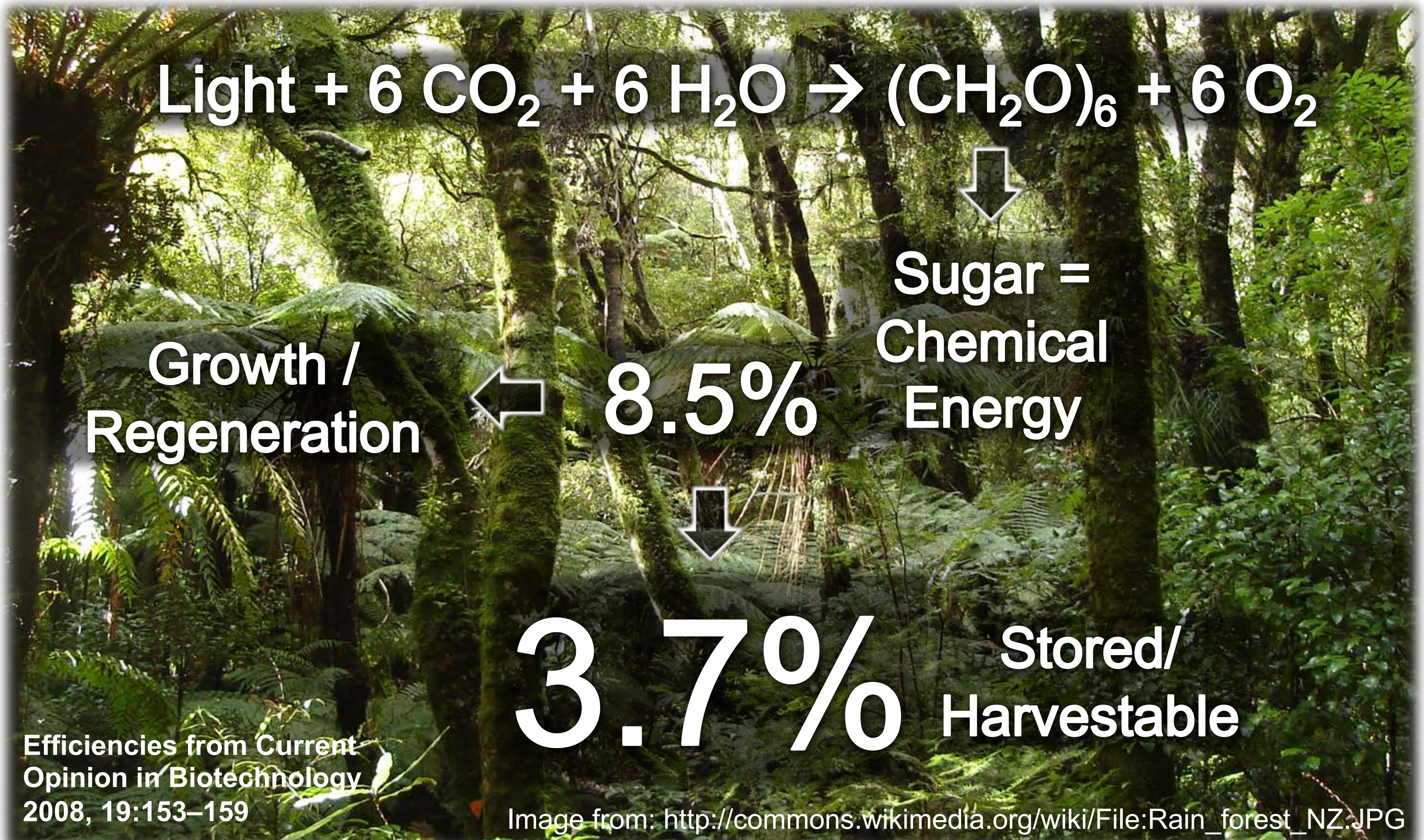
NREL National Center for Photovoltaics

http://www.nrel.gov/ncpv/



Observation #1: Efficiency up with time! Ranges from 10-46%!!!

Aside: How Efficient is Photosynthesis?



Light + 6 CO_2 + 6 H_2O → $(CH_2O)_6$ + 6 O_2

Sugar = Chemical Energy

Growth / Regeneration ← 8.5%

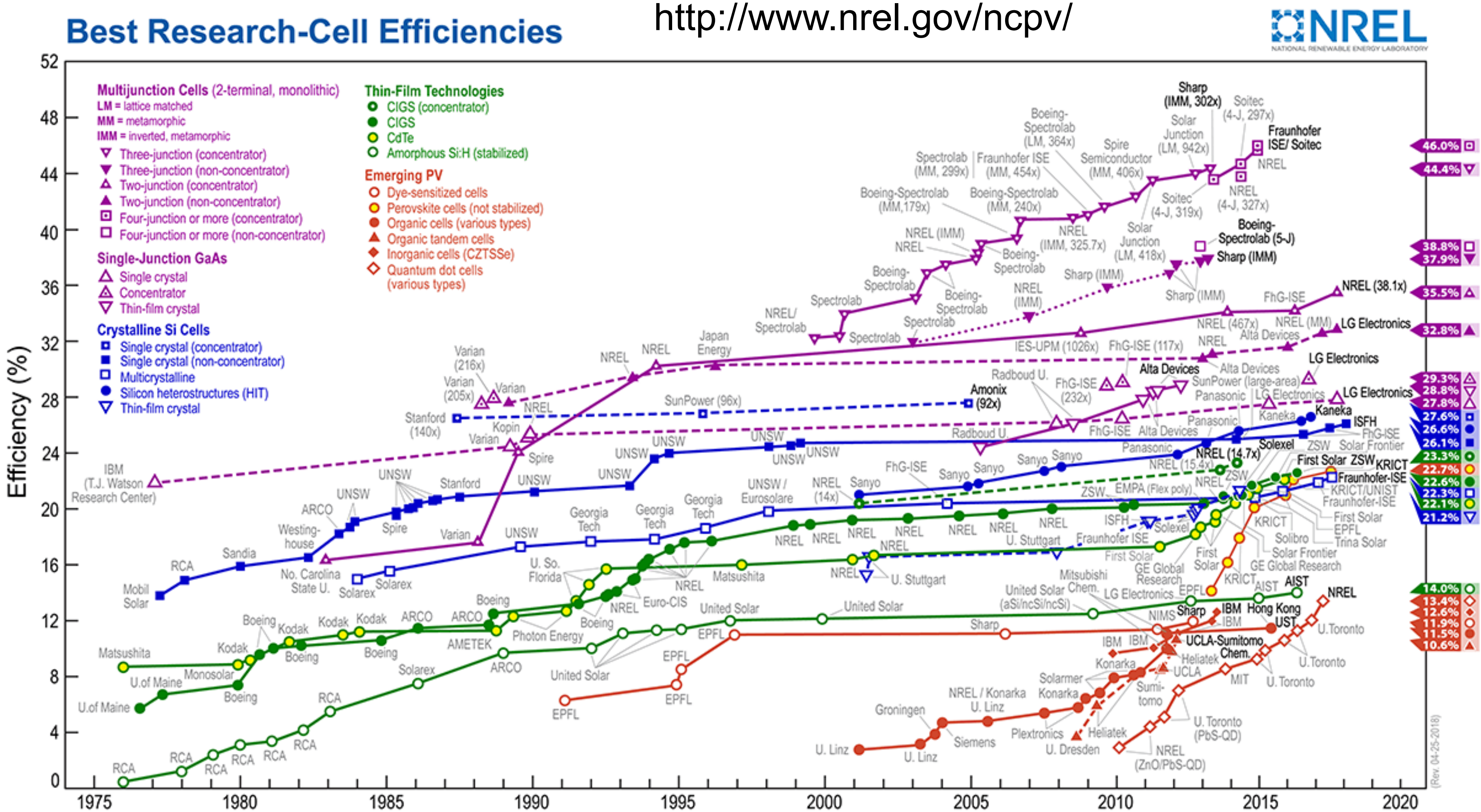
3.7% Stored/ Harvestable

Efficiencies from Current Opinion in Biotechnology 2008, 19:153–159

Image from: http://commons.wikimedia.org/wiki/File:Rain_forest_NZ.JPG

NREL National Center for Photovoltaics

http://www.nrel.gov/ncpv/



Observation #2: Lots of different cell-types!

Cell-Type Classifications

Crystallinity

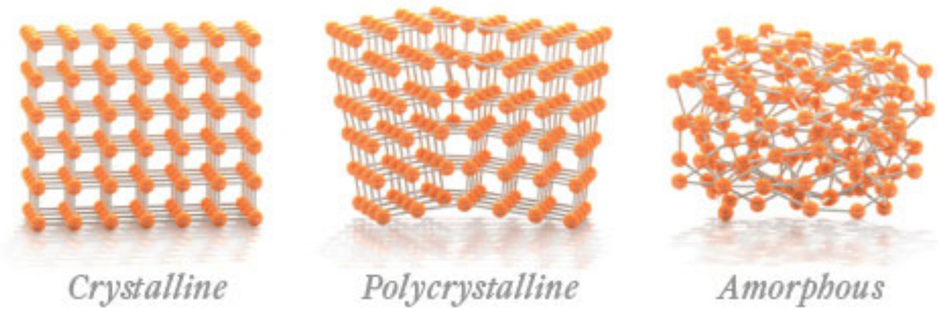
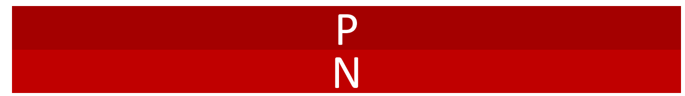


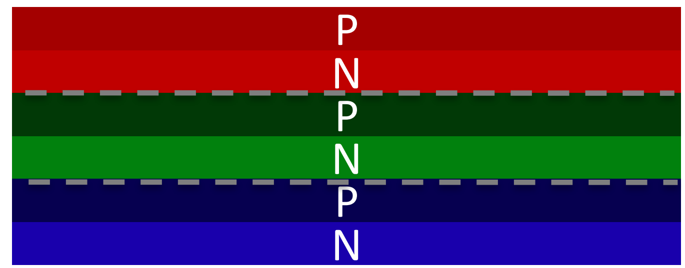
Image from: http://spectrum.ieee.org/image/1838375

Number of Junctions

Single-Junction:



Multi-Junction:



Small Bandgap

Medium Bandgap

Large Bandgap

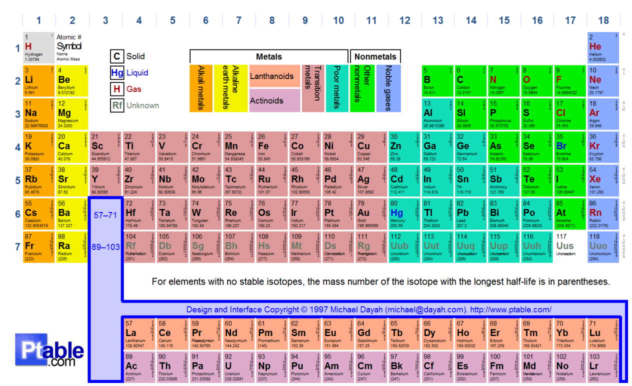
Thick Crystal or Thin Film

Thin-Film

Thick Crystal

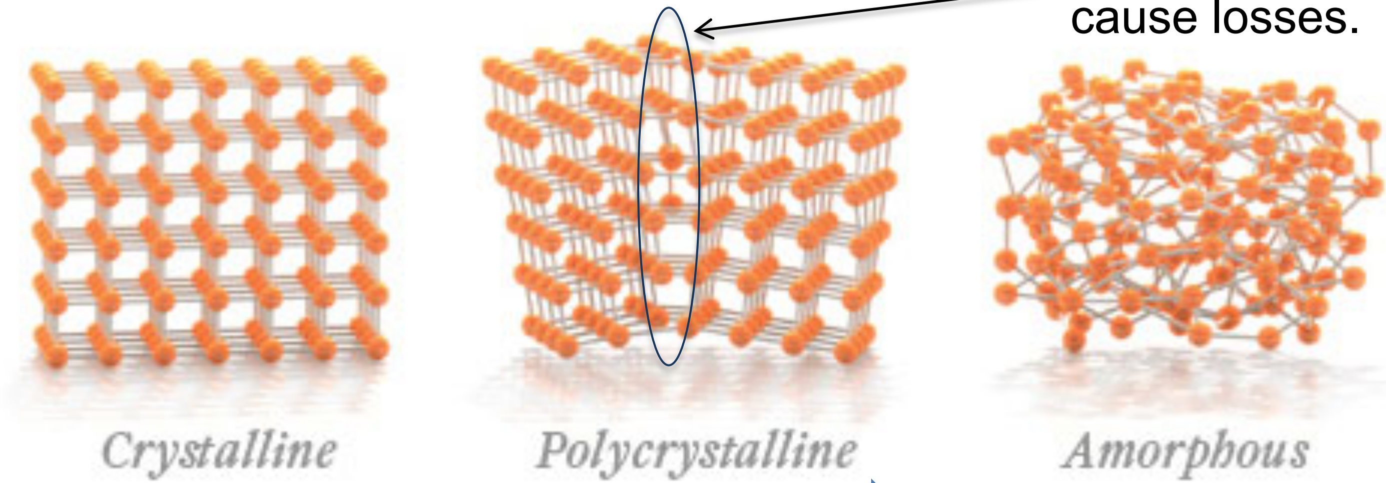
Composition

Periodic Table of Elements



Crystallinity

Defects slow charges and cause losses.



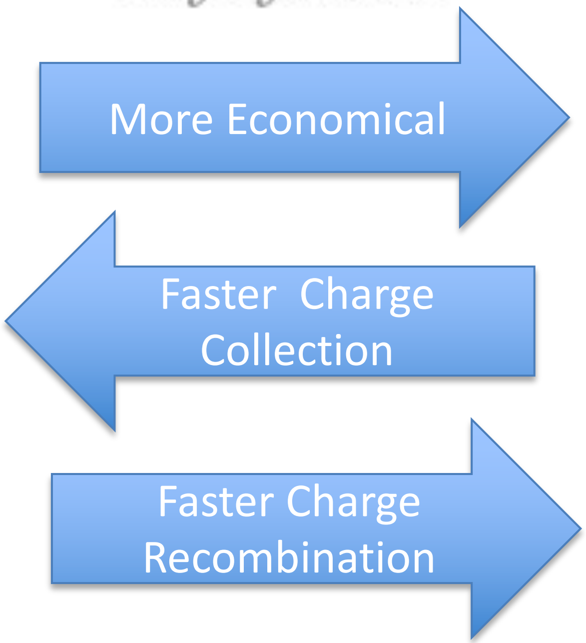
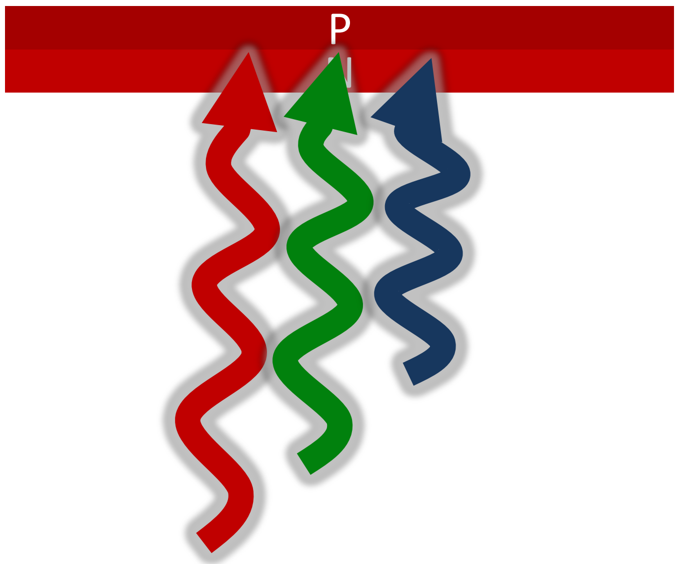


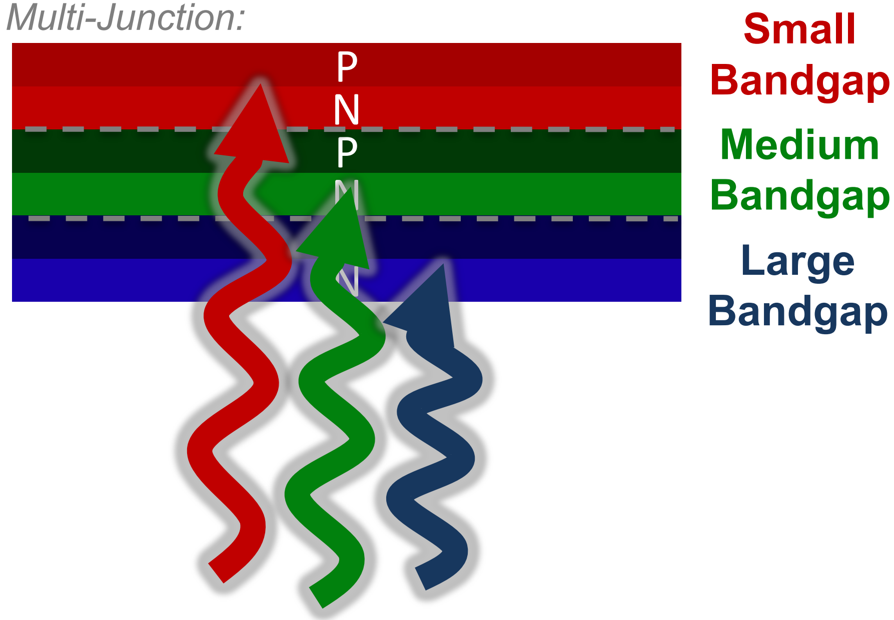
Image from: http://spectrum.ieee.org/image/1838375

Number of Junctions

Single-Junction:



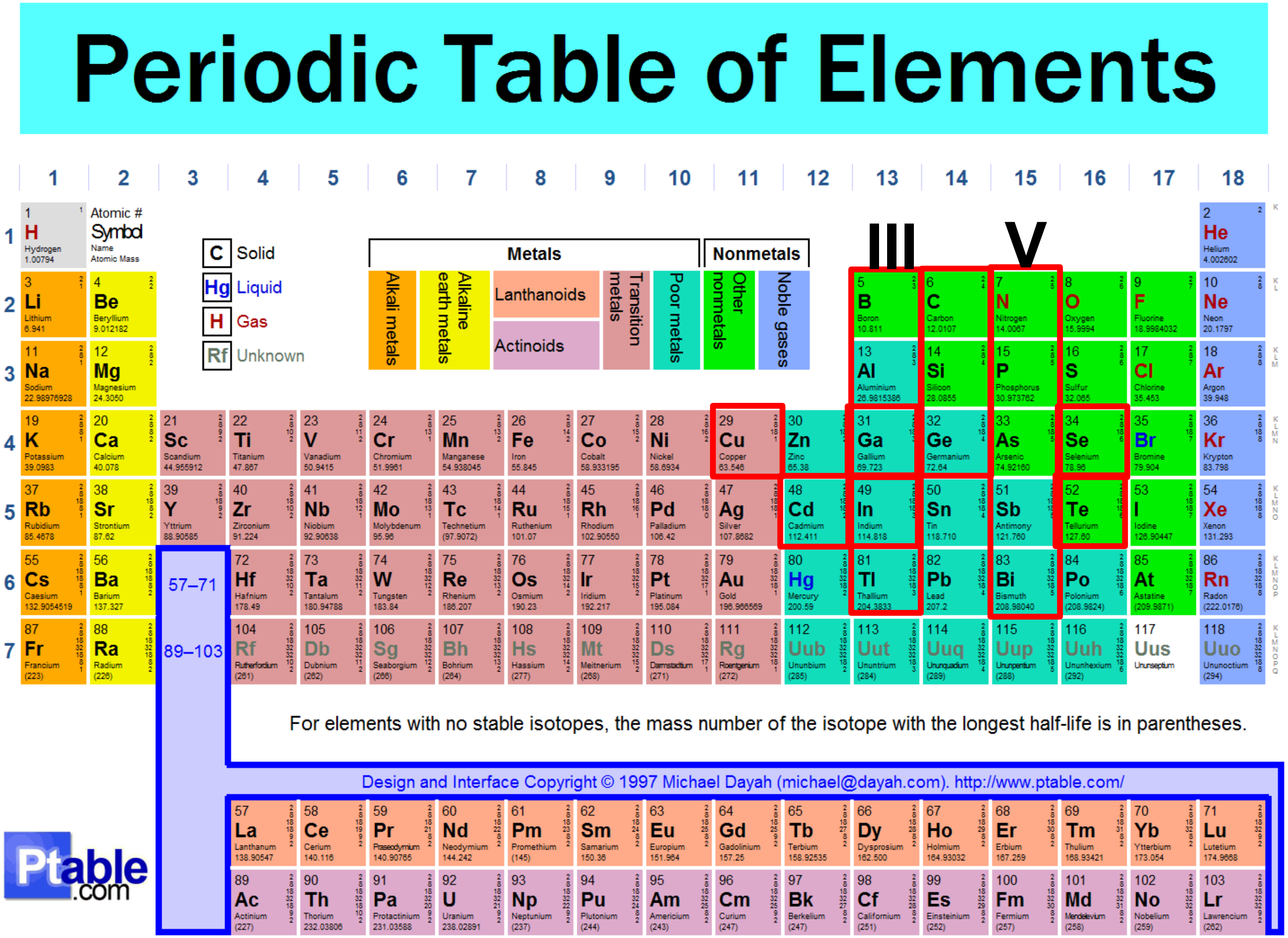
Multi-Junction:



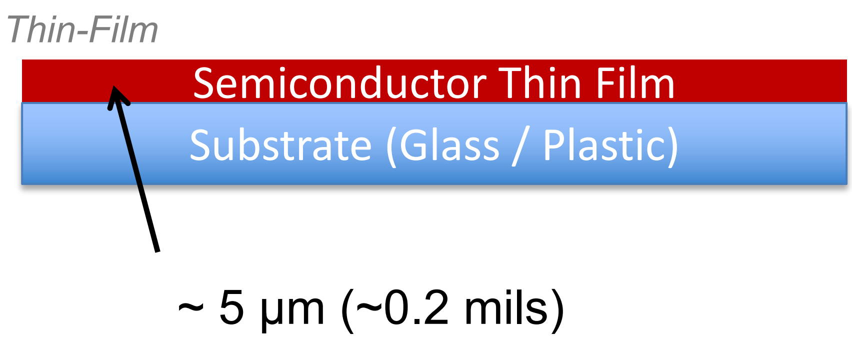
- ❑ When the photon energy > band gap, extra energy is wasted.
- ❑ For example, a blue photon produces same energy as red photon).
- ❑ Maximum efficiency ~30%.

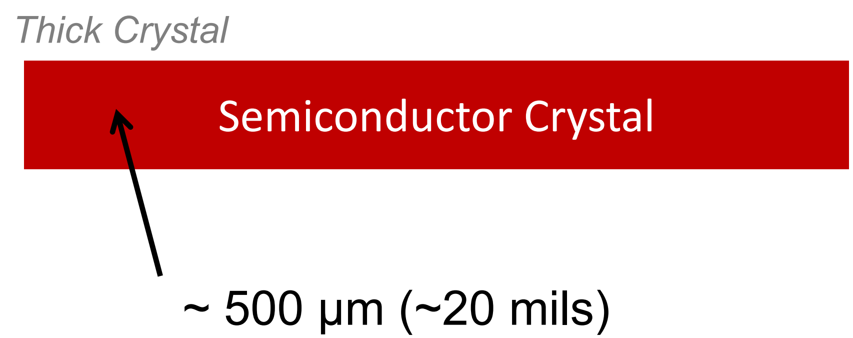
- ❑ In multi-junction cell, blue photon can produce more energy than red photon.
- ❑ Maximum efficiency ~50% (for 3 cells).
- ❑ More complex fabrication → More $$$.

Composition (Different Semiconductors)



Thick Crystal or Thin Film



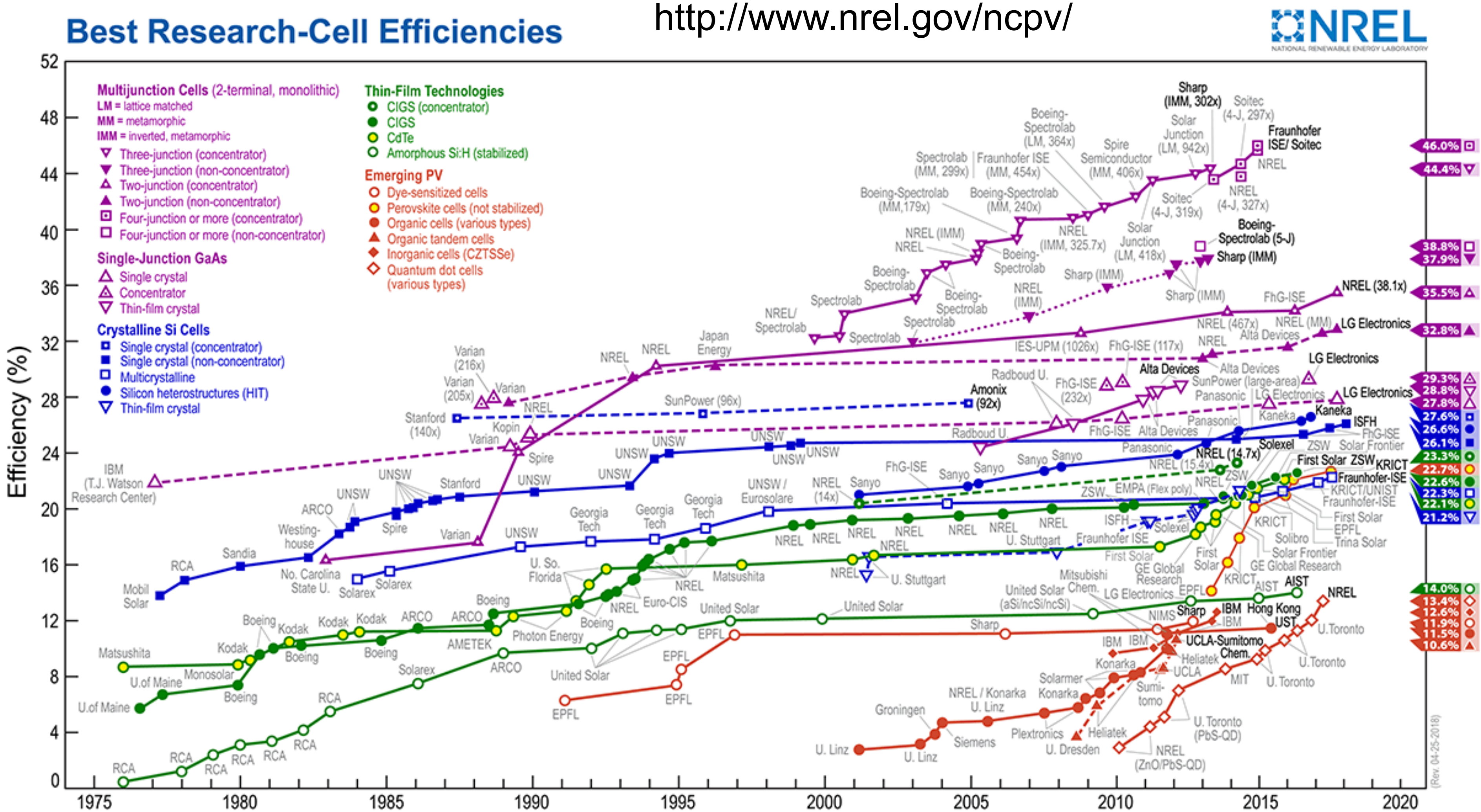


- Very thin films possible if semiconductor absorbs light strongly (depends on composition).
- Uses less material.
- Requires supporting substrate.
- Typically polycrystalline.

- Self-supporting.
- Single crystalline.

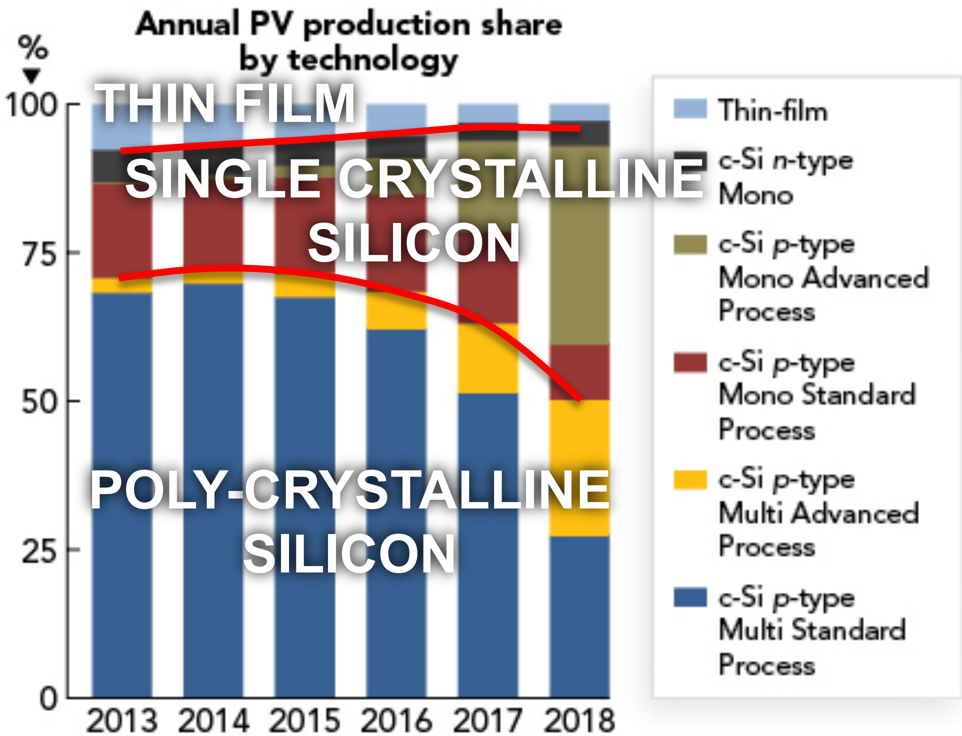
NREL National Center for Photovoltaics

http://www.nrel.gov/ncpv/



Observation #2: Lots of different cell-types!

Only 3 of these different types have significant market share.



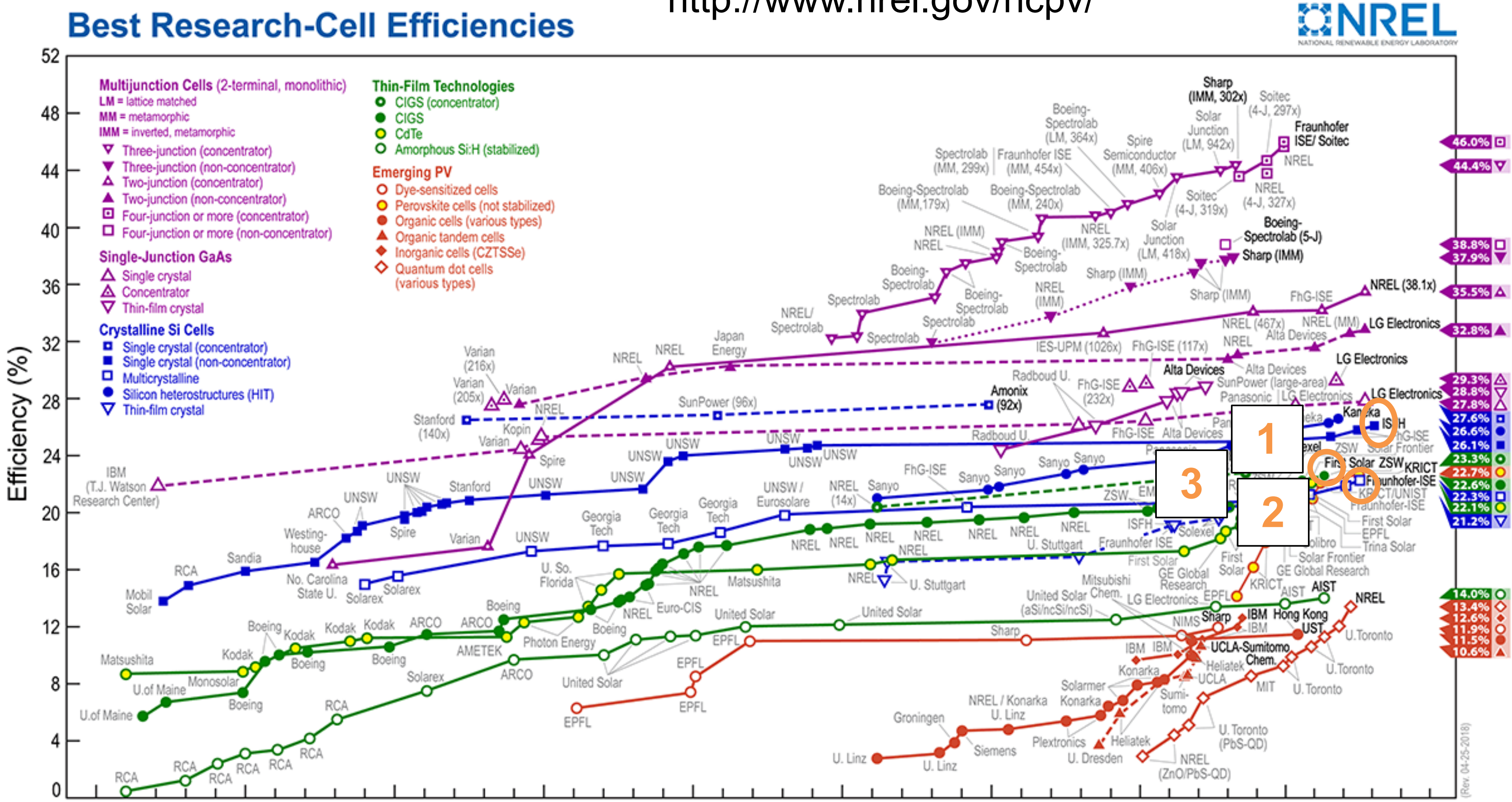
- *c-Si indicates crystalline silicon where*
  - *mono = single crystalline*
  - *multi = poly crystalline*
- *n,p refers to doping of the original silicon wafer*

"Until 2016, standard processed c-Si p-type solar cells dominated PV production; during 2017, p-type mono cells have increased market-share contributions in addition to advanced process flows including PERC cells."

Data source: INDUSTRIAL LASER SOLUTIONS FOR MANUFACTURING

More Detailed Comparison

http://www.nrel.gov/ncpv/



Single-Junction Single-Crystal Si Solar Cells

Crystallinity

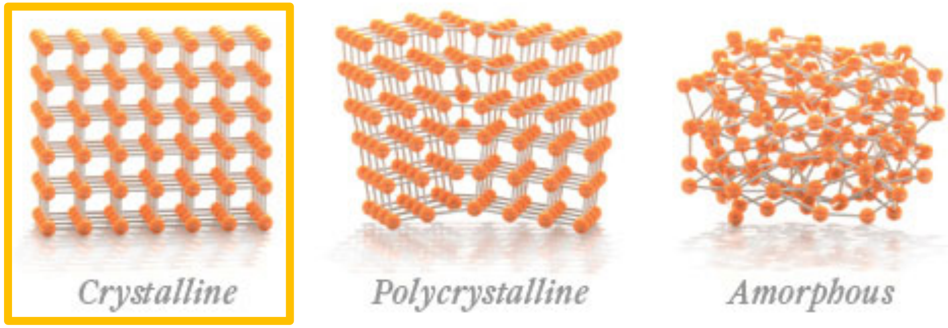
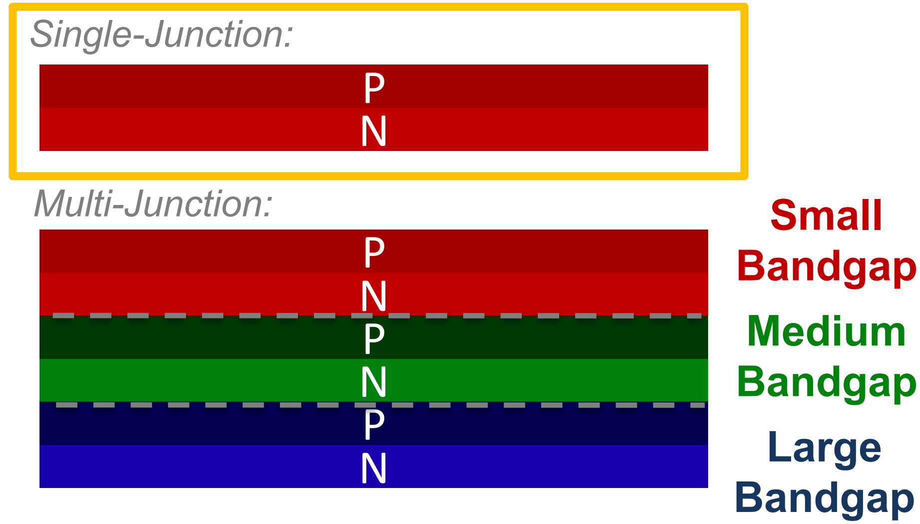
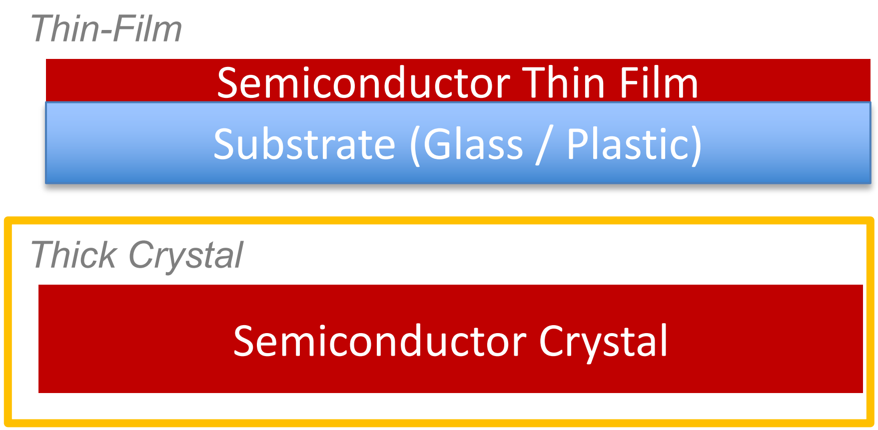


Image from: http://spectrum.ieee.org/image/1838375

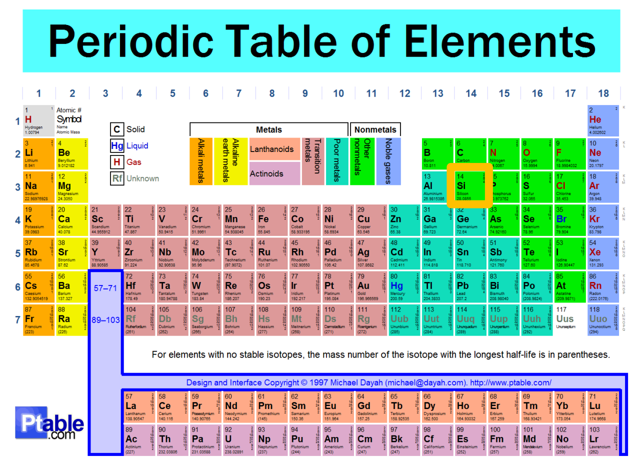
Number of Junctions



Thick Crystal or Thin Film



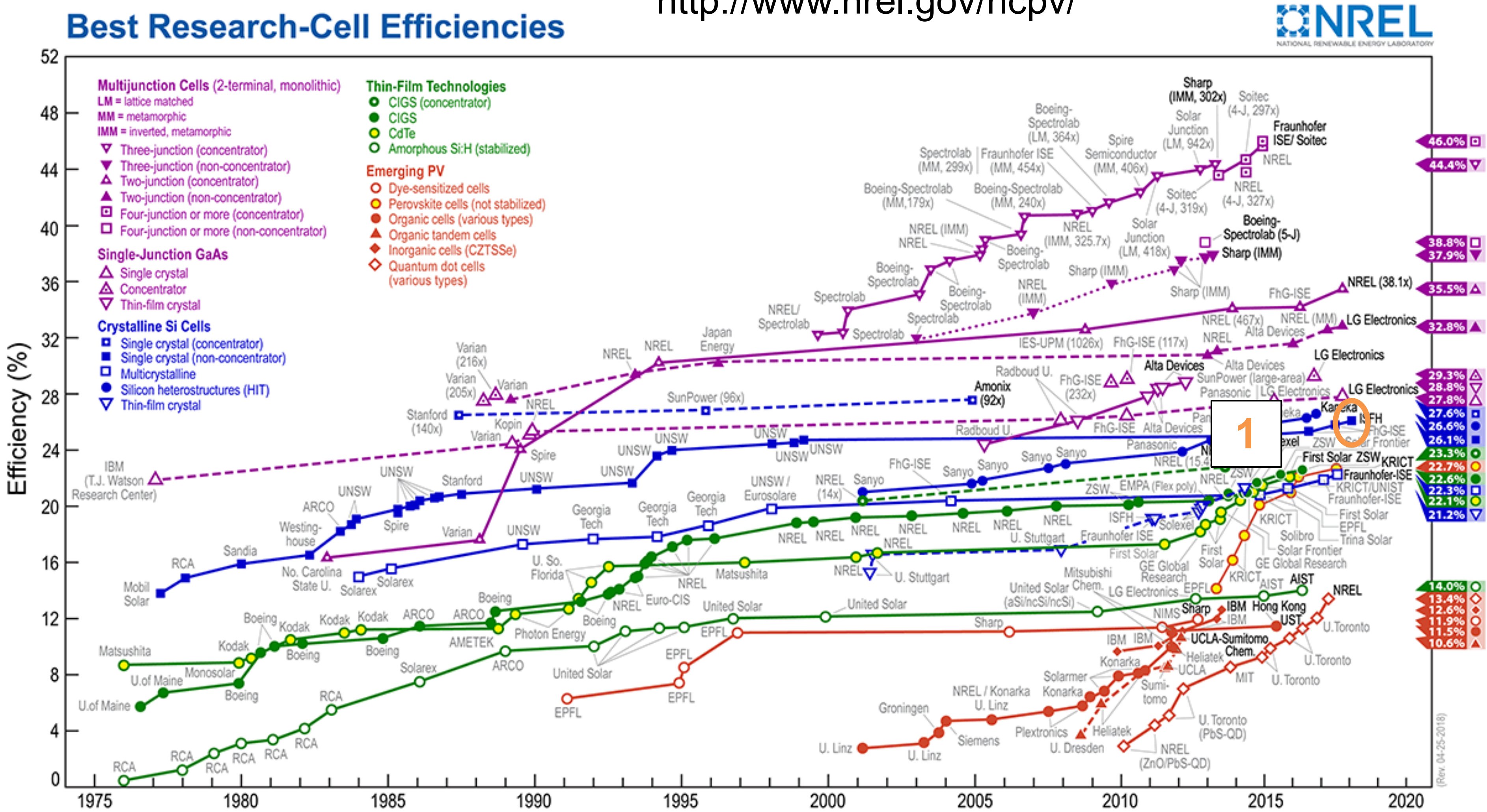
Composition



1

Efficiency ~ 26%

http://www.nrel.gov/ncpv/



Challenge: *Expensive Manufacturing*

Polycrystalline Si
> 99.9999%

1400 °C

Single crystalline Si

http://www.youtube.com/watch?v=aWVywhzuHnQ&NR=1
(start @ 1:48)

Single-Junction Polycrystalline-Crystal Si Cells

Crystallinity

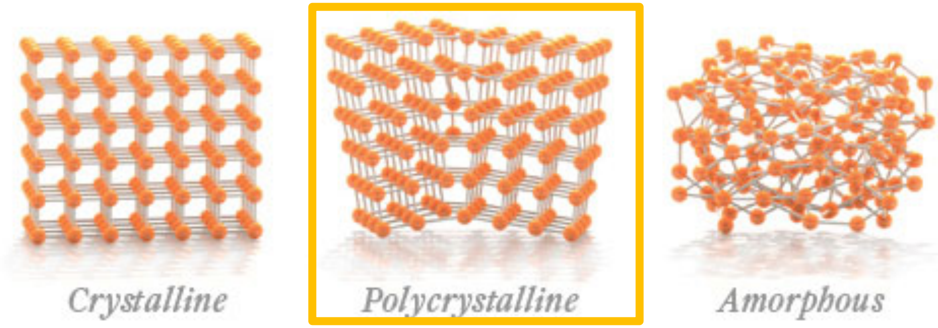


Image from: http://spectrum.ieee.org/image/1838375

Number of Junctions

Single-Junction:

P
N

Multi-Junction:

P
N
P
N
P
N

Small Bandgap

Medium Bandgap

Large Bandgap

Thick Crystal or Thin Film

Thin-Film

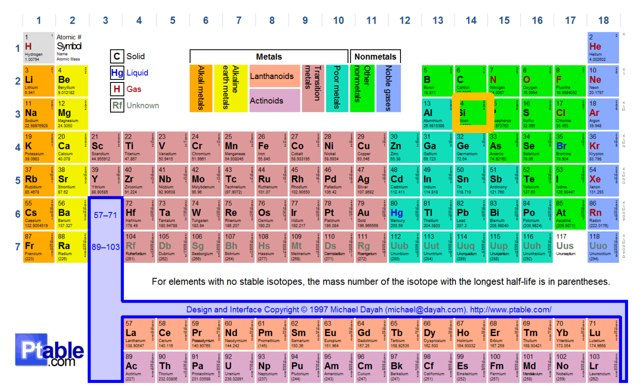
Semiconductor Thin Film
Substrate (Glass / Plastic)

Thick Crystal

Semiconductor Crystal

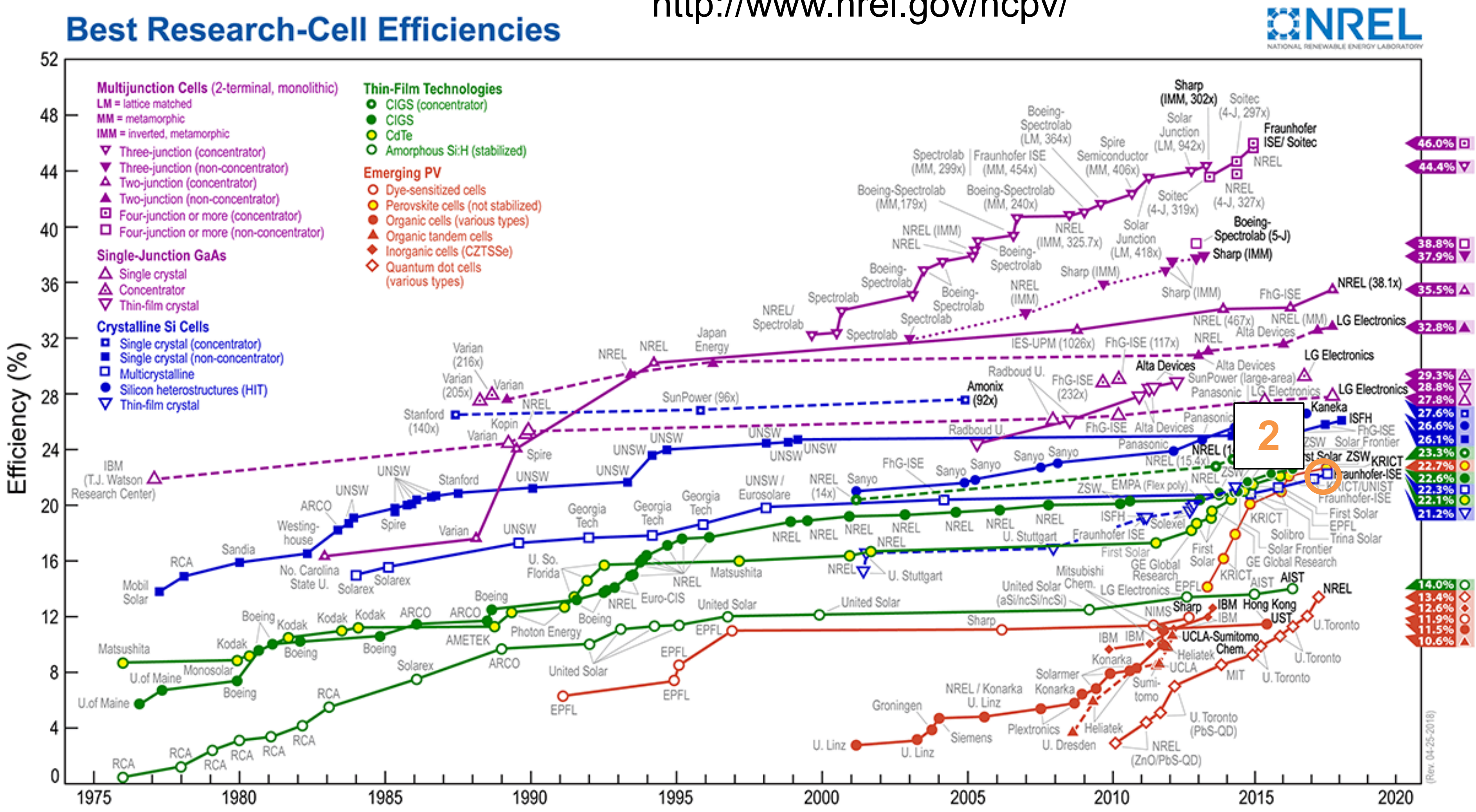
Composition

Periodic Table of Elements



Efficiency ~ 22%

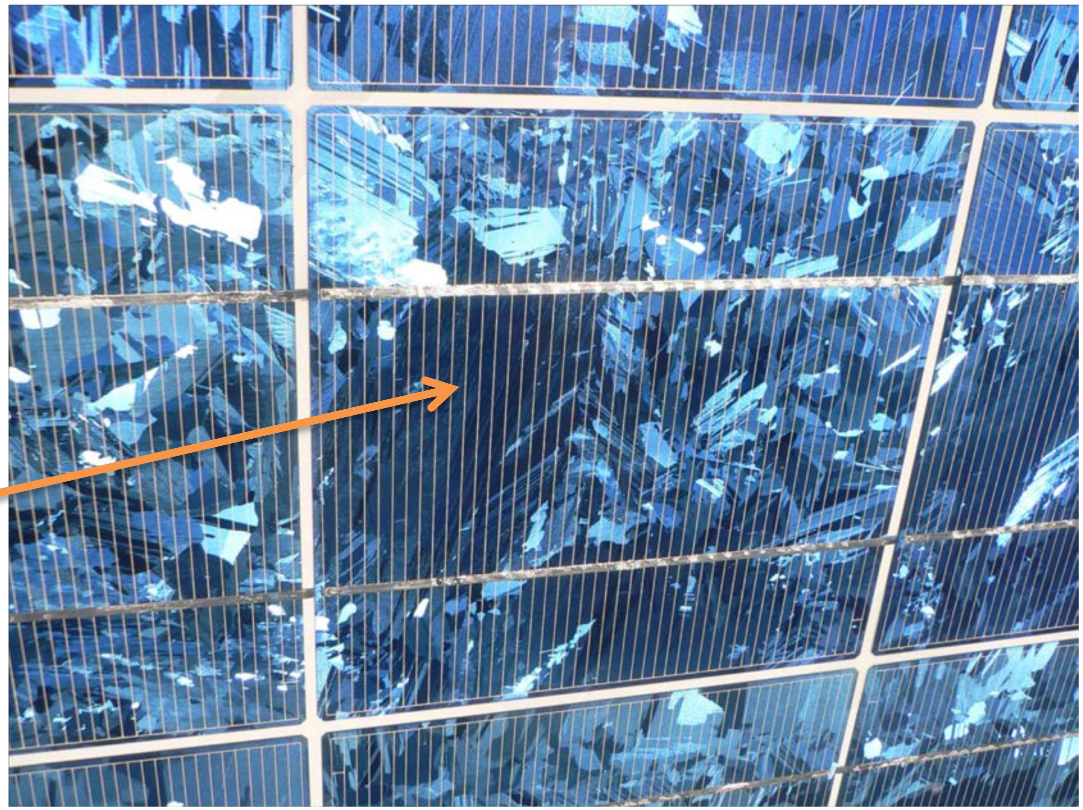
http://www.nrel.gov/ncpv/



Lower Processing Costs

Deposition by chemical vapor deposition: SiH_4 (g) → Si (s) + $2H_2$ (g), 650 °C

Grains



- Lower cost due to lower temperature processing but lower efficiency due to loss at grain boundaries.

Image from: http://upload.wikimedia.org/wikipedia/commons/1/15/Polycristalline-silicon-wafer_20060626_568.jpg

Single-Junction Polycrystalline-Crystal Thin Film Cells (e.g. CdTe)

Crystallinity

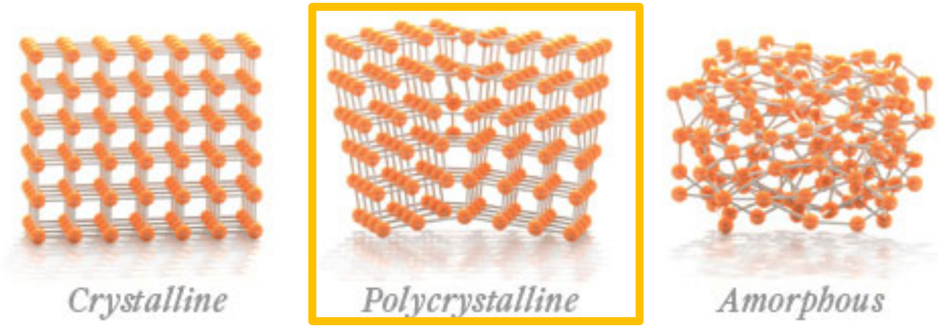
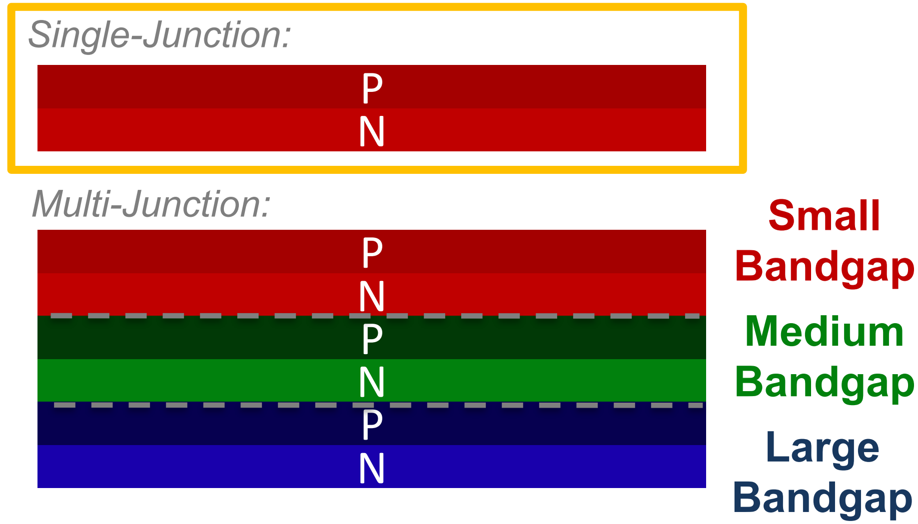
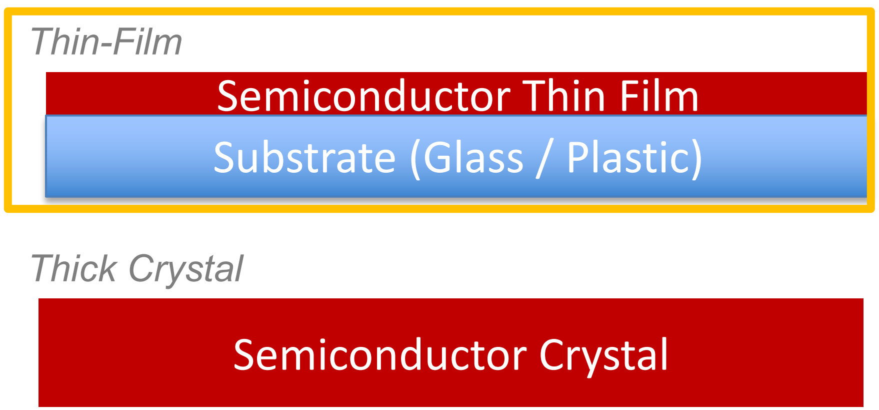


Image from: http://spectrum.ieee.org/image/1838375

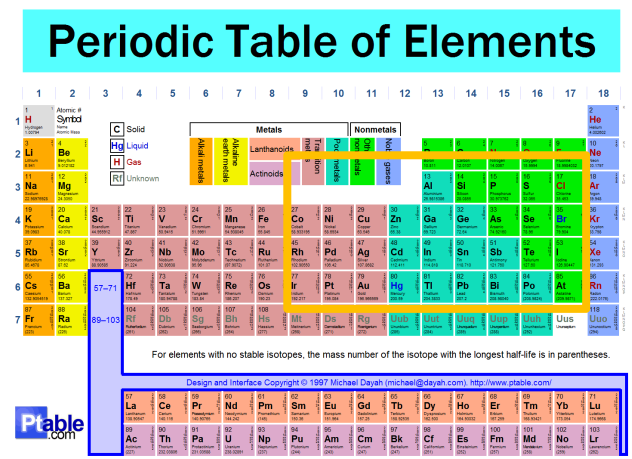
Number of Junctions



Thick Crystal or Thin Film



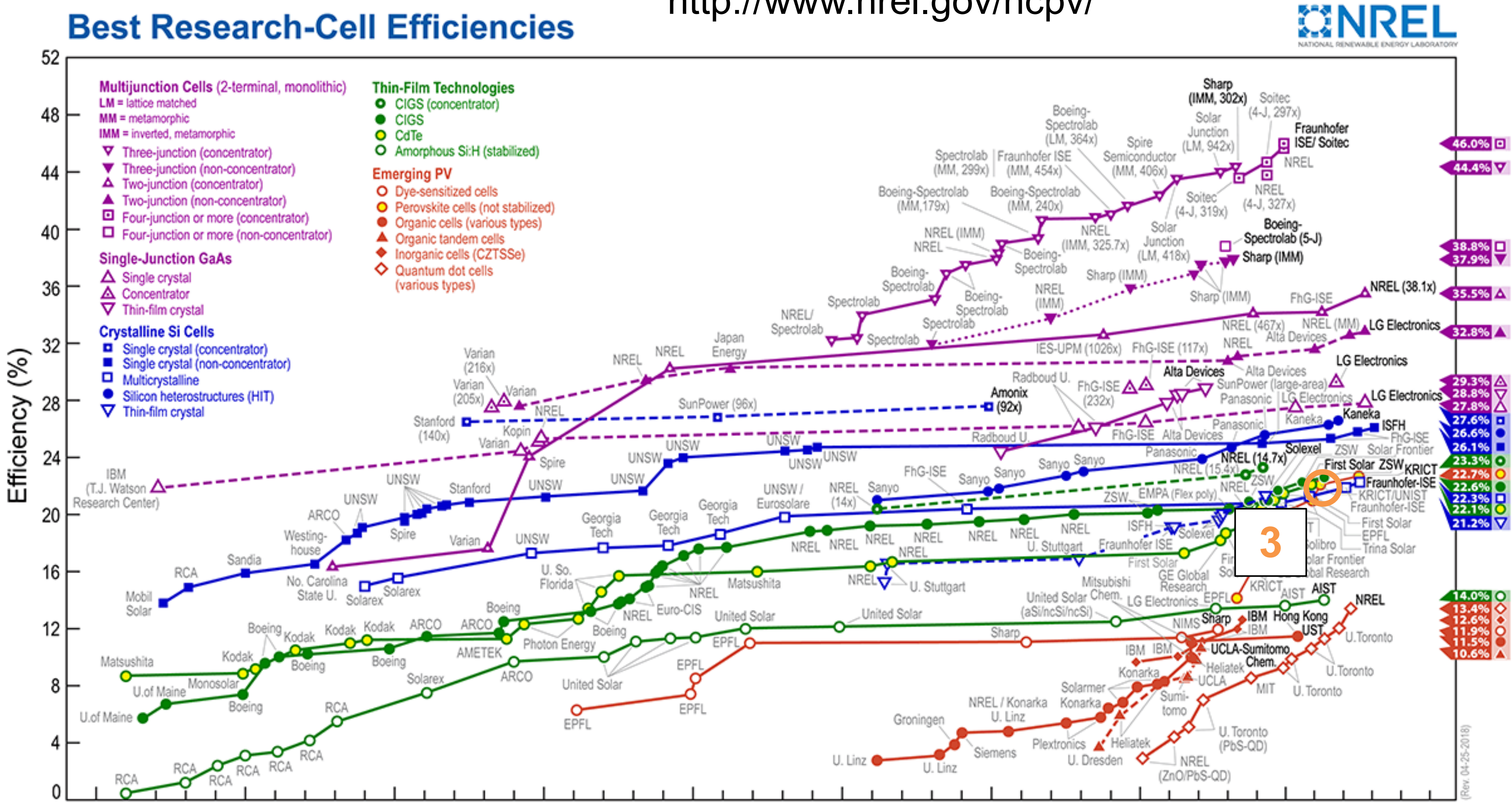
Composition



3

Efficiency ~ 22-23%

http://www.nrel.gov/ncpv/



Lower Processing and Materials Costs: *Vapor Deposited, Thin Films*

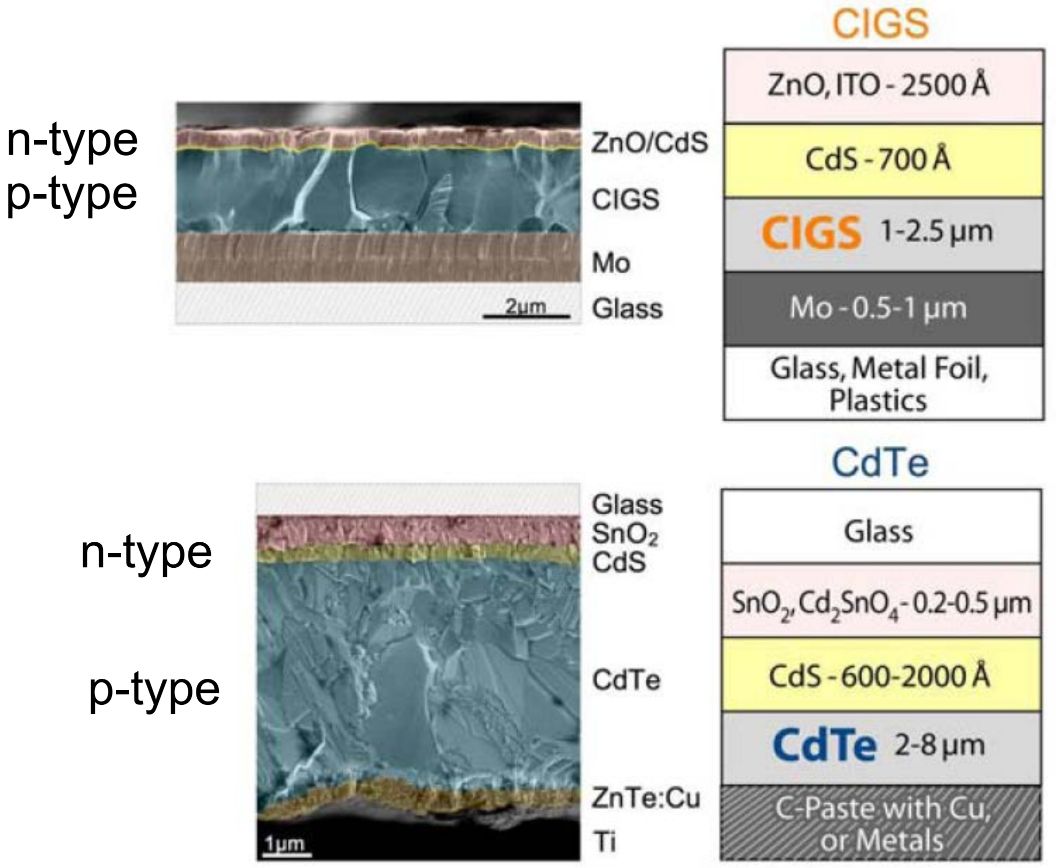
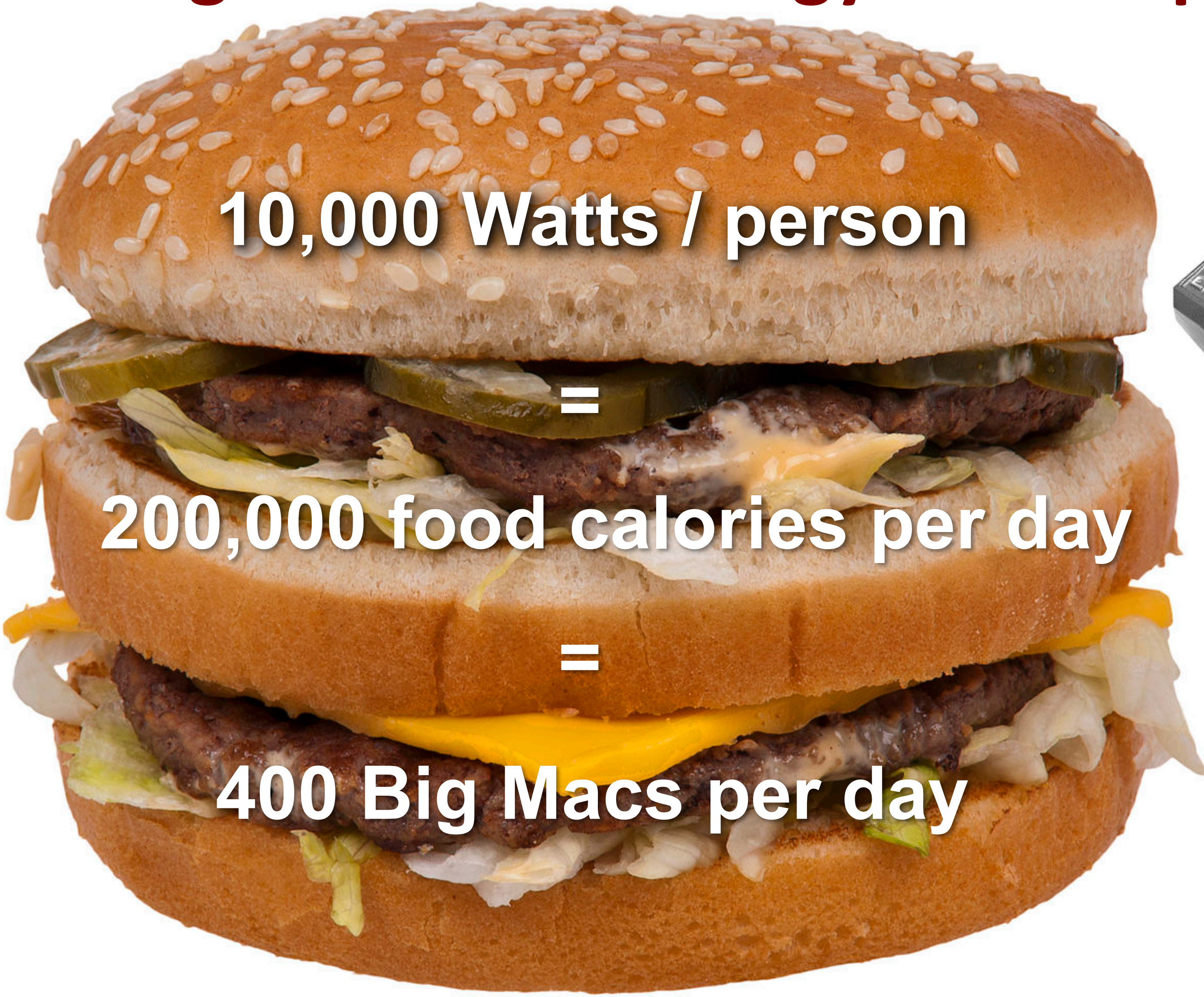


Fig. 1. CdTe and CIGS Device Structure

from: Noufi and Zweibel, IEEE 4th WCPEC-4 (2006)

Revisiting Per Person Energy Consumption



10,000 Watts / person

=

200,000 food calories per day

=

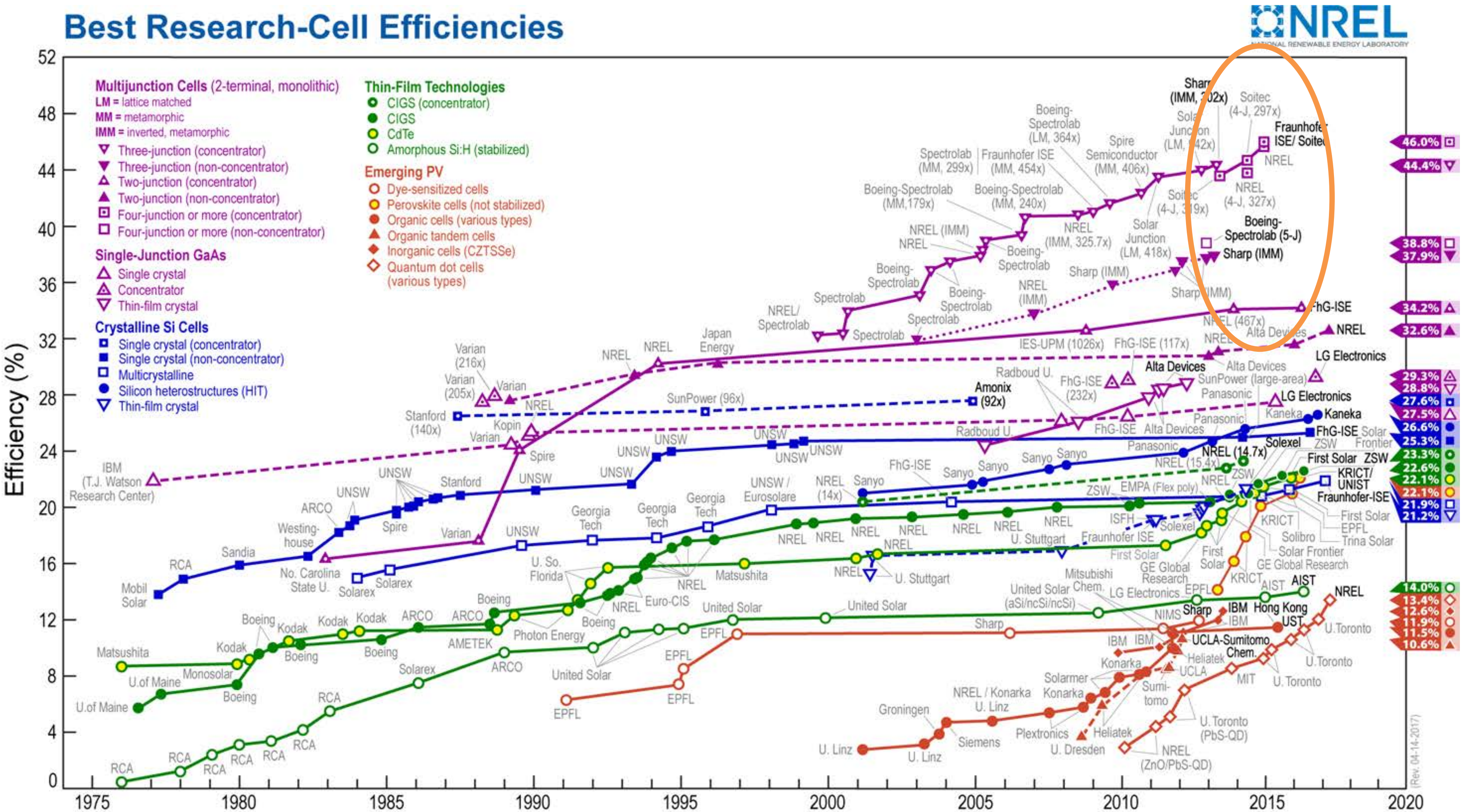
400 Big Macs per day

Other Types of Solar Cells

Technologies on the periphery.

What did I just read in the news about a new discovery in solar cells and is it actually promising?

Advantage: *Work Record Efficiencies (46%)*



Multi-Junction Solar Cells

Crystallinity

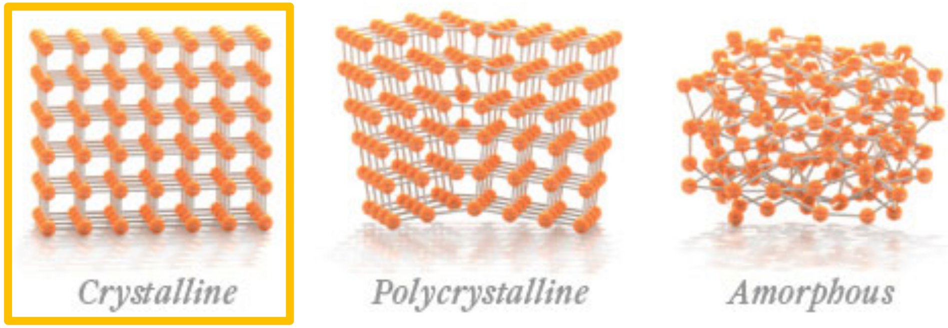


Image from: http://spectrum.ieee.org/image/1838375

Number of Junctions

Single-Junction:

P
N

Multi-Junction:

P
N
P
N
P
N

Small Bandgap

Medium Bandgap

Large Bandgap

Thick Crystal or Thin Film

Thin-Film

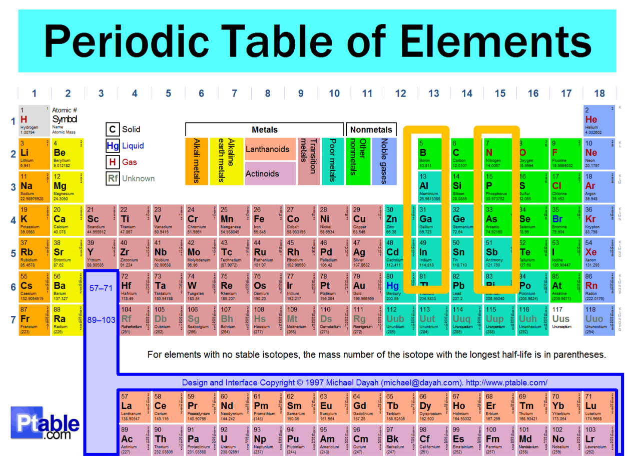
Semiconductor Thin Film

Substrate (Glass / Plastic)

Thick Crystal

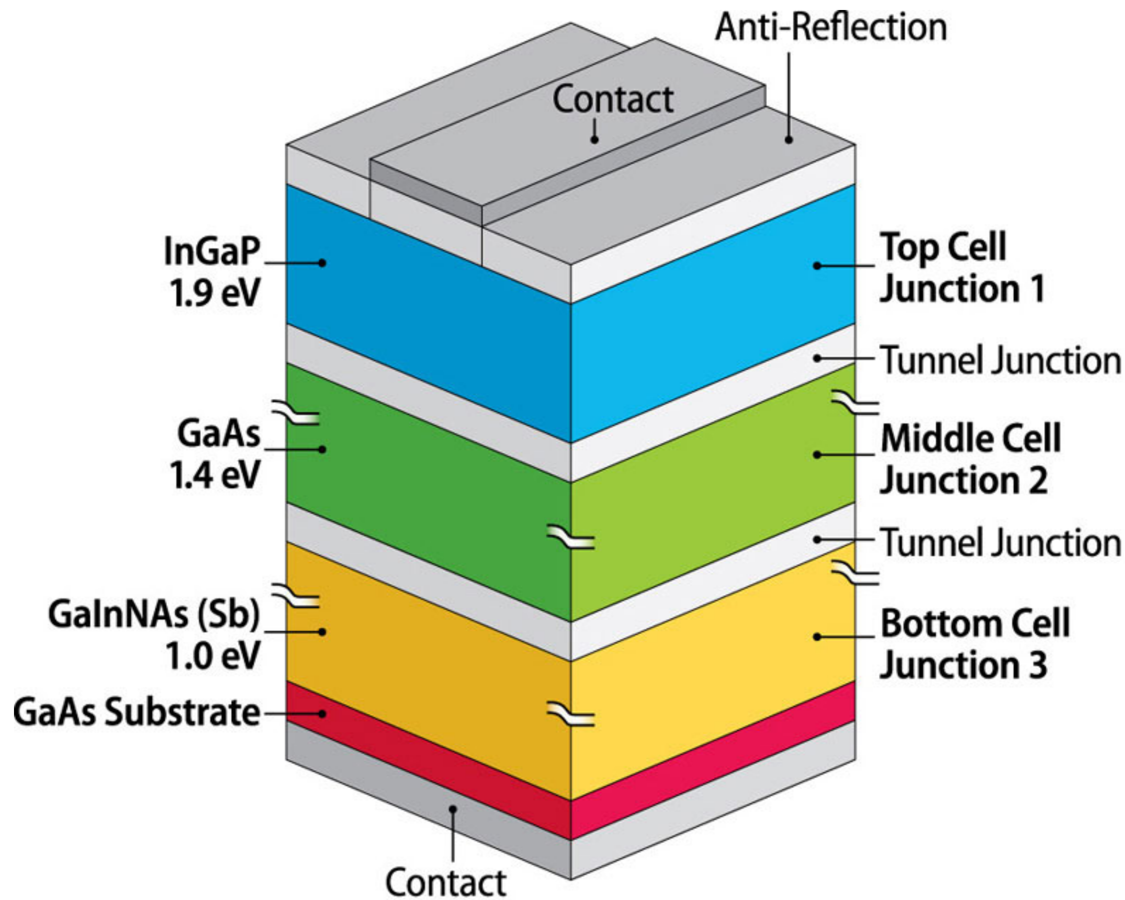
Semiconductor Crystal

Composition



Example: *Near-World Record Multi-Junction Cell*

- ❑ Solar Junctions
- ❑ 43.5% (2012)
- ❑ Recent advances in efficiency due to ability to grow new unique combinations of materials on top of one-another.



from: http://www.nrel.gov/continuum/spectrum/awards.cfm

Disadvantage: *Very Costly*

Many layers of P- and N- doped III,V semiconductors

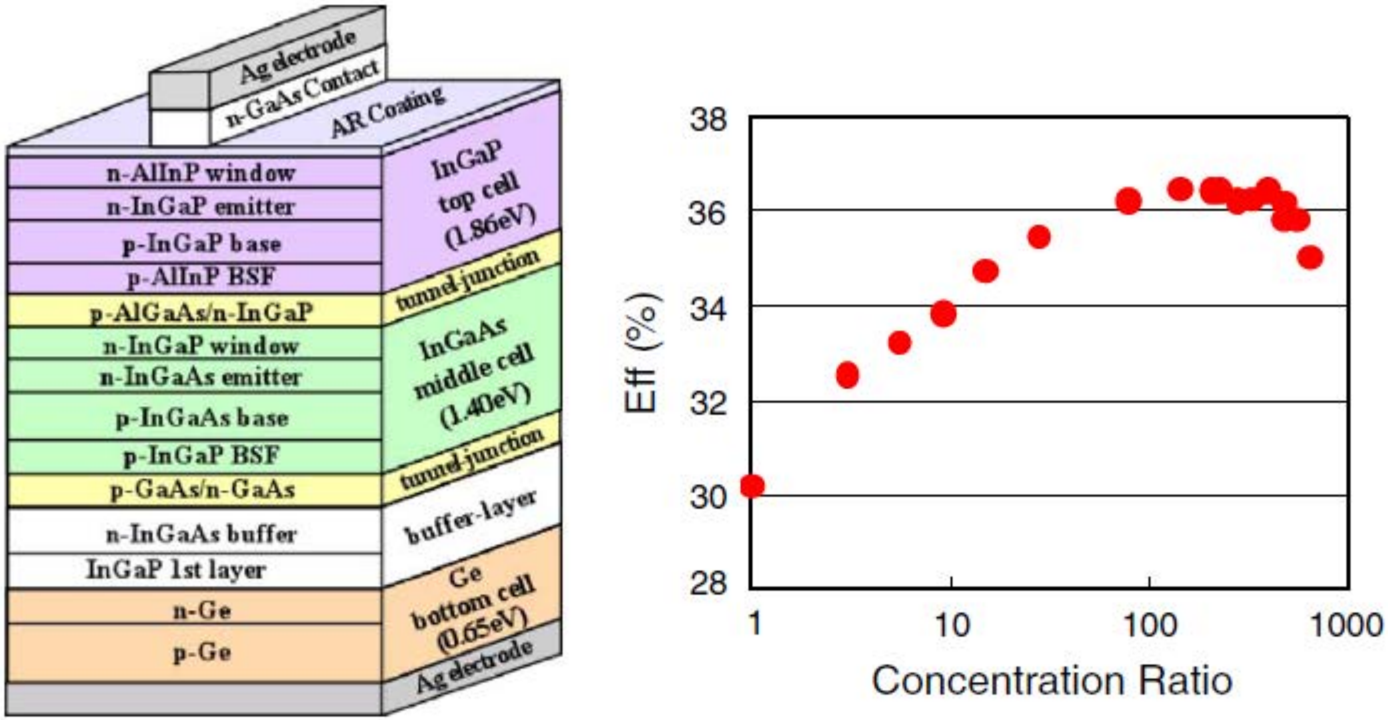
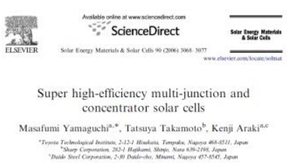


Fig. 5. A schematic cross section of a high-efficiency InGaP/InGaAs/Ge 3-junction soar cell and efficiency of a concentrator cell as a function of concentration ratio.

■ Higher efficiency but much higher cost!


Super high-efficiency multi-junction and concentrator solar cells

Masafumi Yamaguchi, Tatsuya Takamoto, Kenji Araki

Possible Solution: *Concentrators*

- Reduce cost by using lenses to focus light from large areas into smaller solar cells

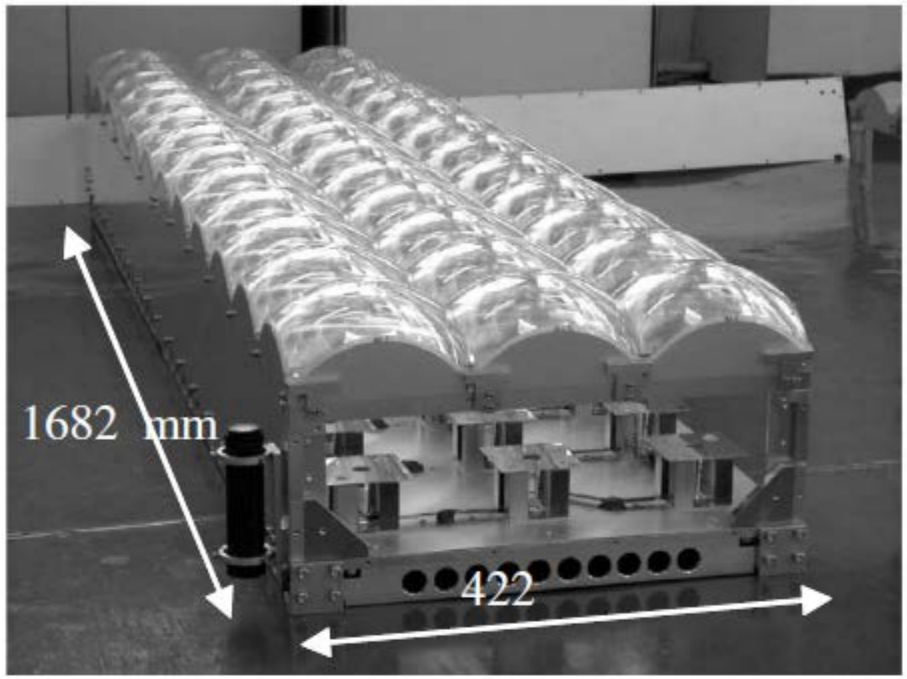
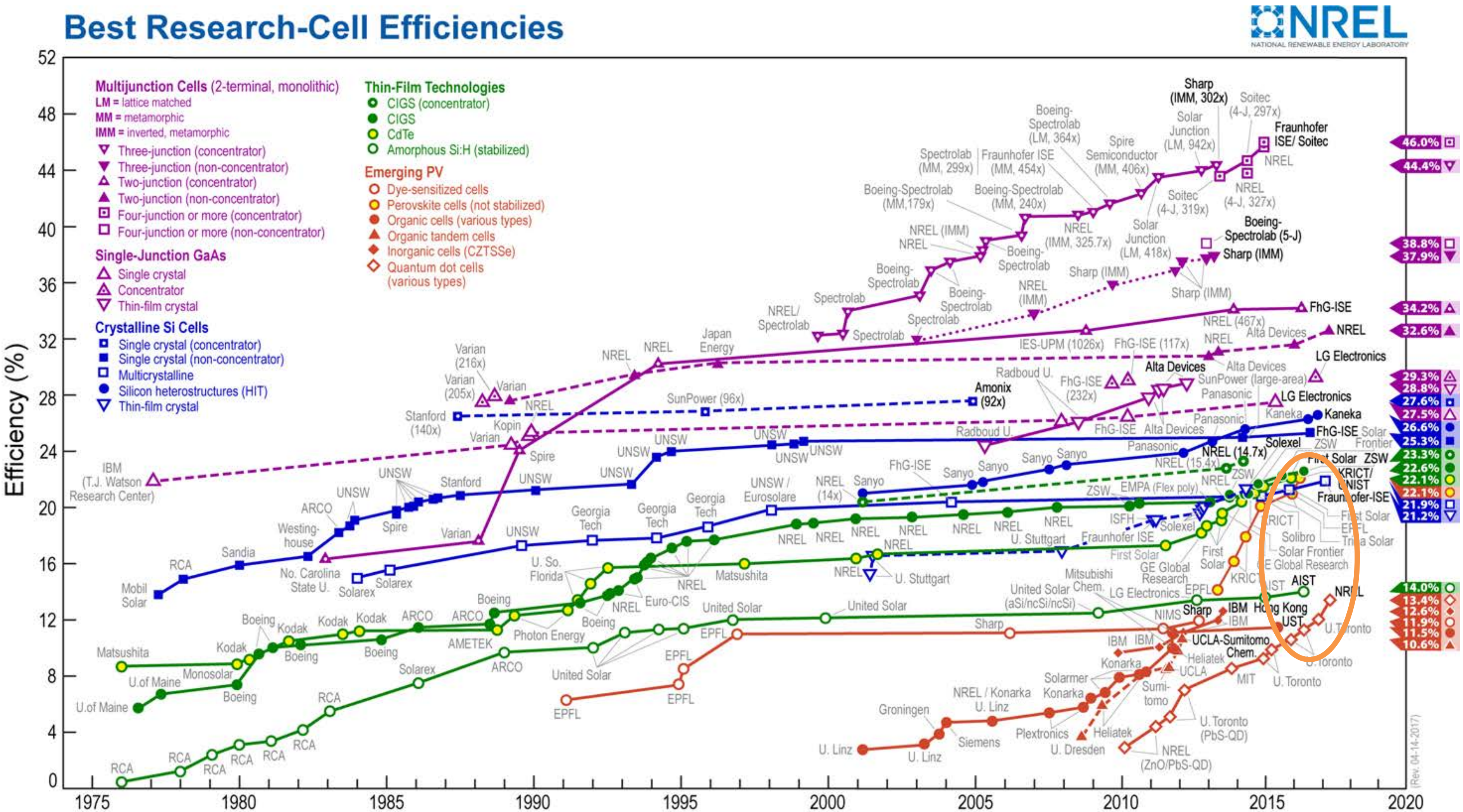


Fig. 6. 7000 cm^2 and 400X concentrator module with the 36 receivers connected in series and dome-shaped Fresnel lens made by injection mold.

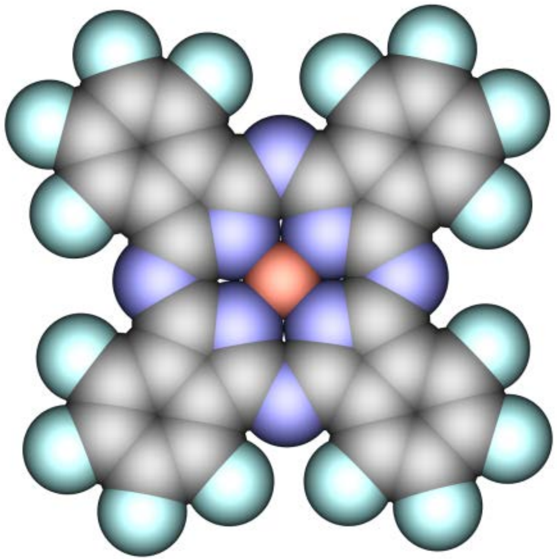
- Must track the sun to enable focusing → expensive.

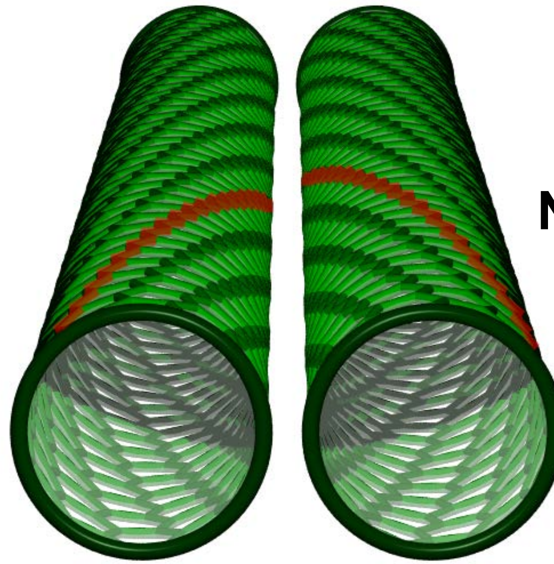
Highly Exploratory Cells



Highly Exploratory Cells: *New Materials*

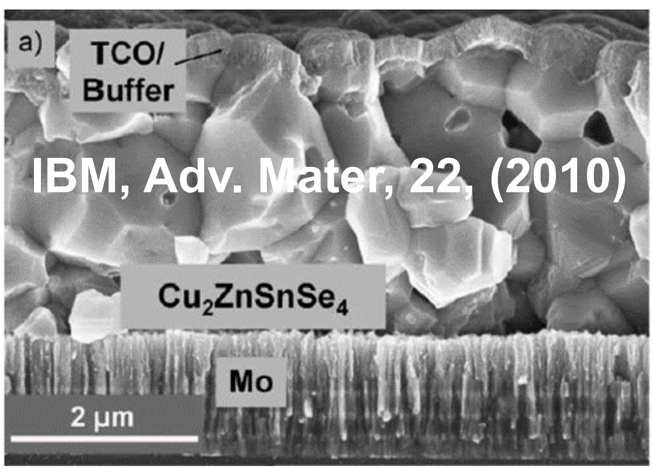
Organic molecules & polymers

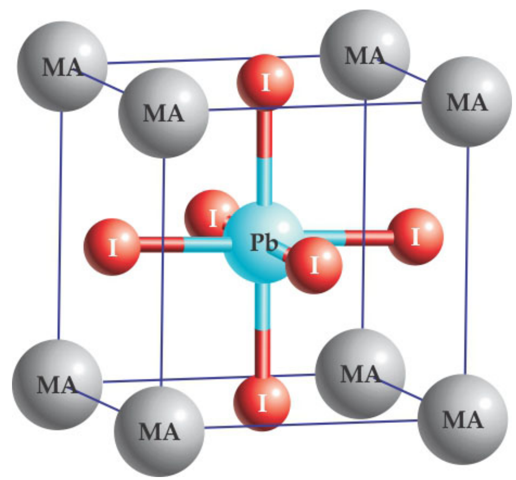




Nanotechnology (quantum dots and carbon nanotubes)

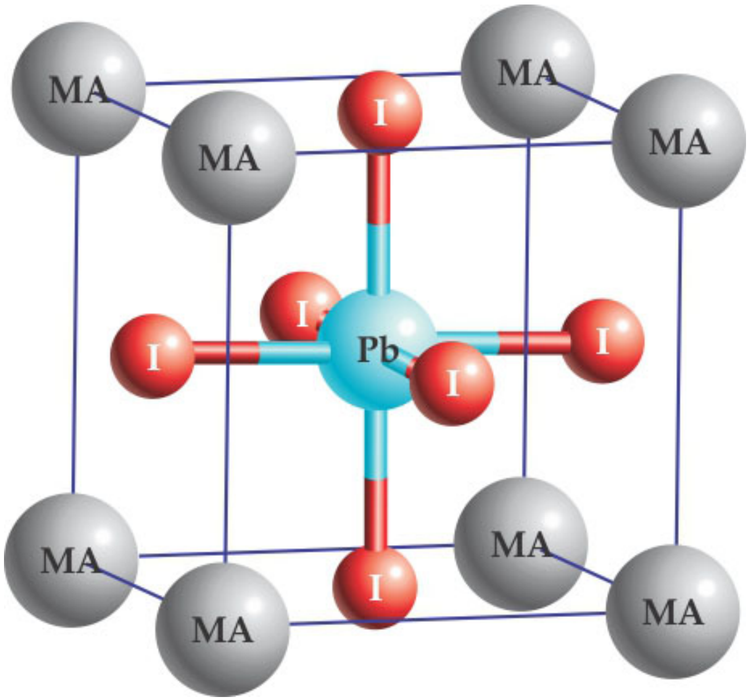
New inorganic semi-conductors





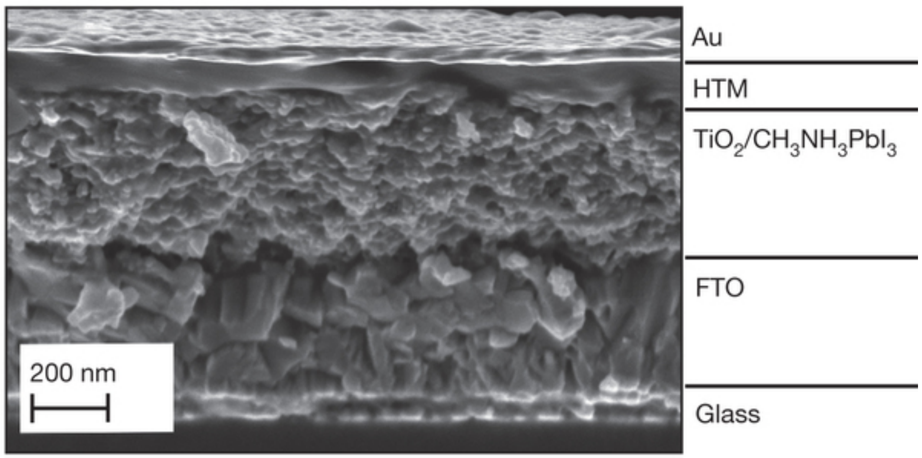
Inorganic/organic hybrid perovskites

Organic-Inorganic Hybrid Perovskites



MA = methylammonium

http://scitation.aip.org/docserver/fulltext/pt.5.7058figure1.jpg



http://www.nature.com/nature/journal/v499/n7458/images_article/nature12340-f2.jpg

- ❑ Discovered just a few years ago.
- ❑ Solution-processable → Inexpensive.
- ❑ >20% already!!!
- ❑ Stability and lifetime still an issue.

Summary

- The active materials in a photovoltaic solar cell are semiconductors.
- A junction between P-doped and N-doped semiconductors (PN junction) is used to separate the positive and negative charges generated by light → electricity.
- Photovoltaic solar cells come in several varieties:
  - Single-crystalline, polycrystalline, amorphous.
  - Single- and multi-junction.
  - Thick crystal and thin film.
  - Si, III-V, II-VI, and other compositions.
- Single- and polycrystalline single-junction Si and polycrystalline thin film single-junction CdTe are currently the most commonly installed photovoltaic technologies.

Thank You!

Are there any Questions?

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