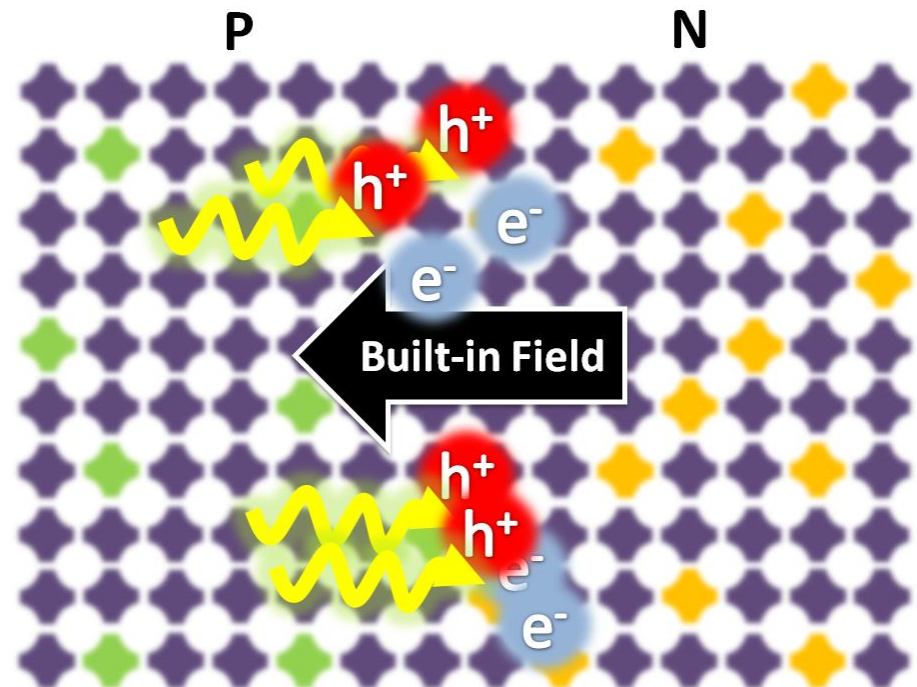




Photovoltaic Basics: *Overview and Materials Options*

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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.

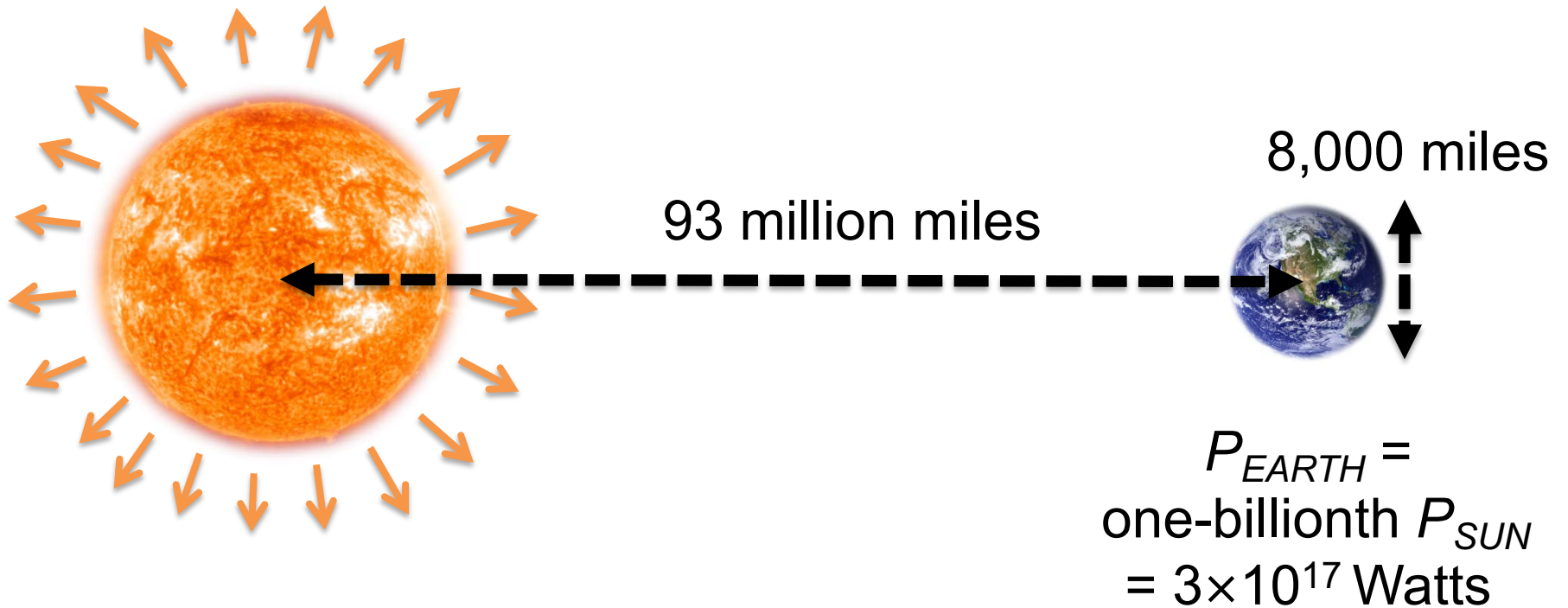


Per Person

- 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



$$T = 6000 \text{ K}$$

$$P_{SUN} = 3.9 \times 10^{26} \text{ Watts}$$

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

How much energy reaches the surface?

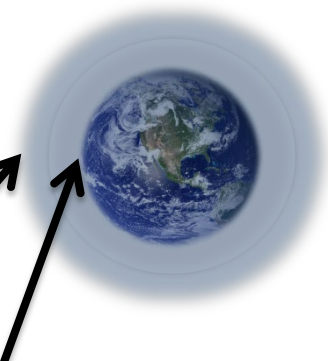
- Most of the solar radiation penetrates the outer atmosphere.



Peak intensities:

1,366 W/m²

~1,000 W/m²



Average intensities?

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

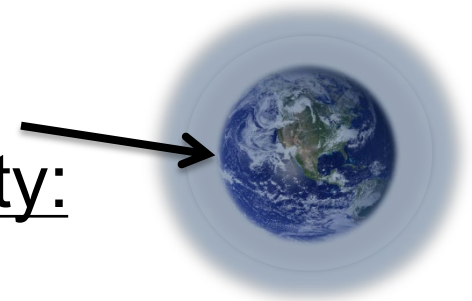


Peak intensity:

$\sim 1,000 \text{ W/m}^2$

Average intensity:

$\sim 100\text{-}300 \text{ W/m}^2$



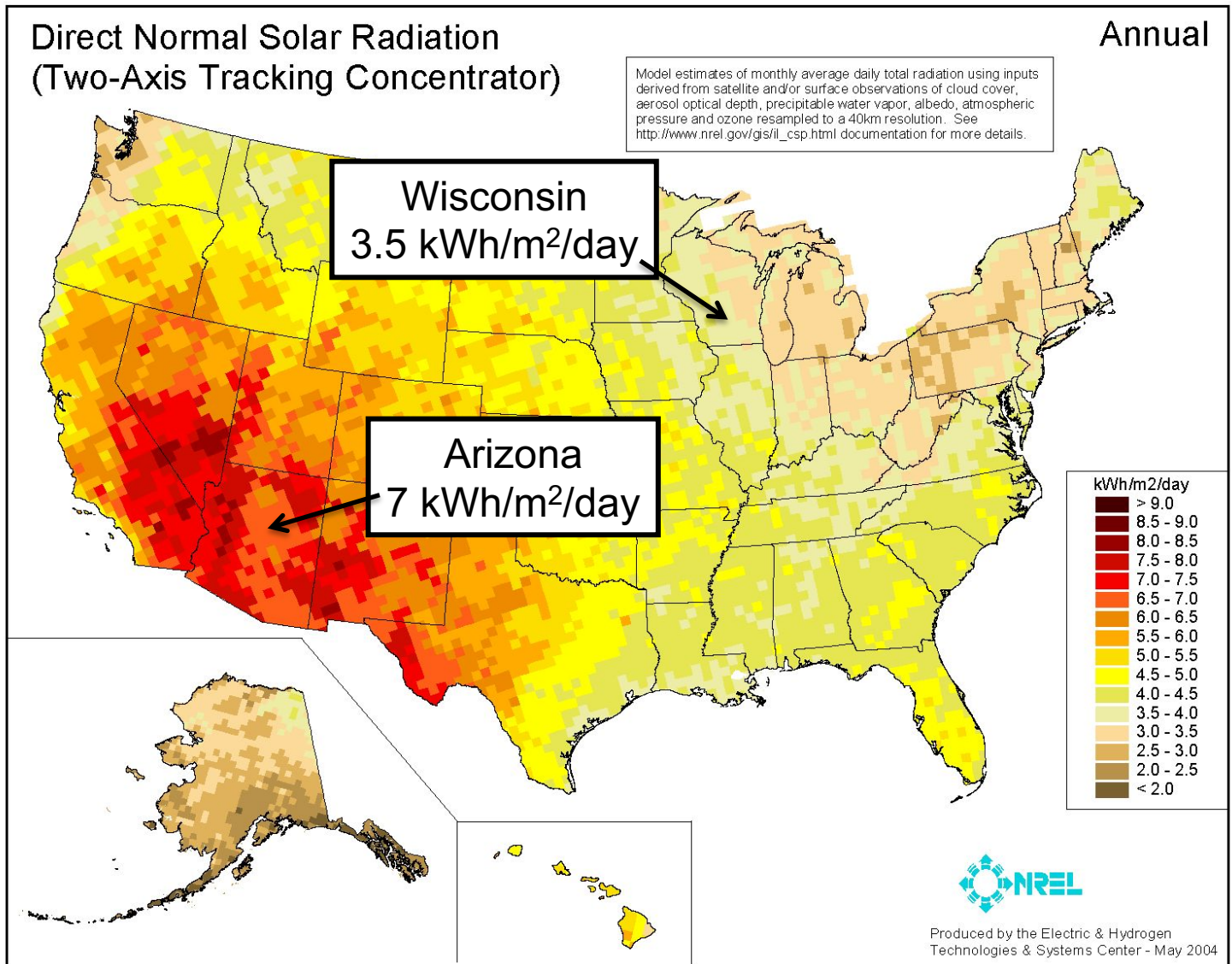
How much energy reaches us?

Yearly Sum of Global Irradiance

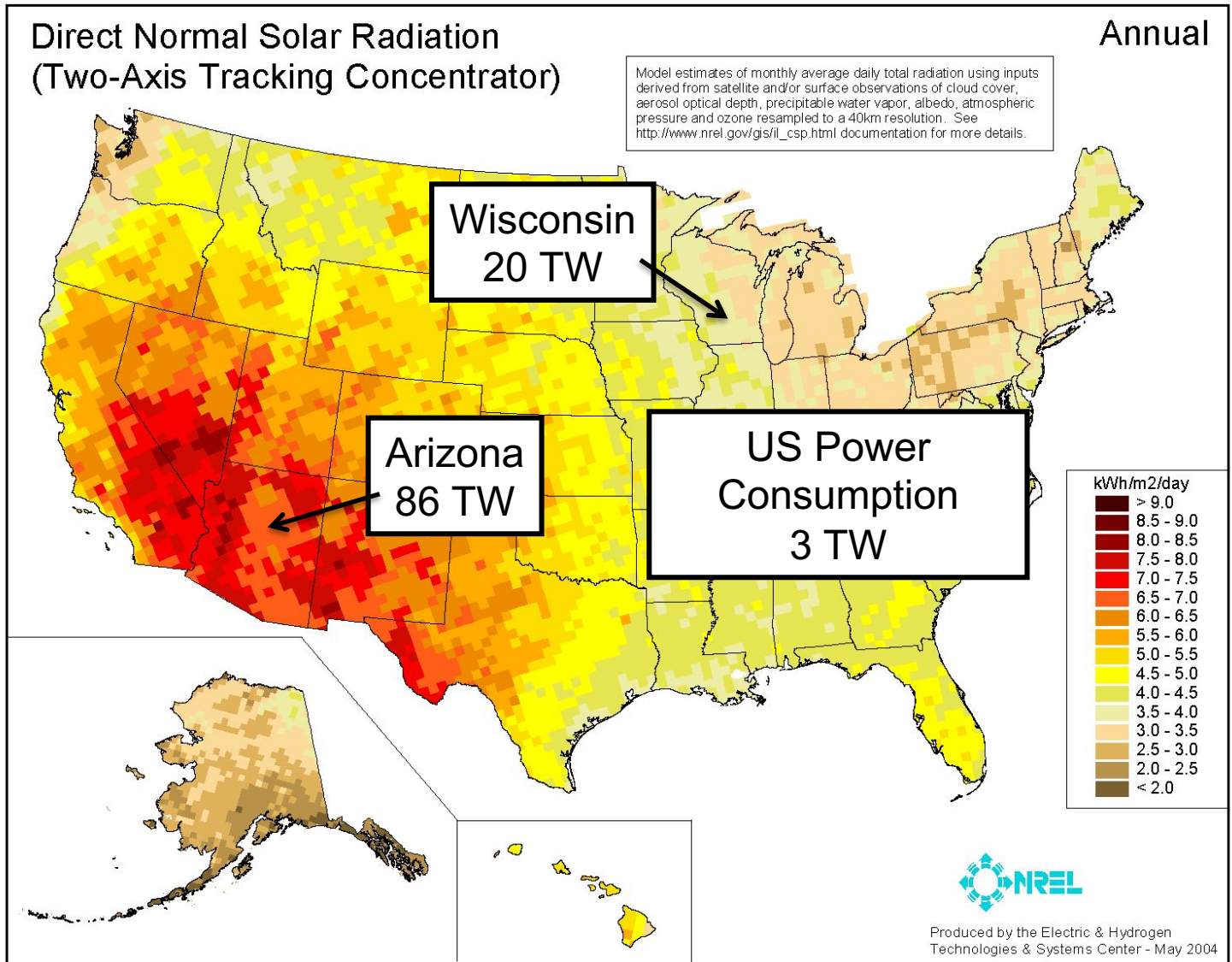


What about Wisconsin?

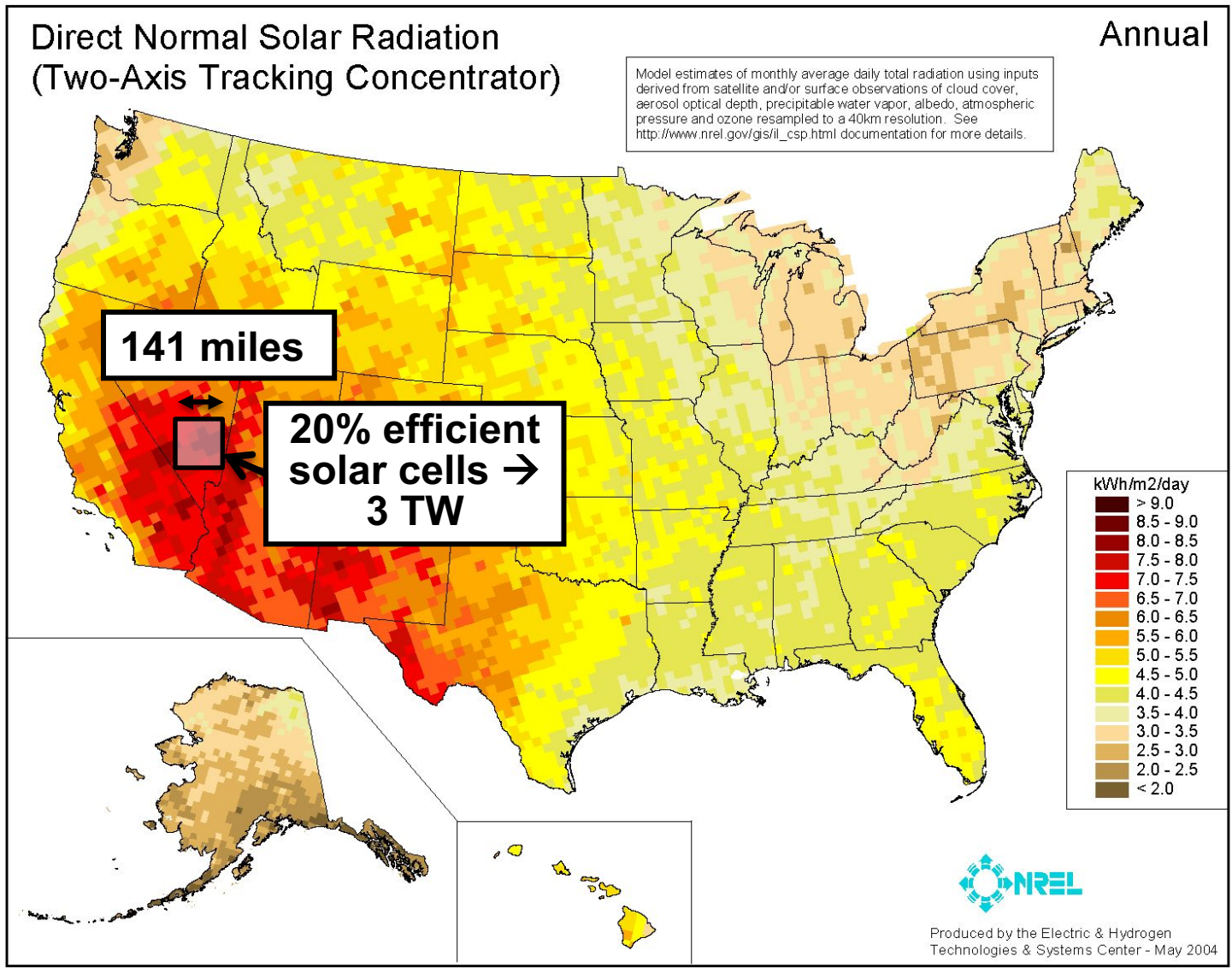
US?



US?



US?



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:

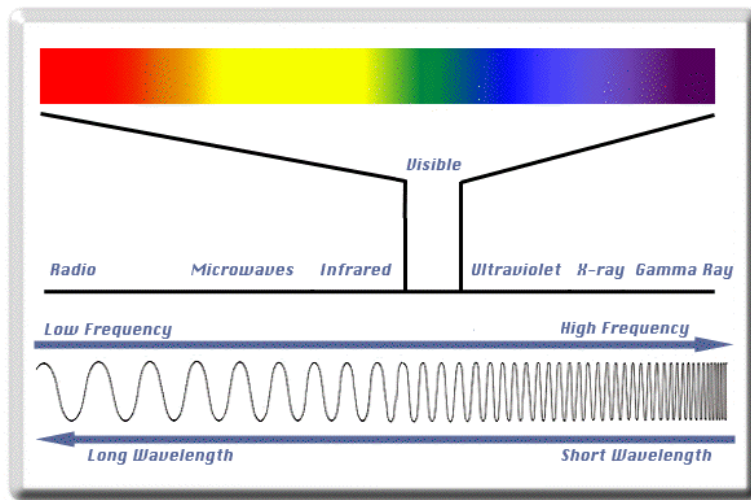


Fundamental Physics Behind Photovoltaic Solar Cells

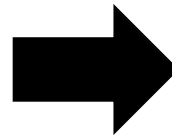
What is a solar cell made from?

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

What is a Solar Cell Made From?

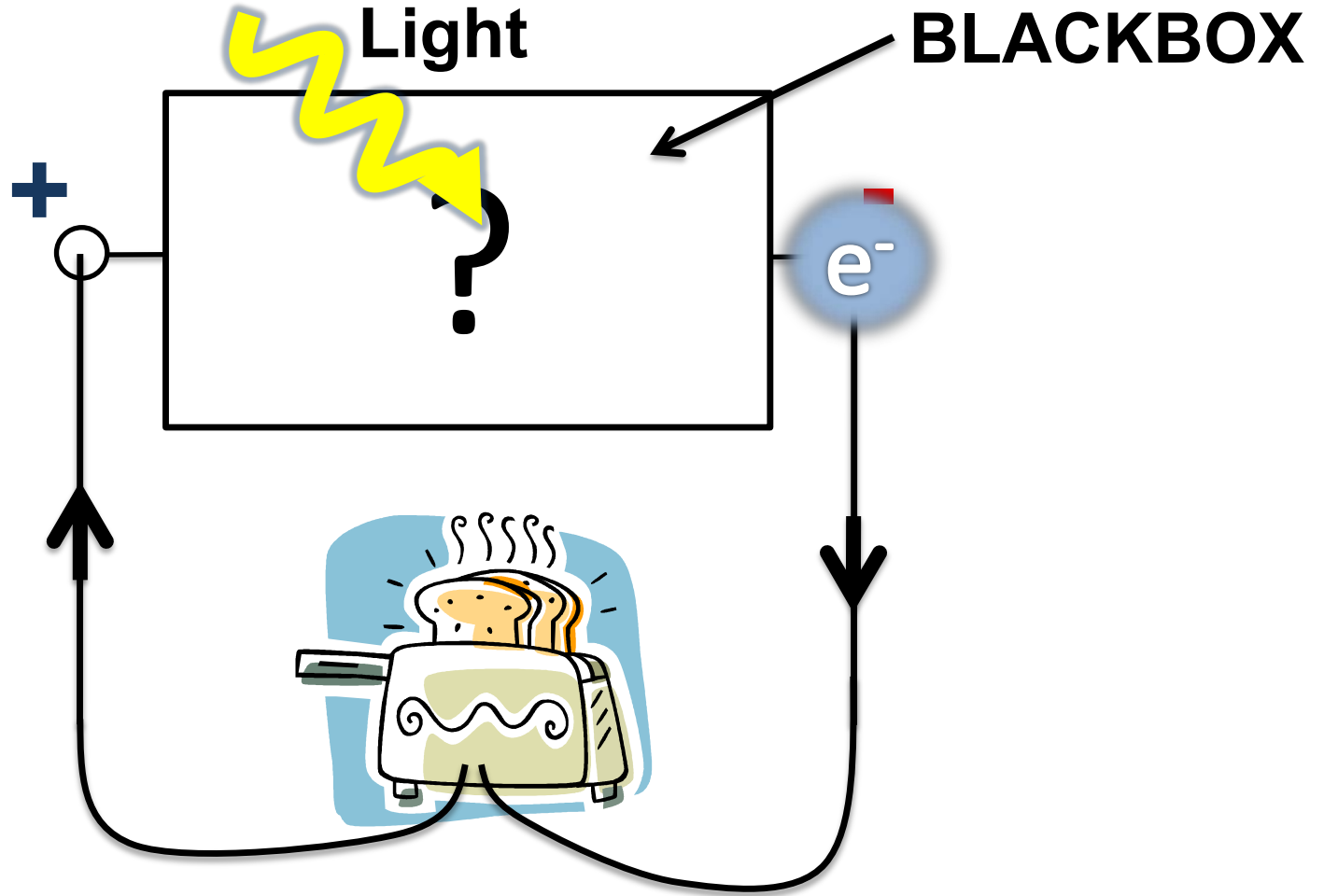


Light



Electricity

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



Other Semiconductors

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

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

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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

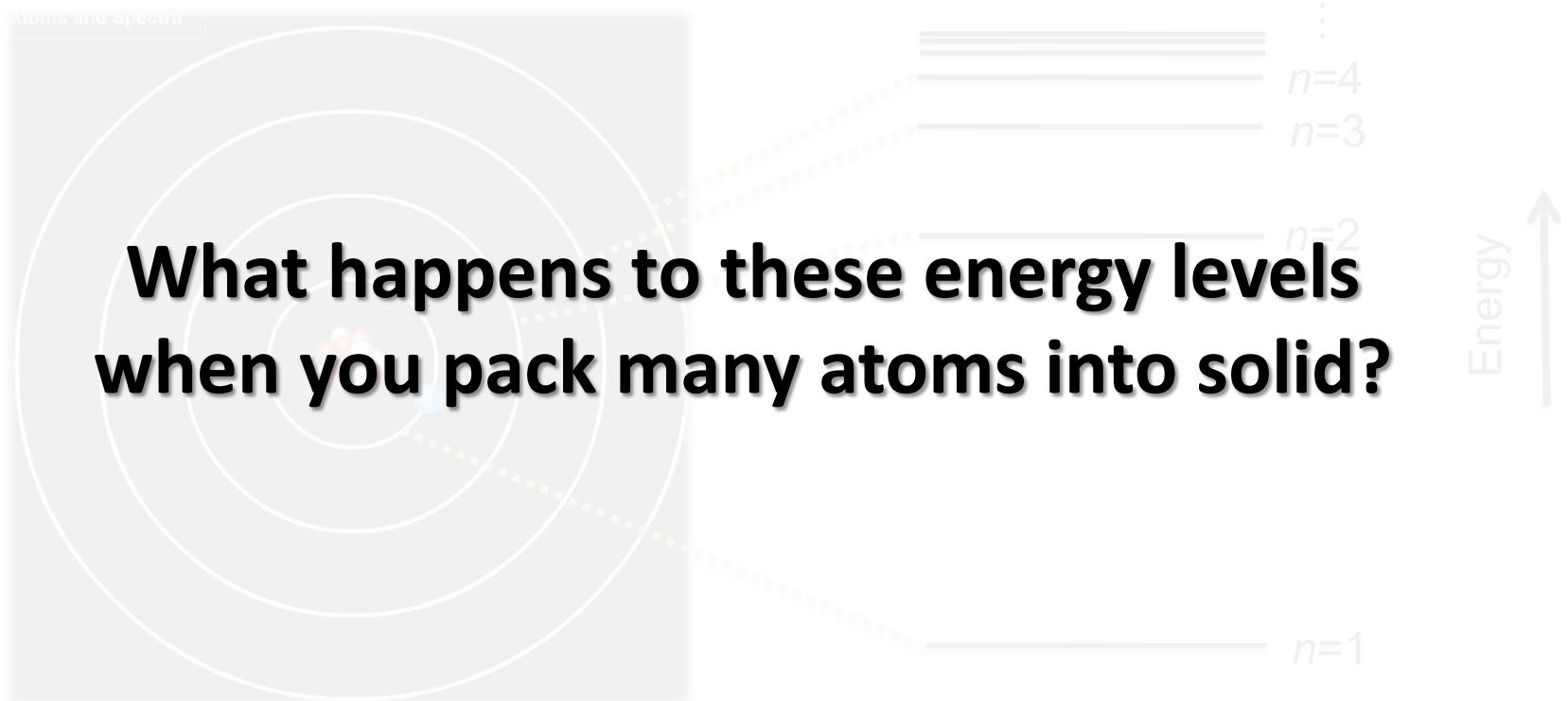
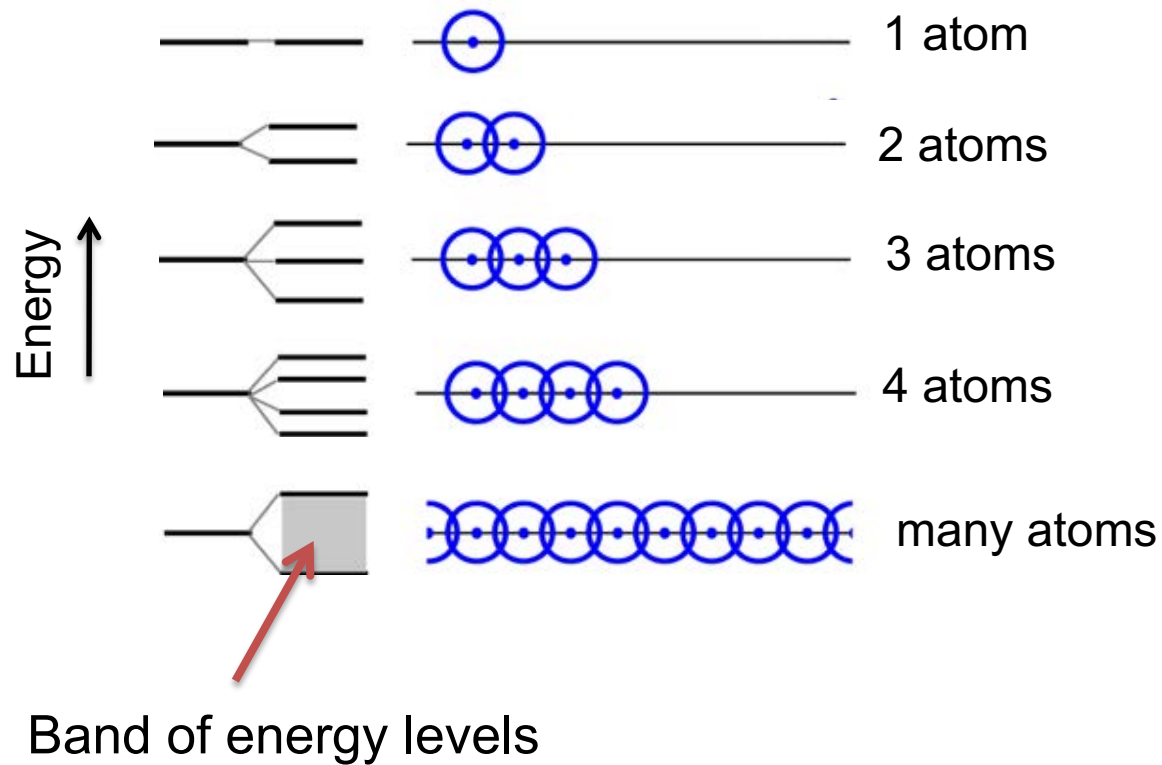


Image from:
http://spiff.rit.edu/classes/phys301/lectures/spec_lines/Atoms_Nav.swf

Energy Levels Split in a Solid to Form Bands

Look at effect on lowest $n=1$ orbital.



Semiconductor Has Gap Between Bands

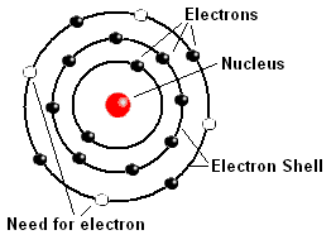


Image from:
electronics-for-
beginners.com

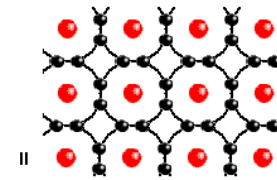
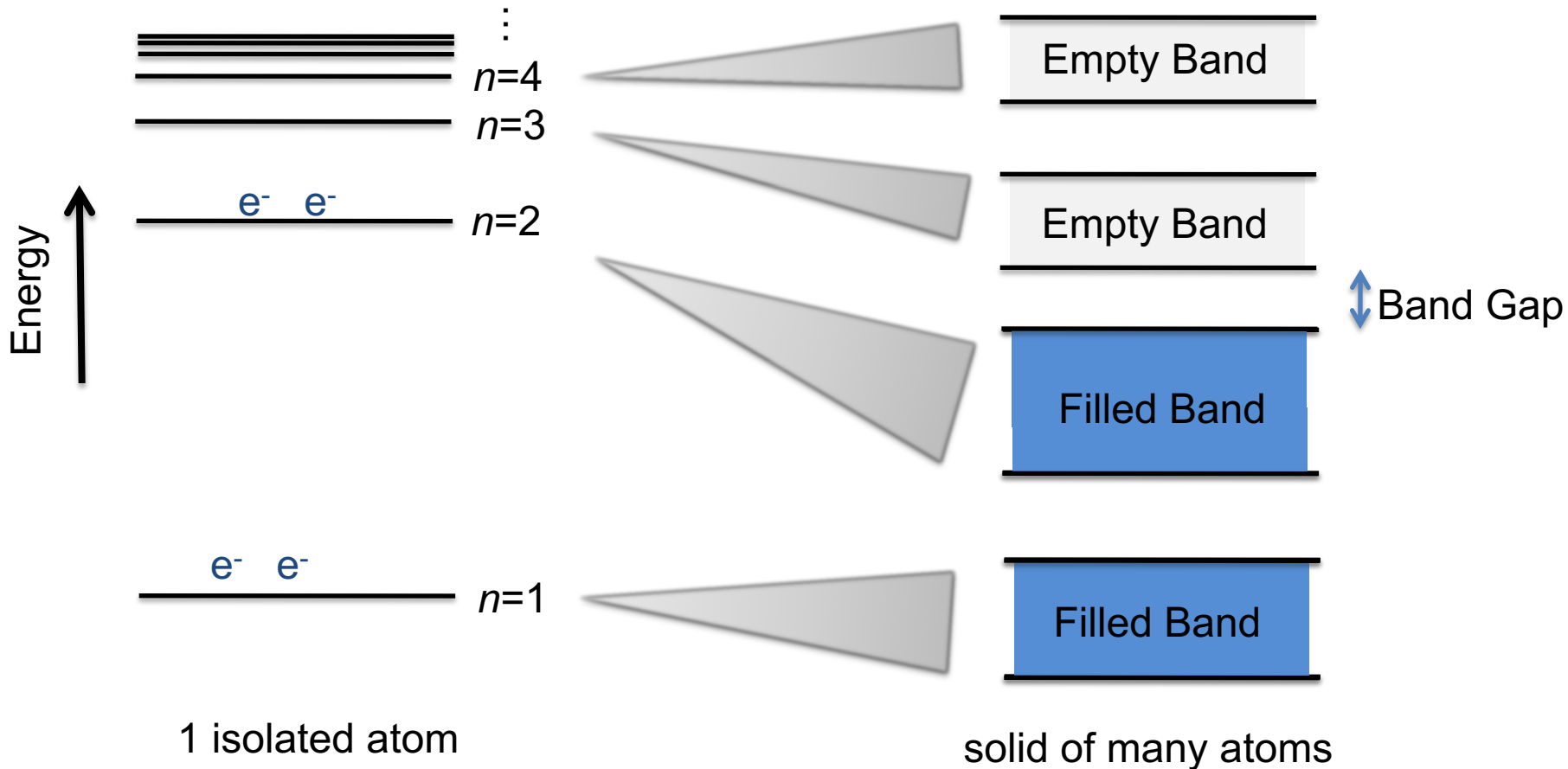
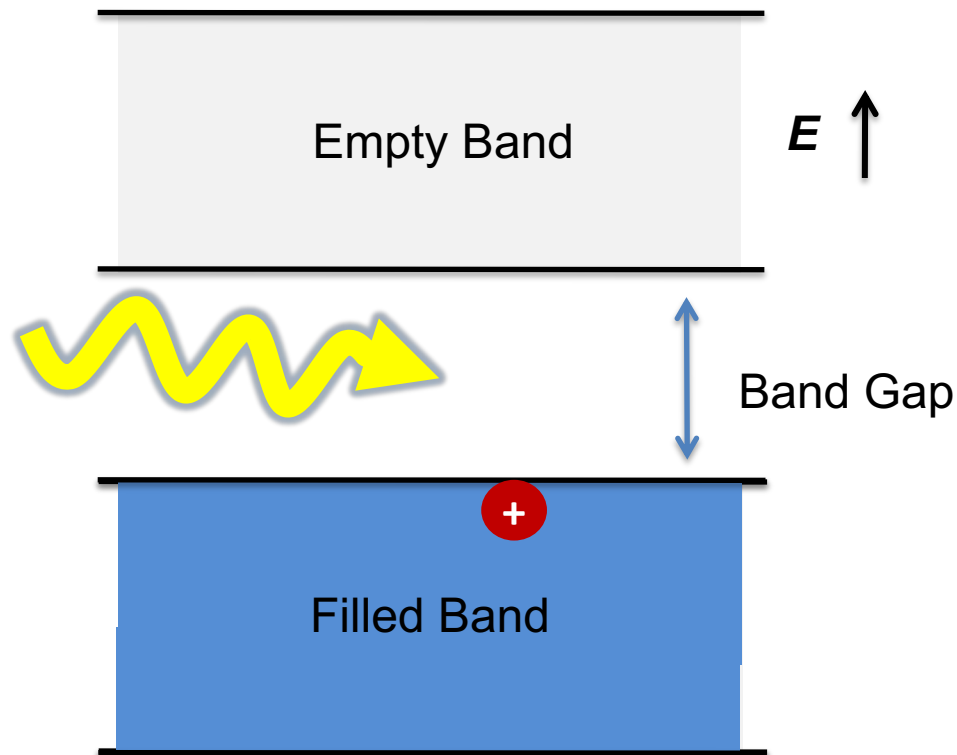


Image from:
electronics-for-
beginners.com

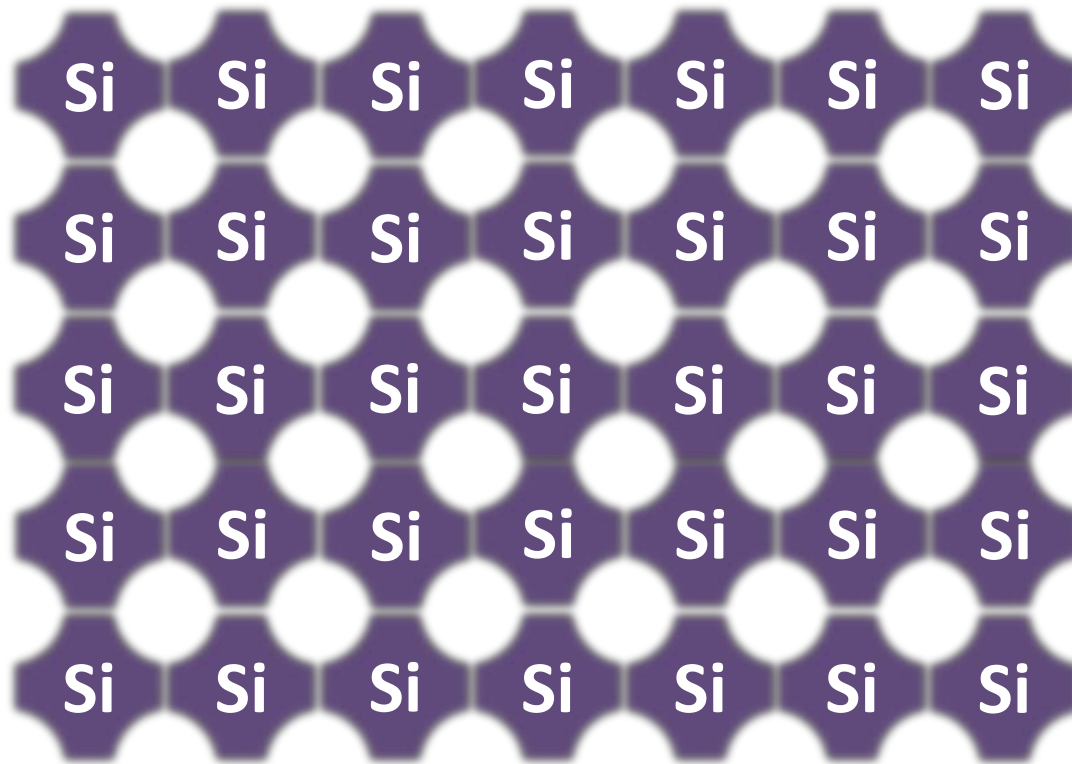


Light Excites Electrons Across Bandgap



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!

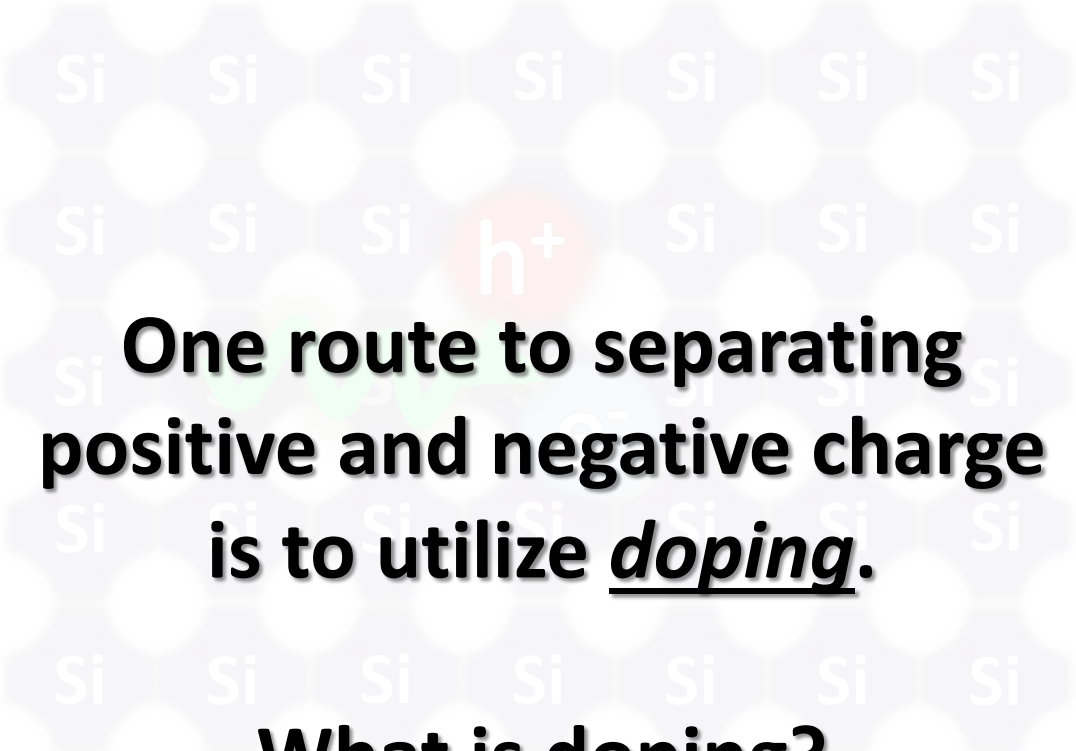
How Can Charge Be Spatially Separated?



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.



380,000 times / hour?

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

1	2	3	4	5	6	7	8	9	10	11	12	13	18										
1 H Hydrogen 1.00794	3 Li Lithium 6.941	4 Be Beryllium 9.012182	11 Na Sodium 22.98976928	19 K Potassium 39.0983	21 Sc Scandium 44.955912	22 Ti Titanium 47.887	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938045	26 Fe Iron 55.845	27 Co Cobalt 58.933195	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798	54 Xe Xenon 131.293	86 Rn Radon (222.0176)	118 Uuo Ununoctium (294)

C Solid
Hg Liquid
H Gas
Rf Unknown

Metals
 Alkali metals
 Alkaline earth metals
 Lanthanoids
 Actinoids
 Transition metals
 Poor metals

Nonmetals
 Other nonmetals
 Noble gases

Silicon is a Group IV element → 4 electrons short of a complete "shell" of 8 electrons

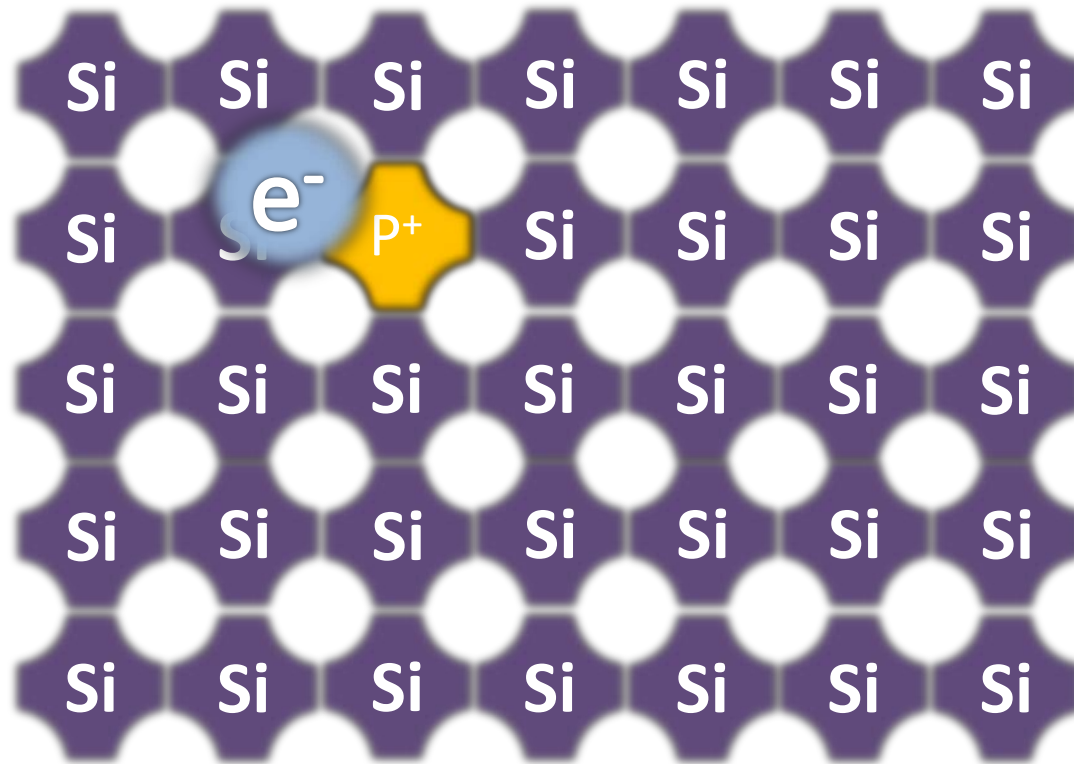
For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

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57 La Lanthanum 138.90547	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.38	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.9688
89 Ac Actinium (227)	90 Th Thorium 232.03806	91 Pa Protactinium 231.03688	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

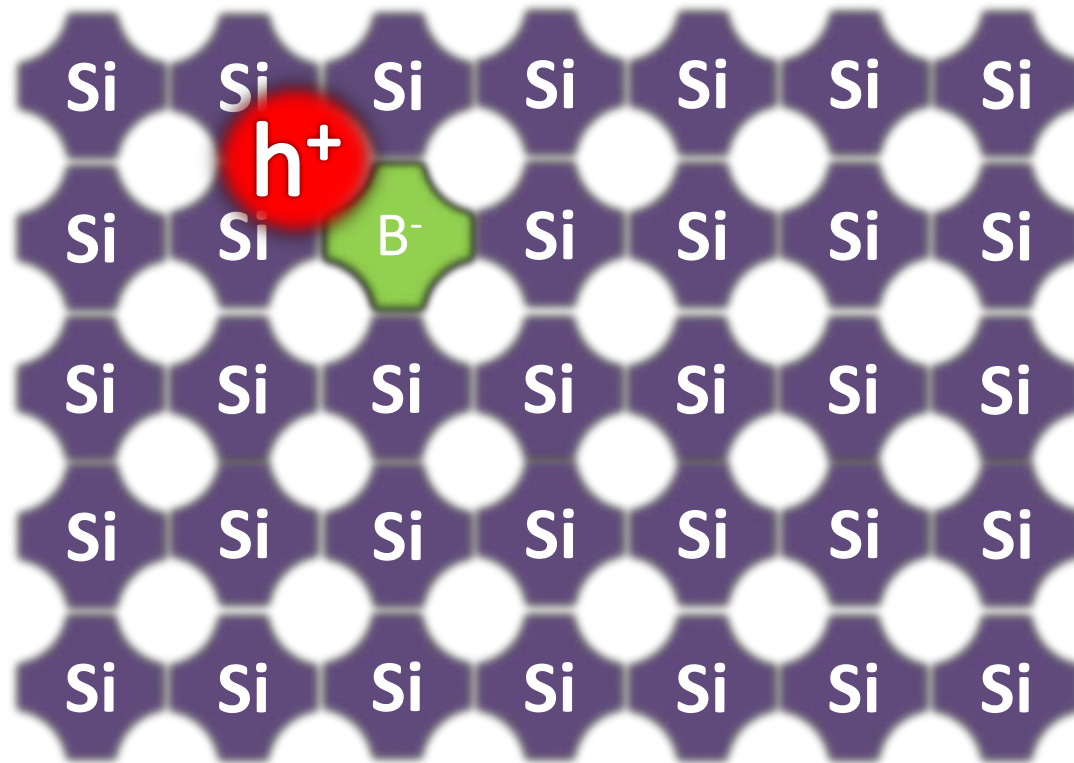


N-type (Electron Doped) Silicon (Si)



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

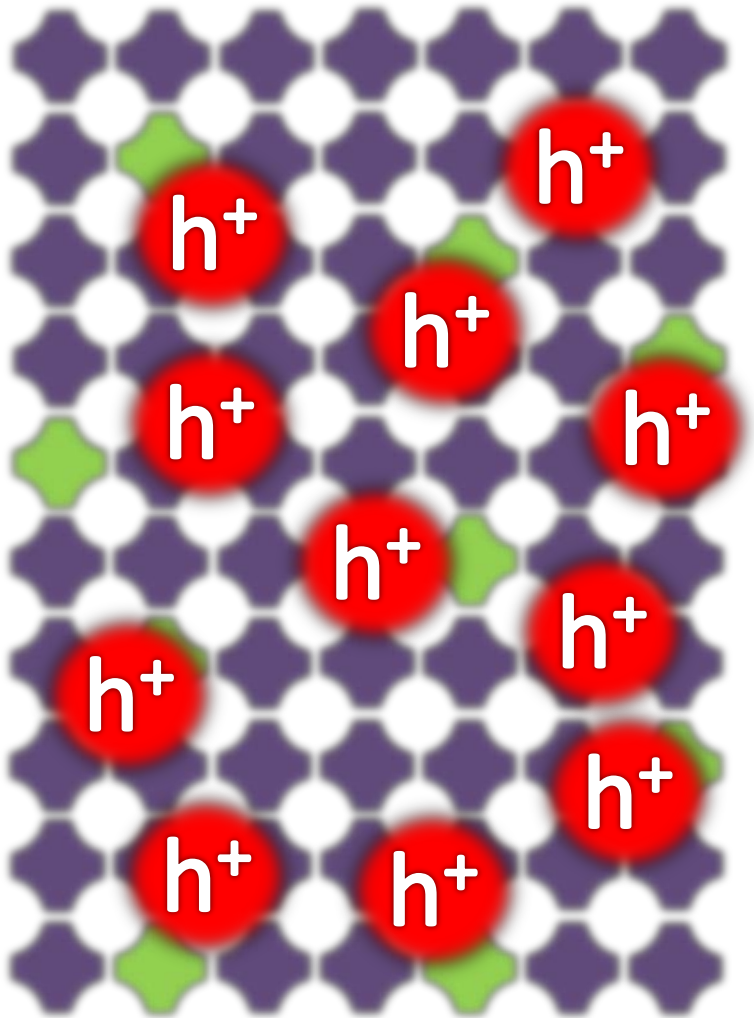
P-type (“Hole” Doped) Silicon (Si)



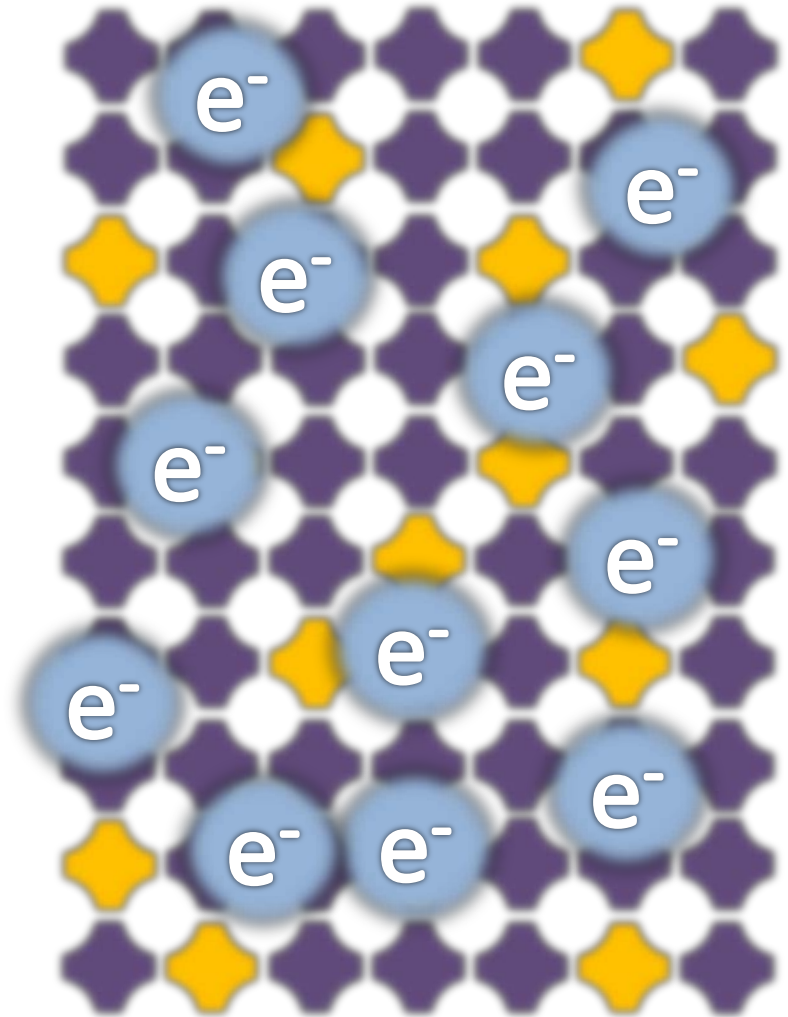
- Replacement of Group IV Si atom with Group III B atom
- B atom becomes negatively ionized, effectively releasing positive charge called a hole that can move and conduct.

A Common Device is: P-N Junction

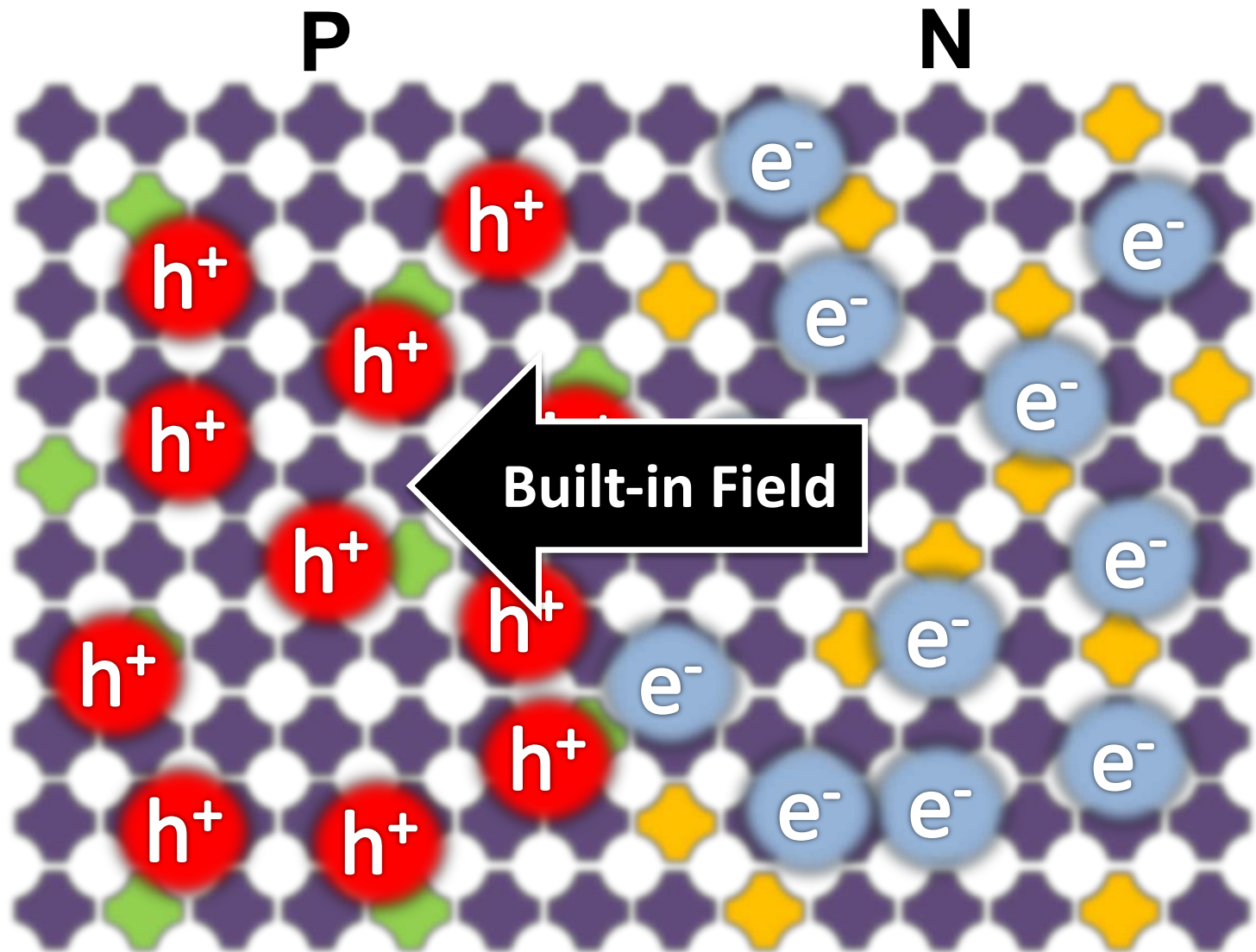
P



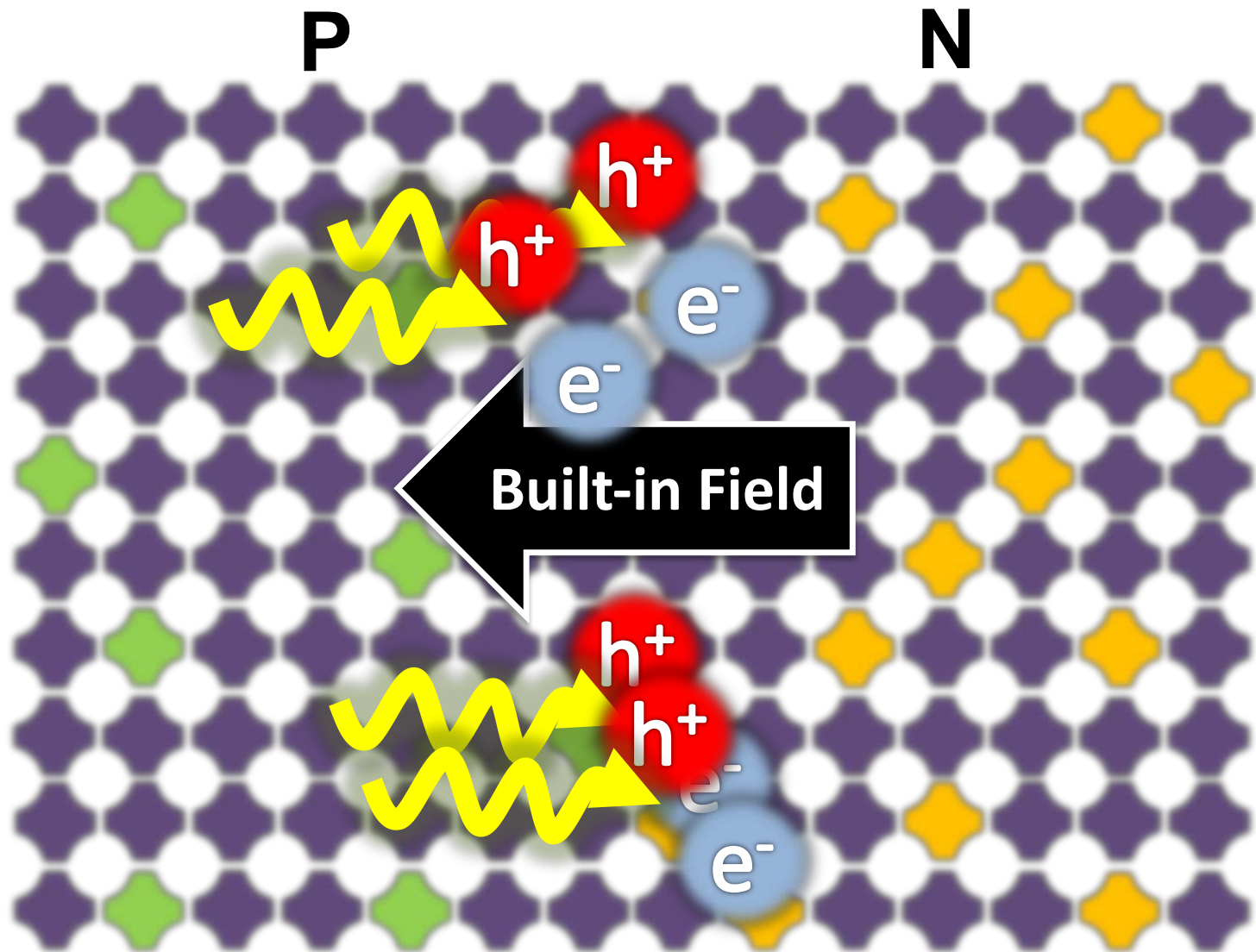
N



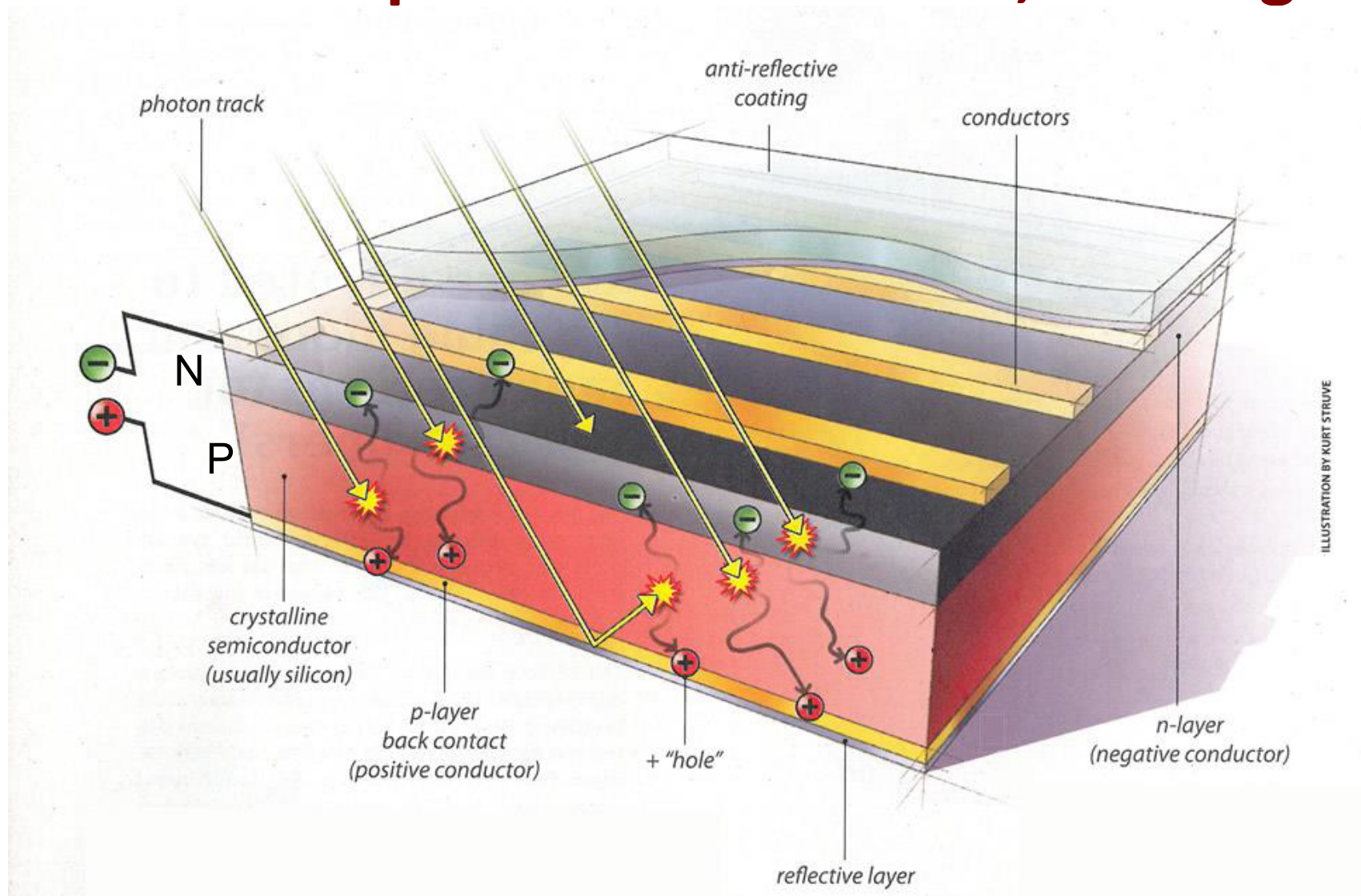
P-N Junction



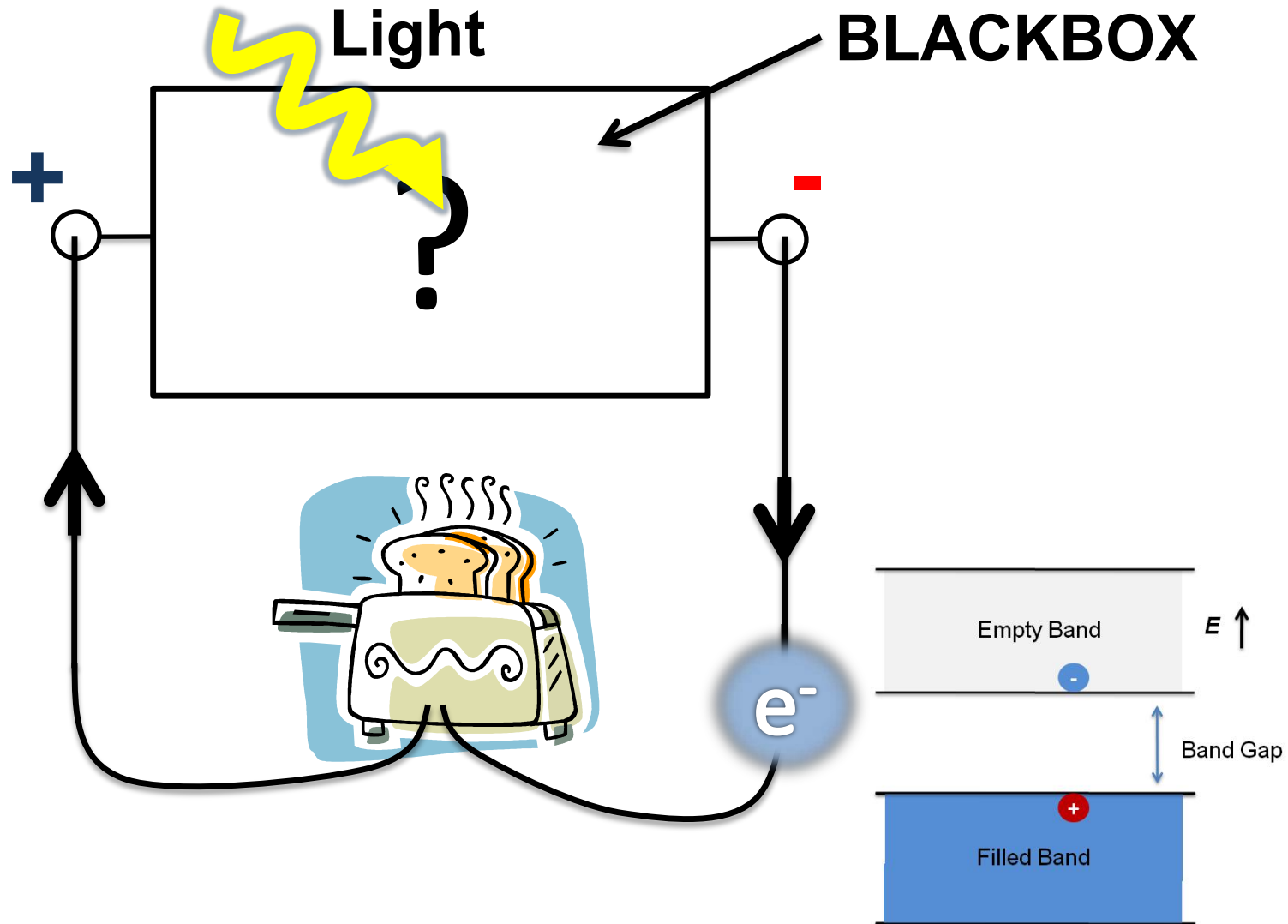
P-N Junction



Other Components: Electrodes, Coatings



Our Blackbox



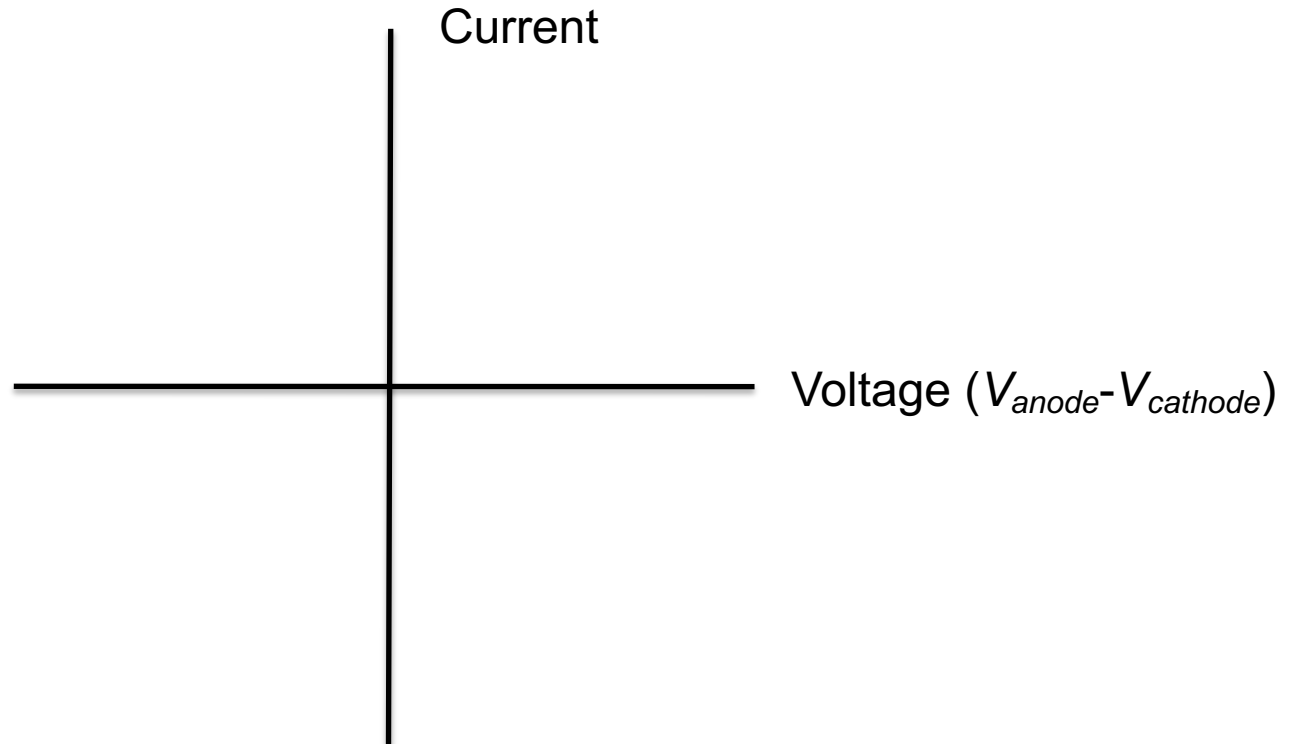
Conclusions About How a Solar Cell Works on the Level of Electrons and Atoms

- 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.

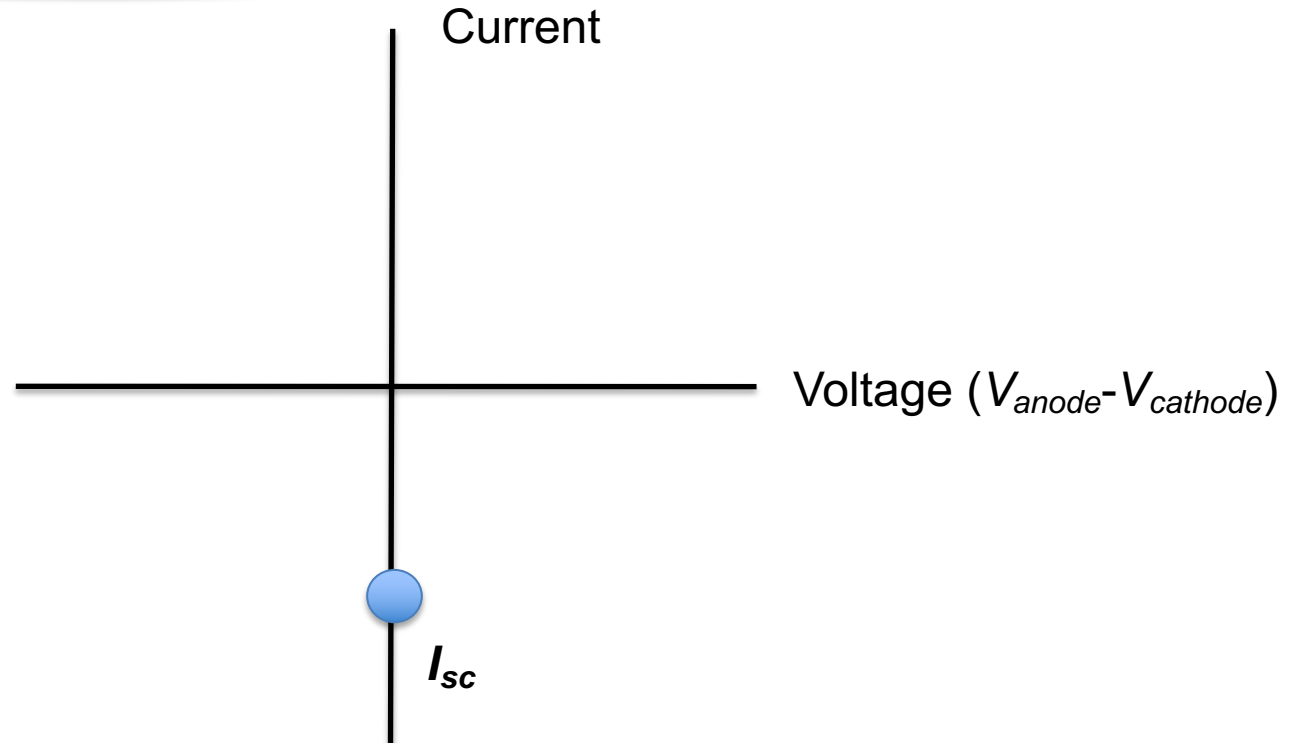
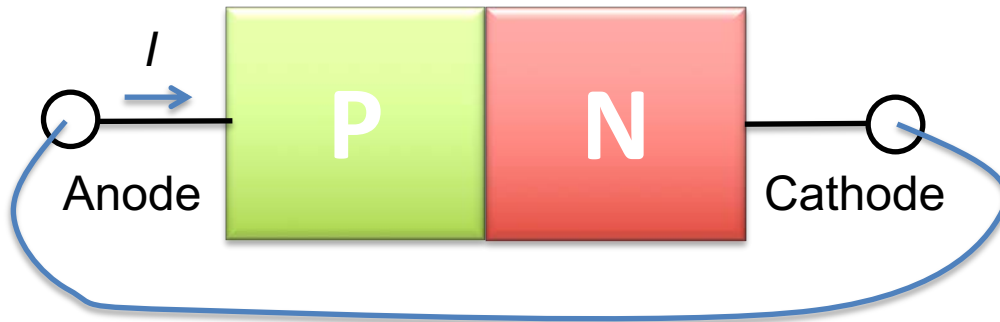
Fundamental Physics Behind Photovoltaic Solar Cells

What are the current voltage characteristics of a single cell?

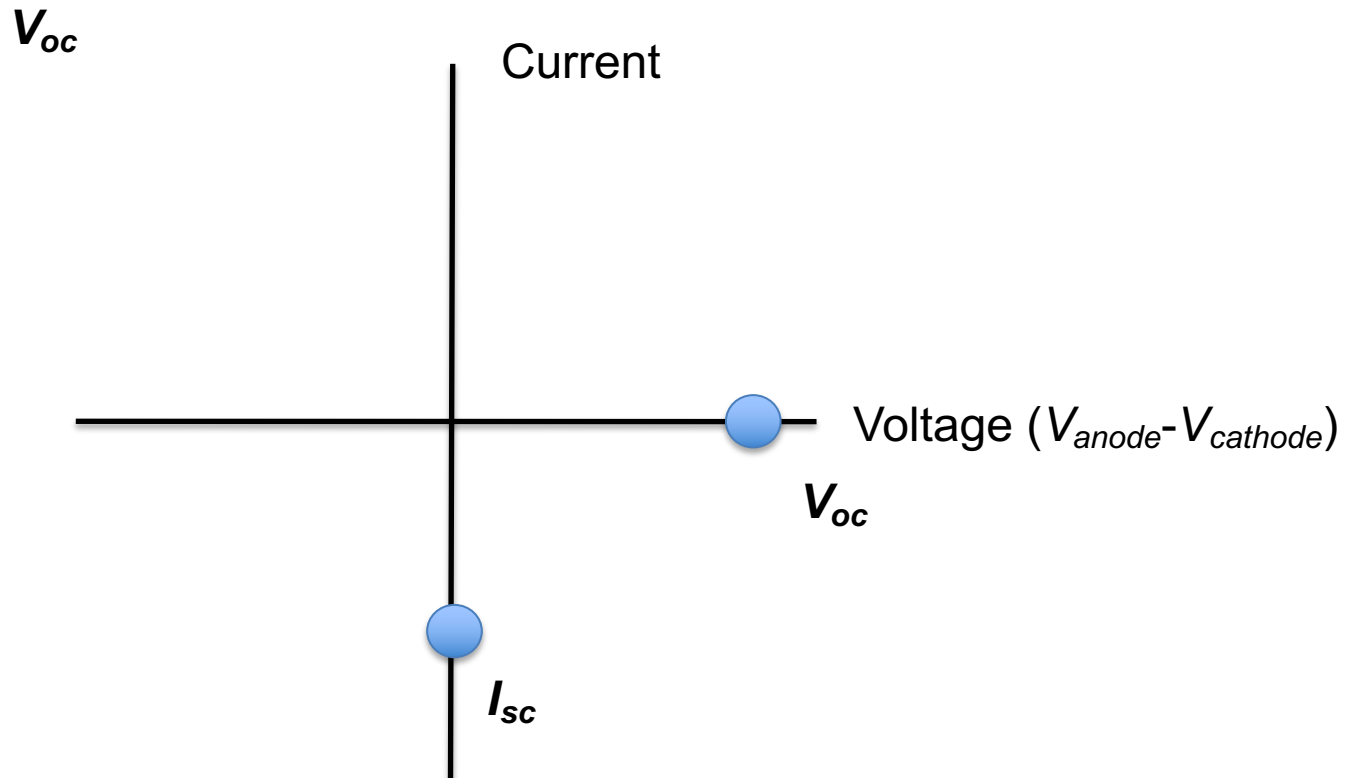
Current-Voltage Characteristics



Short-Circuit Current (I_{sc})



Open-Circuit Voltage (V_{oc})



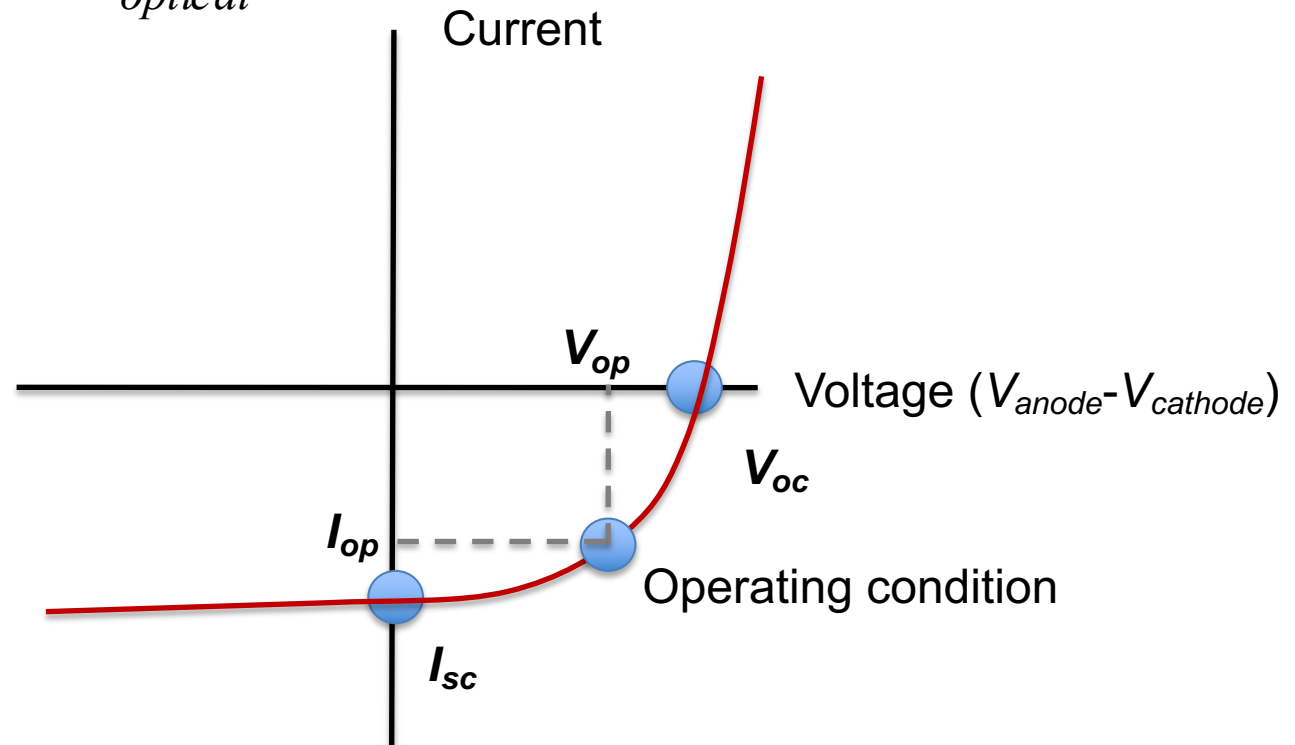
$$P=IV$$

FF = "Fill Factor"

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

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

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



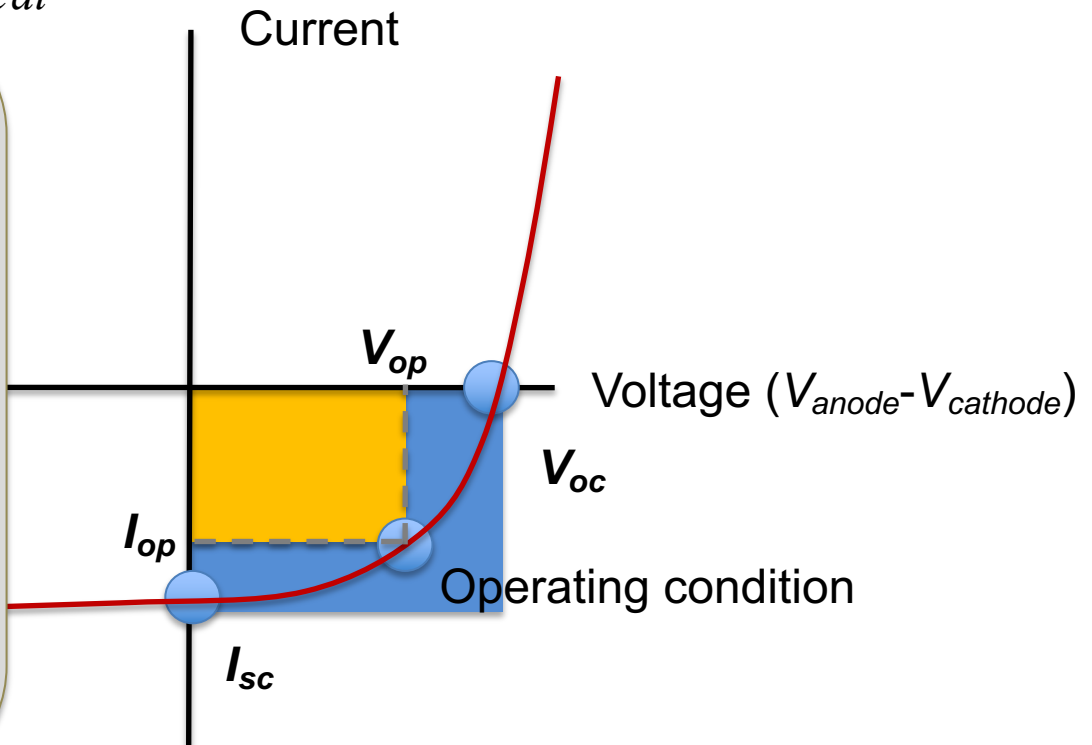
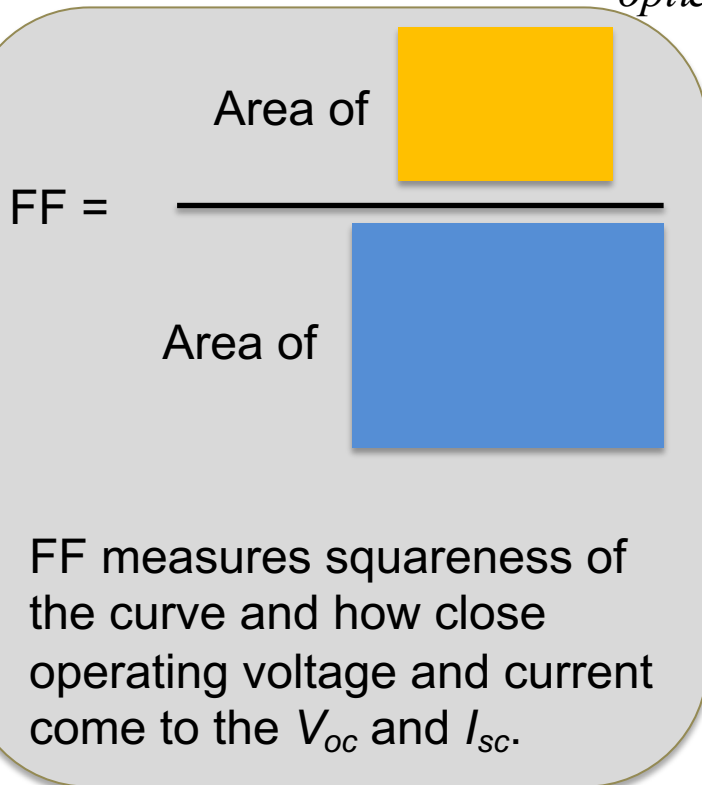
What is the *FF*?

FF = "Fill Factor"

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

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

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



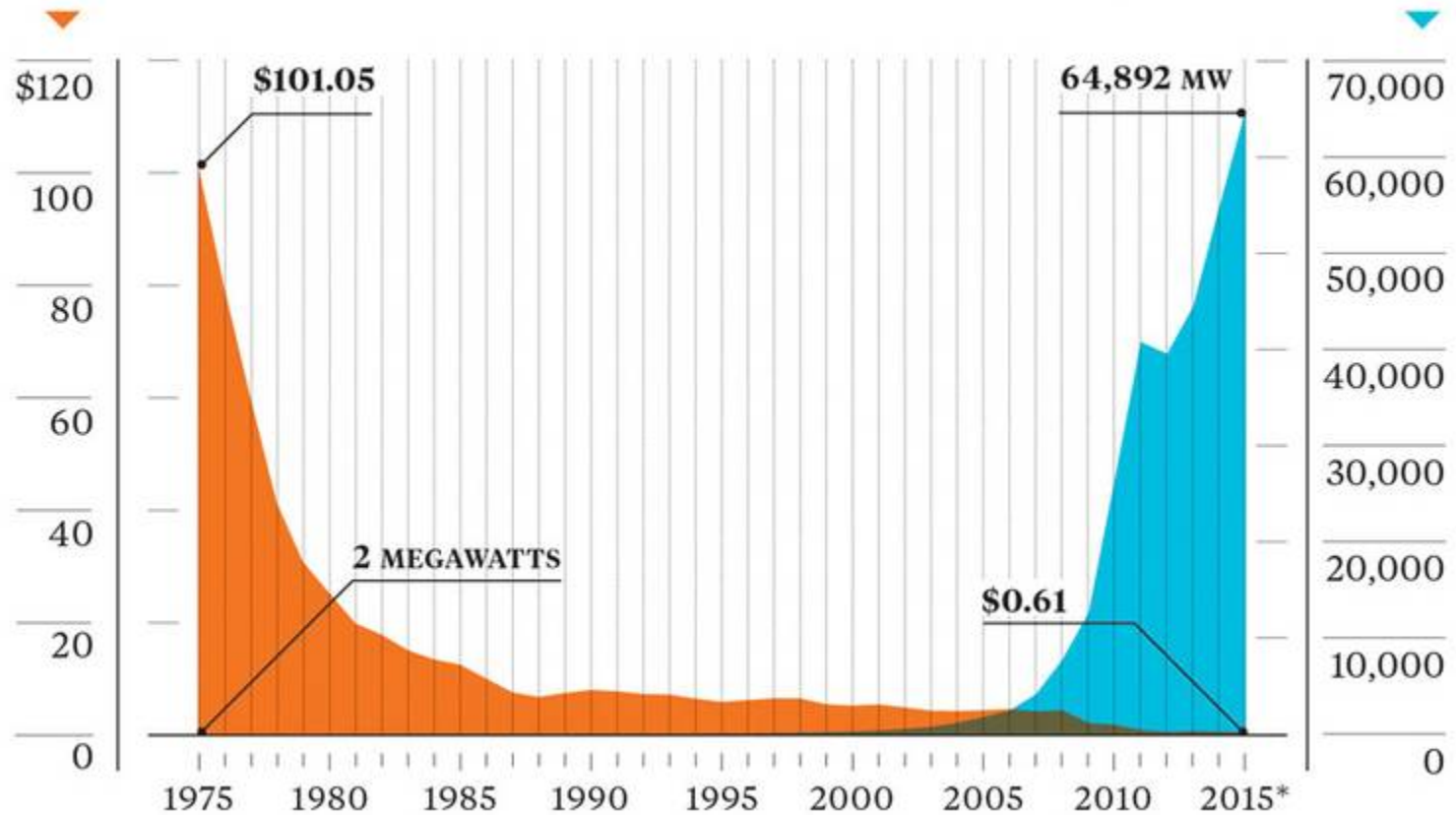
Trends

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

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

Price of a solar panel per watt

Global solar panel installations

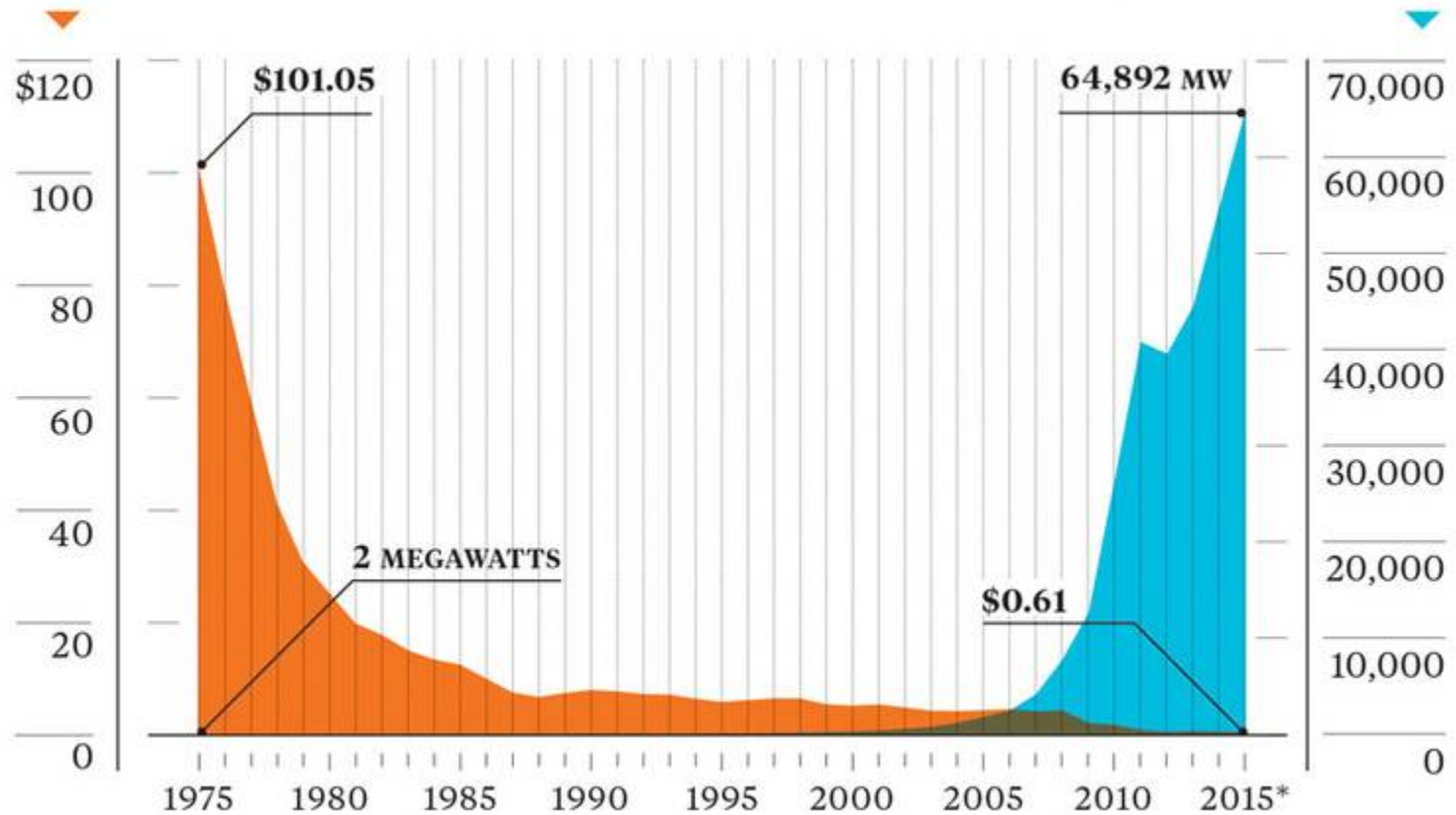


Data/image source: Earth Policy Institute/Bloomberg

Meanwhile, price has plummeted.

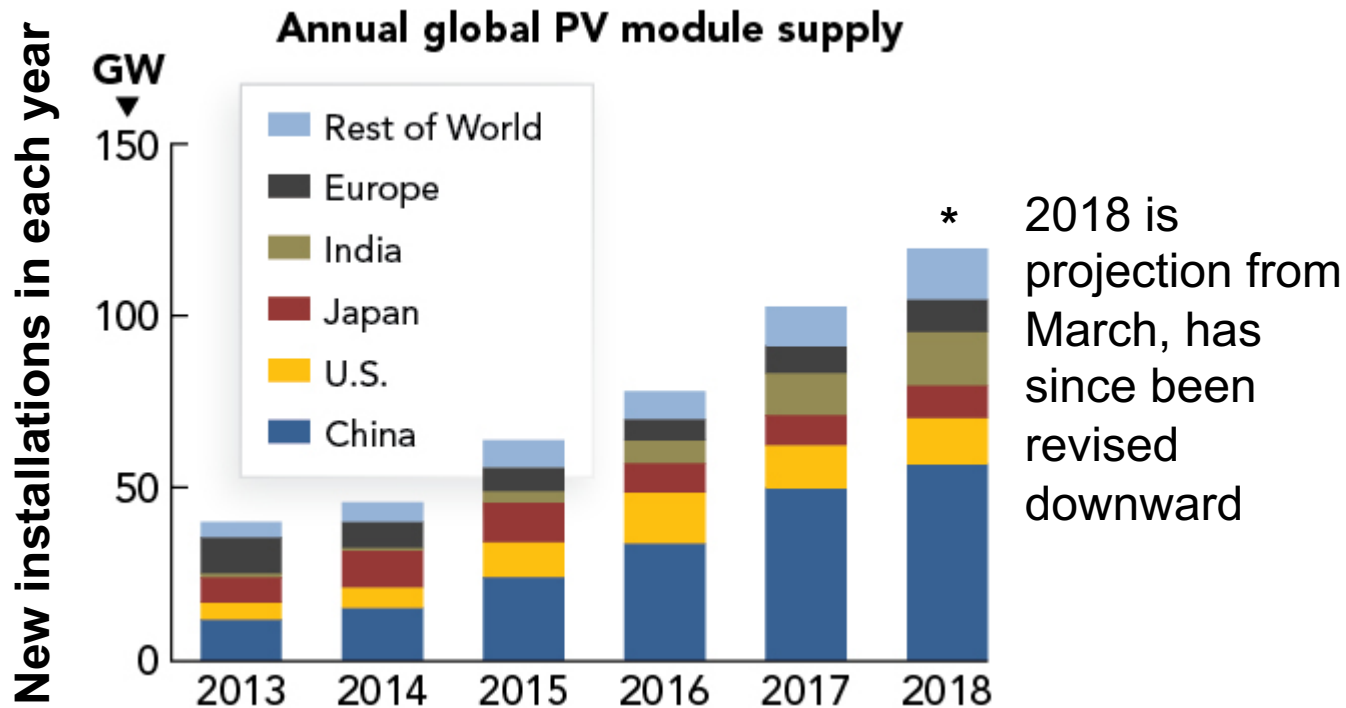
Price of a solar panel per watt

Global solar panel installations



Data/image source: Earth Policy Institute/Bloomberg

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



“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?

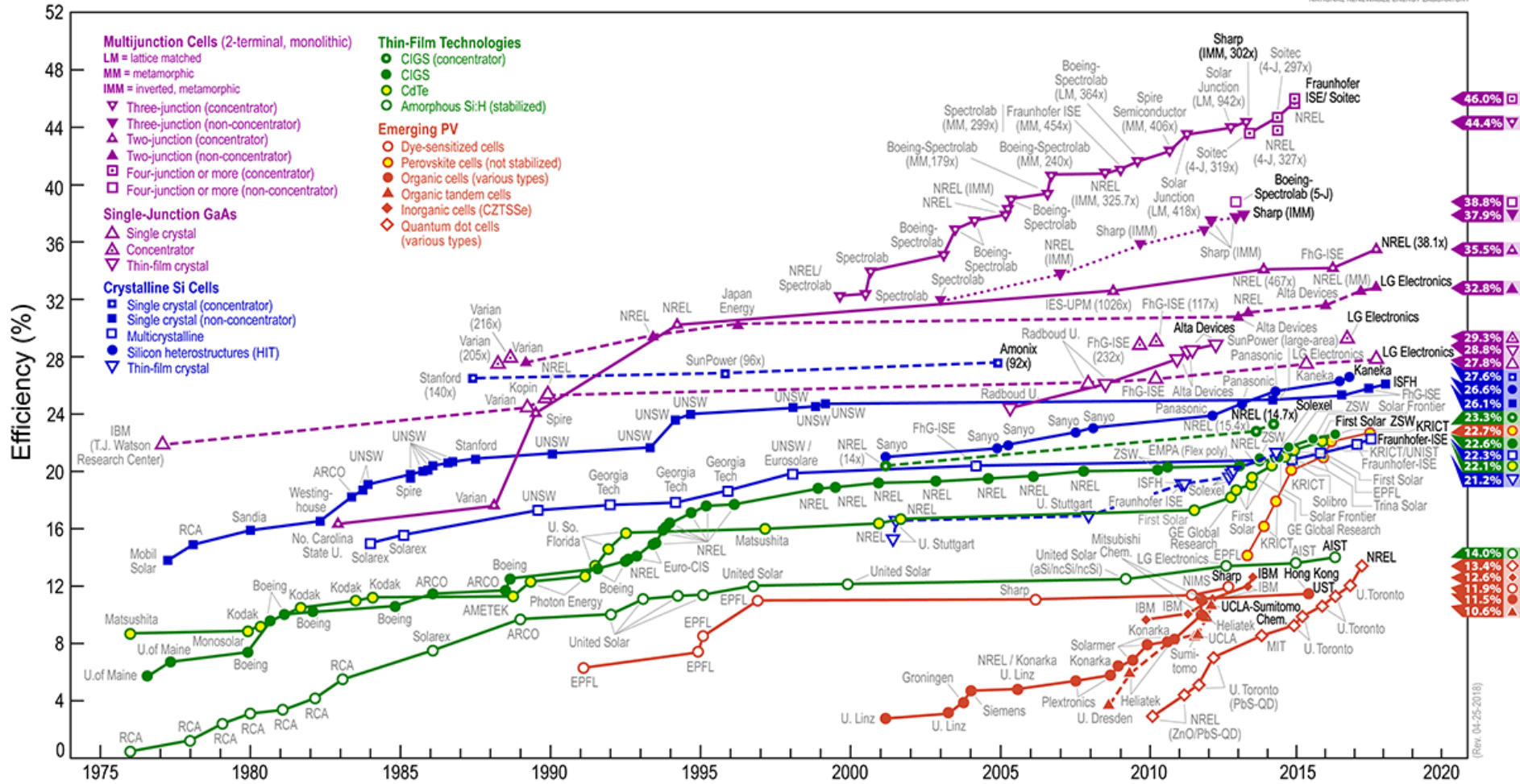
What are the challenges in materials science to making solar cells more efficient and economical?

NREL National Center for Photovoltaics

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



Best Research-Cell Efficiencies



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

Aside: How Efficient is Photosynthesis?



Sugar =
Chemical
Energy

Growth /
Regeneration



8.5%



3.7%

Stored/
Harvestable

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

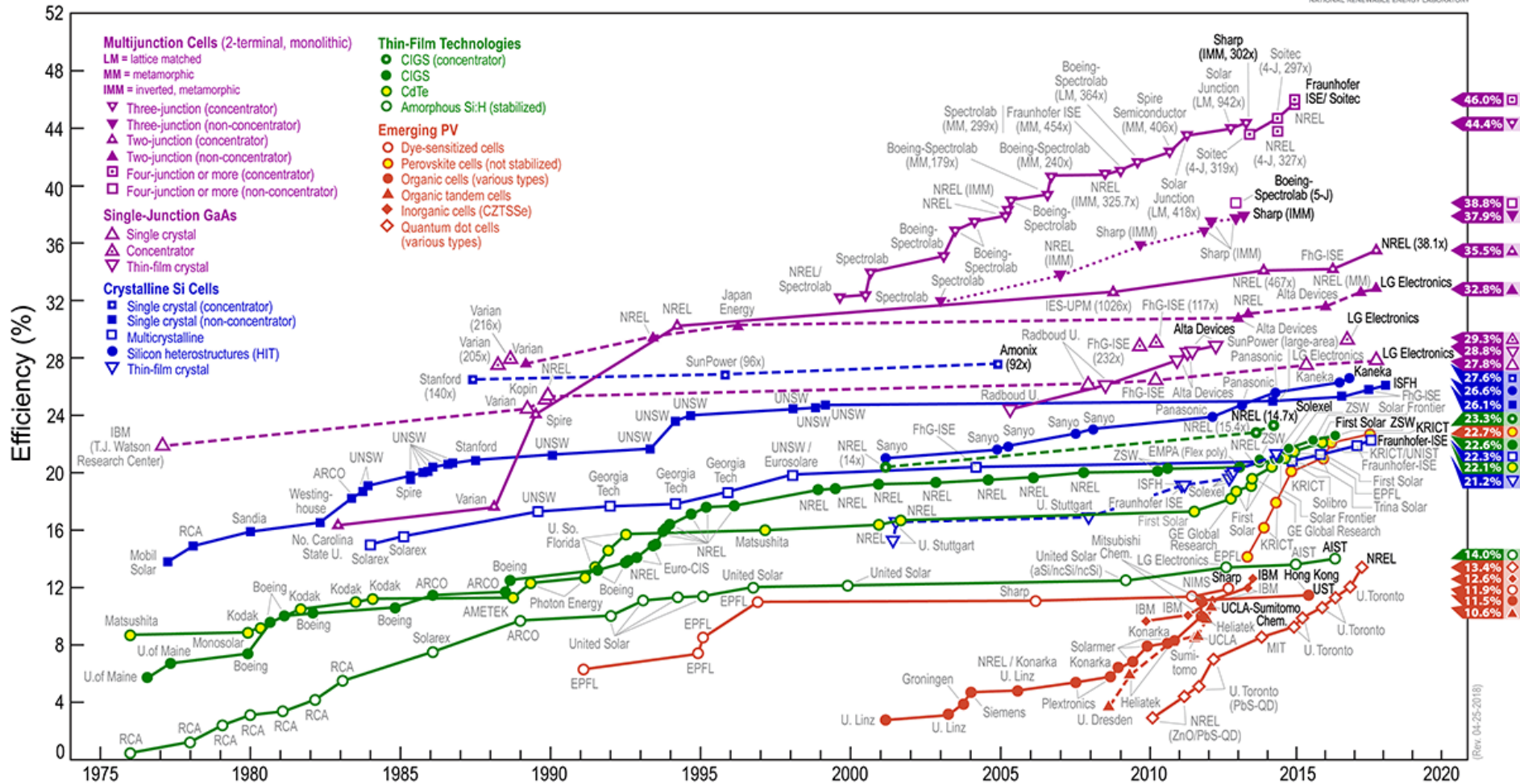
Image from: http://commons.wikimedia.org/wiki/File:Rain_forest_NZ.JPG

NREL National Center for Photovoltaics

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



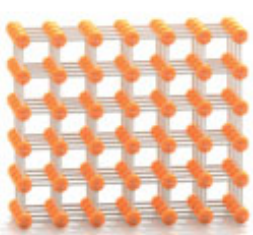
Best Research-Cell Efficiencies



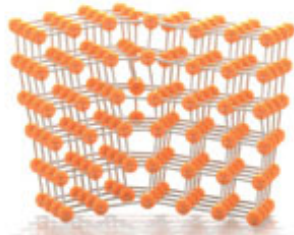
Observation #2: Lots of different cell-types!

Cell-Type Classifications

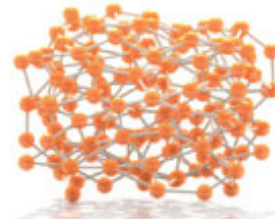
Crystallinity



Crystalline



Polycrystalline



Amorphous

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

Thick Crystal or Thin Film

Thin-Film



Thick Crystal

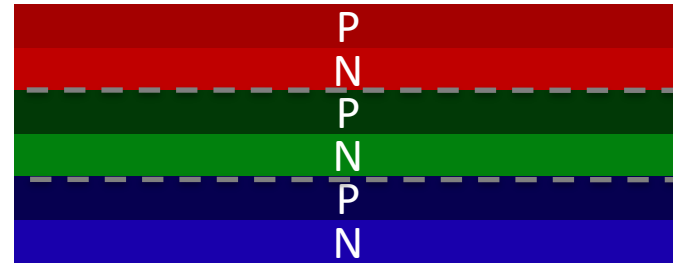


Number of Junctions

Single-Junction:



Multi-Junction:



Small Bandgap
Medium Bandgap
Large Bandgap

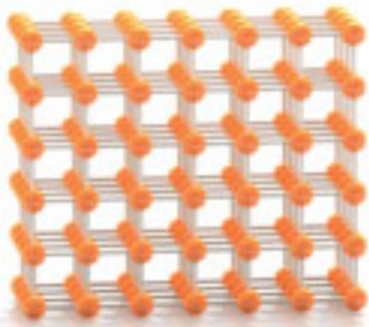
Composition

Periodic Table of Elements

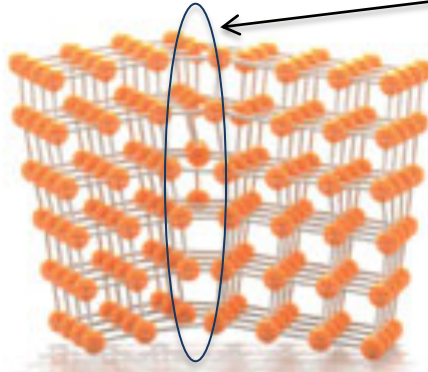
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Crystallinity

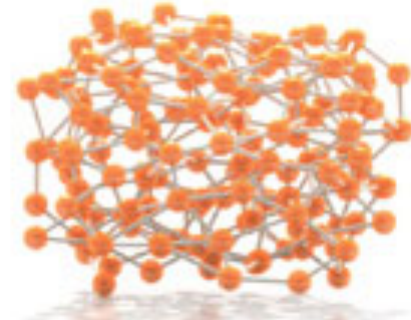
Defects slow charges and cause losses.



Crystalline



Polycrystalline



Amorphous

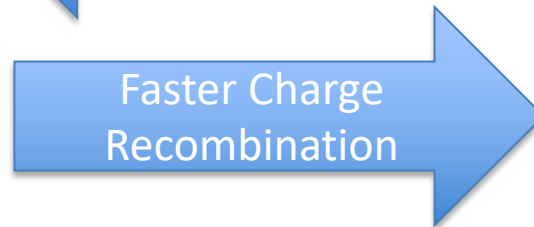
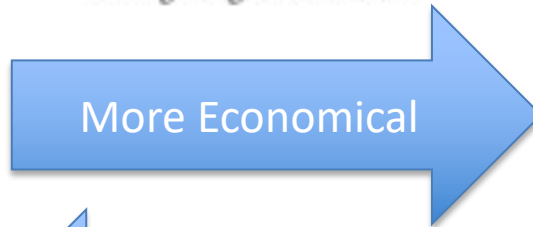
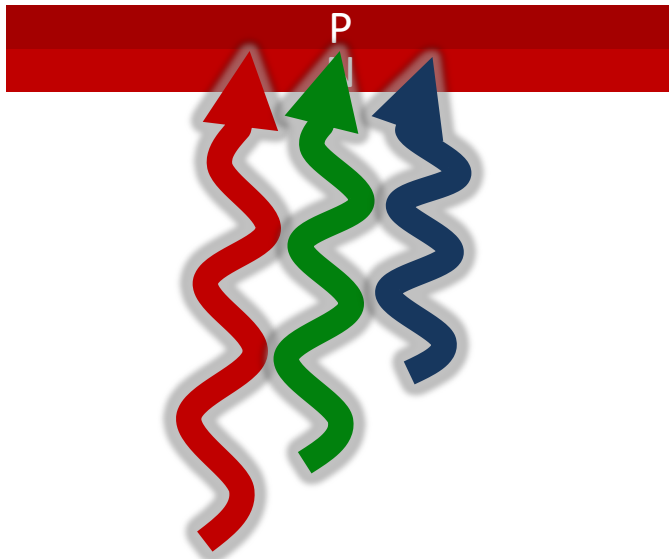


Image from: <http://spectrum.ieee.org/image/1838375>

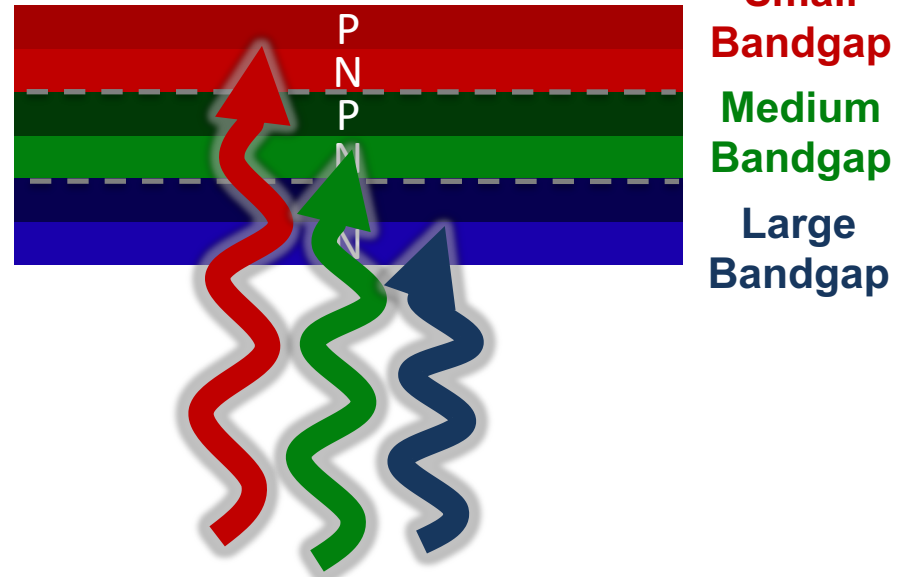
Number of Junctions

Single-Junction:



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

Multi-Junction:



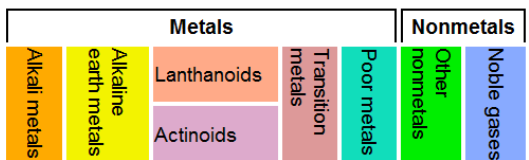
- ❑ In multi-junction cell, blue photon can produce more energy than red photon.
- ❑ Maximum efficiency $\sim 50\%$ (for 3 cells).
- ❑ More complex fabrication \rightarrow More \$\$\$.

Composition (Different Semiconductors)

Periodic Table of Elements

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
1	H Hydrogen 1.00794																	He Helium 4.002602	
2	Li Lithium 6.941	Be Beryllium 9.012182																	Ne Neon 20.1797
3	Na Sodium 22.98976928	Mg Magnesium 24.3050																	Ar Argon 39.948
4	K Potassium 39.0983	Ca Calcium 40.078	Sc Scandium 44.955912	Ti Titanium 47.887	V Vanadium 50.9415	Cr Chromium 51.9961	Mn Manganese 54.938045	Fe Iron 55.845	Co Cobalt 58.933195	Ni Nickel 58.6934	Cu Copper 63.546	Zn Zinc 65.38	Ga Gallium 69.723	Ge Germanium 72.64	As Arsenic 74.92160	Se Selenium 78.96	Br Bromine 79.904	Kr Krypton 83.798	
5	Rb Rubidium 85.4678	Sr Strontium 87.62	Y Yttrium 88.90585	Zr Zirconium 91.224	Nb Niobium 92.90638	Mo Molybdenum 95.96	Tc Technetium (97.9072)	Ru Ruthenium 101.07	Rh Rhodium 102.90550	Pd Palladium 106.42	Ag Silver 107.8682	Cd Cadmium 112.411	In Indium 114.818	Sn Tin 118.710	Sb Antimony 121.760	Te Tellurium 127.60	I Iodine 126.90447	Xe Xenon 131.293	
6	Cs Cesium 132.9054519	Ba Barium 137.327	57-71	Hf Hafnium 178.49	Ta Tantalum 180.94788	W Tungsten 183.84	Re Rhenium 186.207	Os Osmium 190.23	Ir Iridium 192.217	Pt Platinum 195.084	Au Gold 196.966569	Hg Mercury 200.59	Tl Thallium 204.3833	Pb Lead 207.2	Bi Bismuth 208.98040	Po Polonium (209.9824)	At Astatine (209.9871)	Rn Radon (222.0176)	
7	Fr Francium (223)	Ra Radium (226)	89-103	Rf Rutherfordium (261)	Db Dubnium (262)	Sg Seaborgium (266)	Bh Bohrium (264)	Hs Hassium (277)	Mt Meitnerium (268)	Ds Darmstadtium (271)	Rg Roentgenium (272)	Uub Ununbium (285)	Uut Ununtrium (284)	Uuq Ununquadium (289)	Uup Ununpentium (288)	Uuh Ununhexium (282)	Uus Ununseptium	Uuo Ununoctium (284)	

- C** Solid
- Hg** Liquid
- H** Gas
- Rf** Unknown



For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

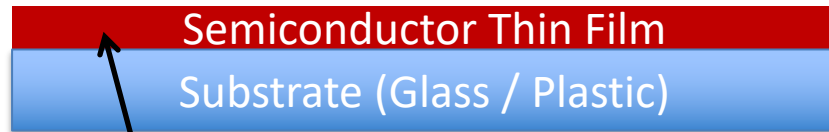
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57 La Lanthanum 138.90547	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.9668
89 Ac Actinium (227)	90 Th Thorium 232.03806	91 Pa Protactinium 231.03688	92 U Uranium 238.02891	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Fermium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

Thick Crystal or Thin Film

Thin-Film



~ 5 μm (~0.2 mils)

Thick Crystal



~ 500 μm (~20 mils)

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

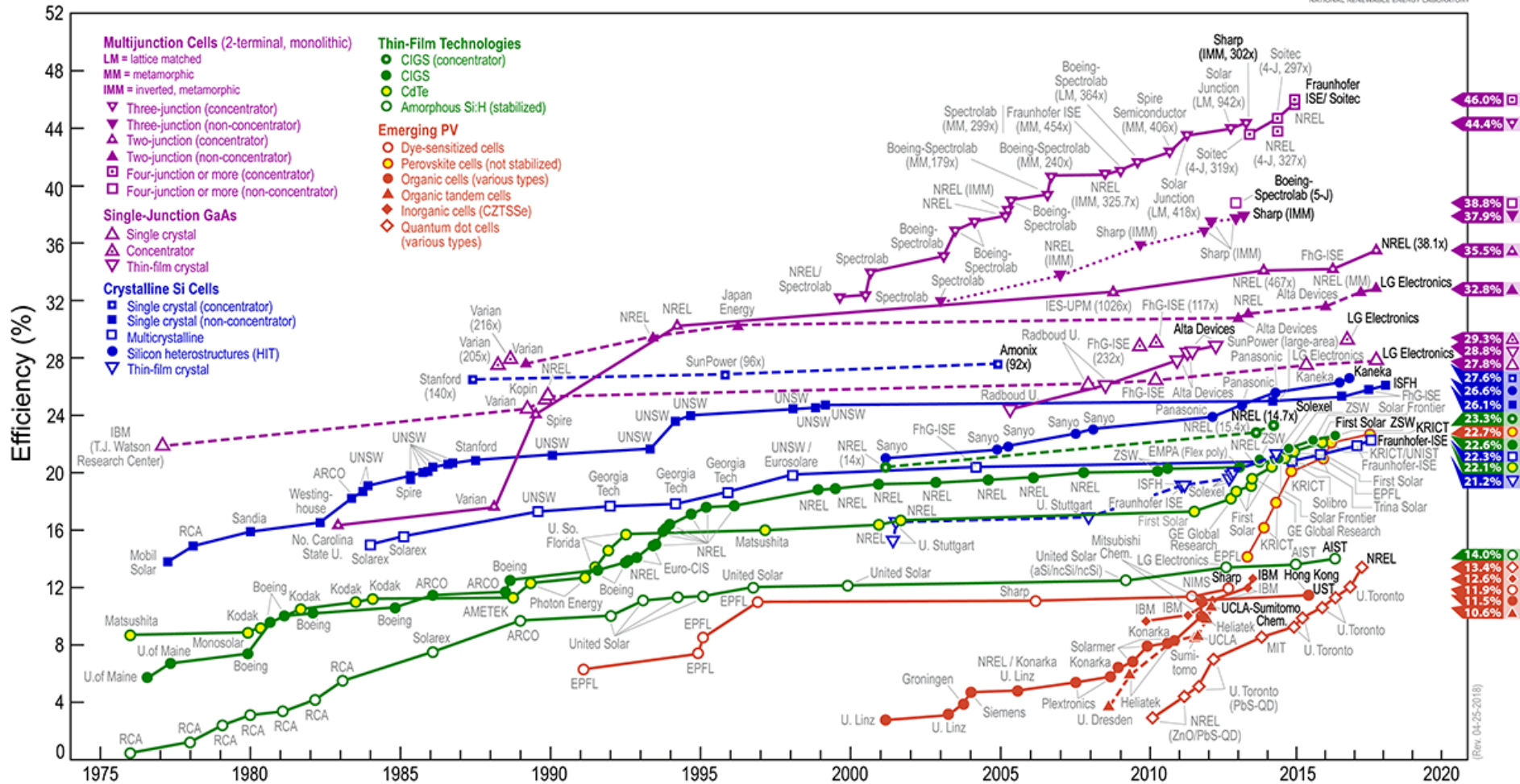
- ◆ Self-supporting.
- ◆ Single crystalline.

NREL National Center for Photovoltaics

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

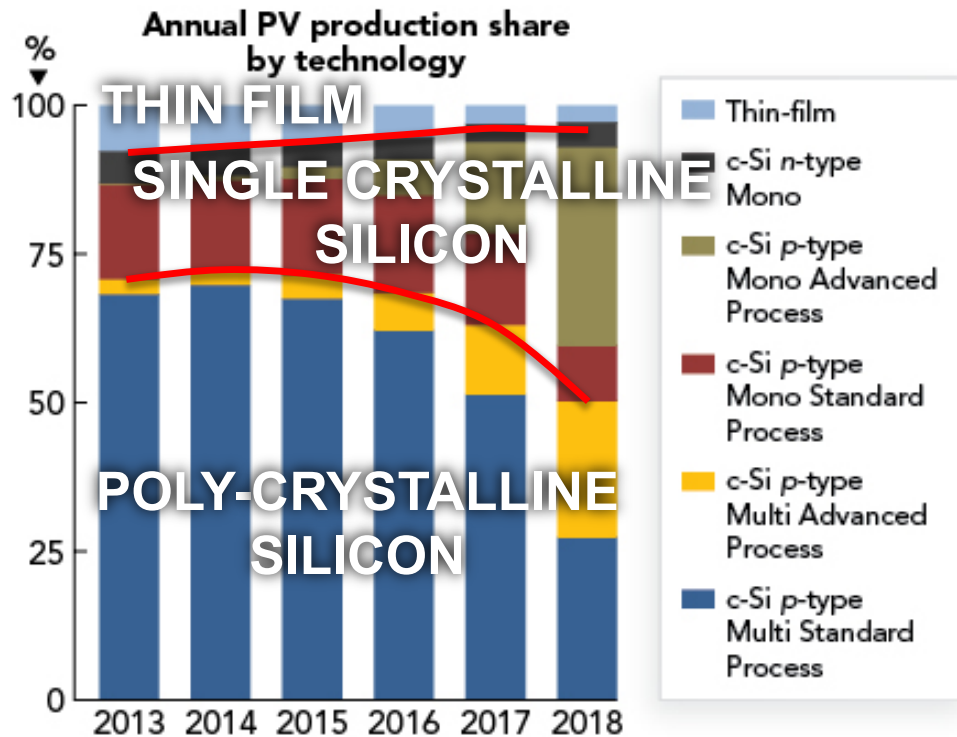


Best Research-Cell Efficiencies



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:

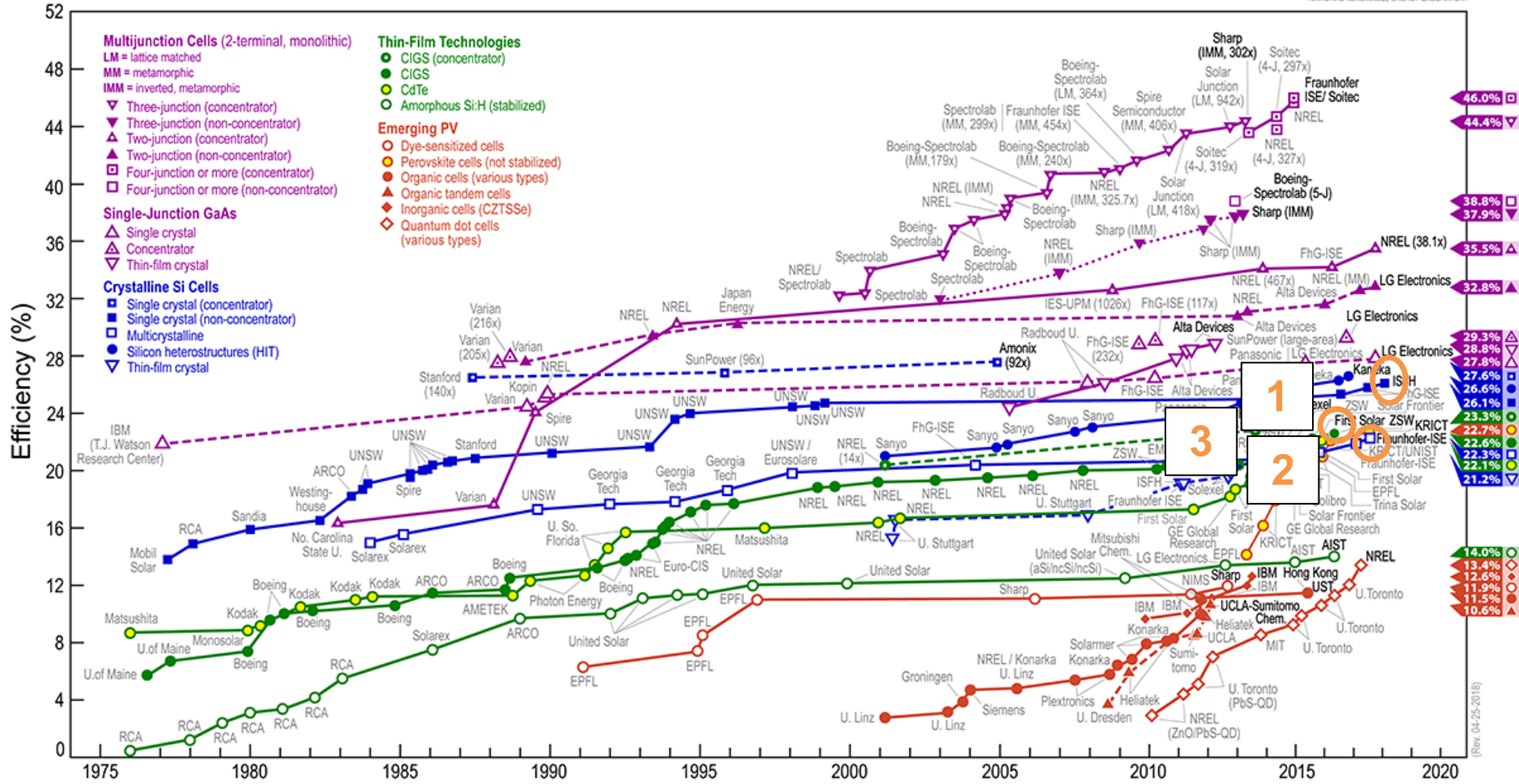


More Detailed Comparison

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



Best Research-Cell Efficiencies



Single-Junction Single-Crystal Si Solar Cells

Crystallinity

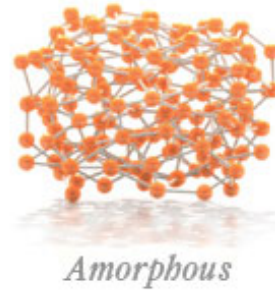
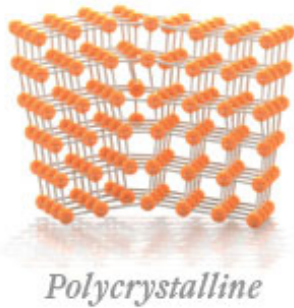
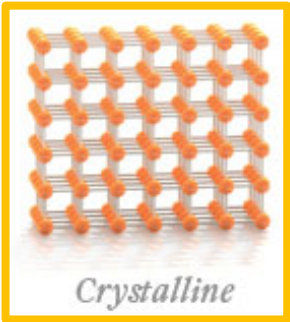


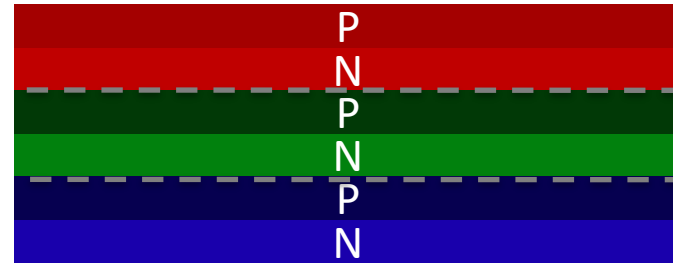
Image from: <http://spectrum.ieee.org/image/1838375>

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

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

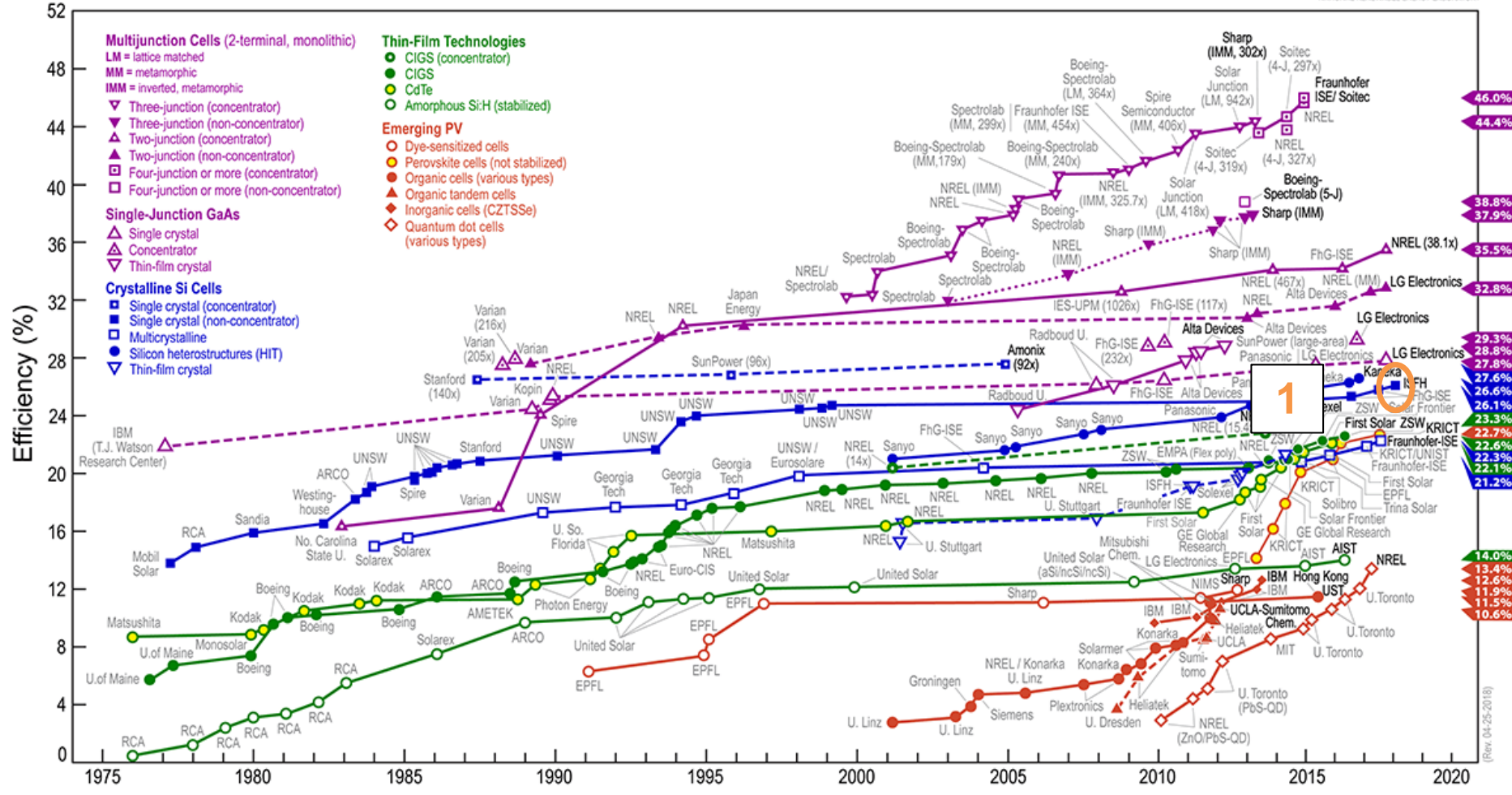
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Efficiency ~ 26%

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



Best Research-Cell Efficiencies



Challenge: *Expensive Manufacturing*



Polycrystalline Si
> 99.9999%

→
1400 °C



<http://www.quora.com/Semiconductor-Fabrication/How-do-silicon-boules-not-break-off-during-semiconductor-fabrication>

Single crystalline Si

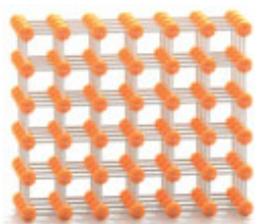
<http://www.youtube.com/watch?v=aWVywhzuHnQ&NR=1>
(start @ 1:48)



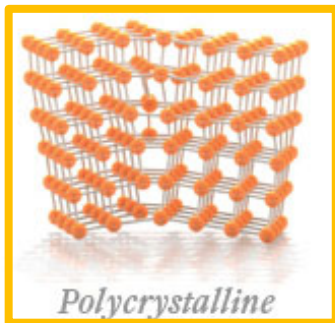
<http://www.products.cvdequipment.com/applications/polysilicon/1/>

Single-Junction Polycrystalline-Crystal Si Cells

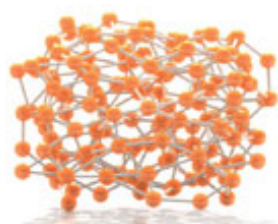
Crystallinity



Crystalline



Polycrystalline



Amorphous

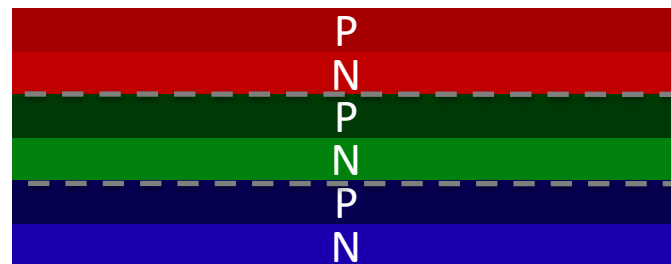
Image from: <http://spectrum.ieee.org/image/1838375>

Number of Junctions

Single-Junction:



Multi-Junction:



Small
Bandgap
Medium
Bandgap
Large
Bandgap

Thick Crystal or Thin Film

Thin-Film

Semiconductor Thin Film

Substrate (Glass / Plastic)

Thick Crystal

Semiconductor Crystal

Composition

Periodic Table of Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18		
1 H Hydrogen 1.008	2 He Helium 4.003		3 Li Lithium 6.941										4 Be Beryllium 9.012	5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305	13 Al Aluminum 26.982										14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948			
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 52.004	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.922	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80		
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.906	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.905	46 Pd Palladium 106.36	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.757	52 Te Tellurium 127.6	53 I Iodine 126.905	54 Xe Xenon 131.29		
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71 La-Lu Lanthanides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.222	78 Pt Platinum 195.084	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)		
87 Fr Francium (223)	88 Ra Radium (226)	89-103 Ac-Lr Actinides	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (263)	107 Bh Bohrium (264)	108 Hs Hassium (265)	109 Mt Meitnerium (266)	110 Ds Darmstadtium (267)	111 Rg Roentgenium (268)	112 Uu Ununbium (269)	113 Uub Ununtrium (270)	114 Uuq Ununquadium (271)	115 Uup Ununpentium (272)	116 Uuq Ununhexium (273)	117 Uuh Ununheptium (274)	118 Uuo Ununoctium (276)		

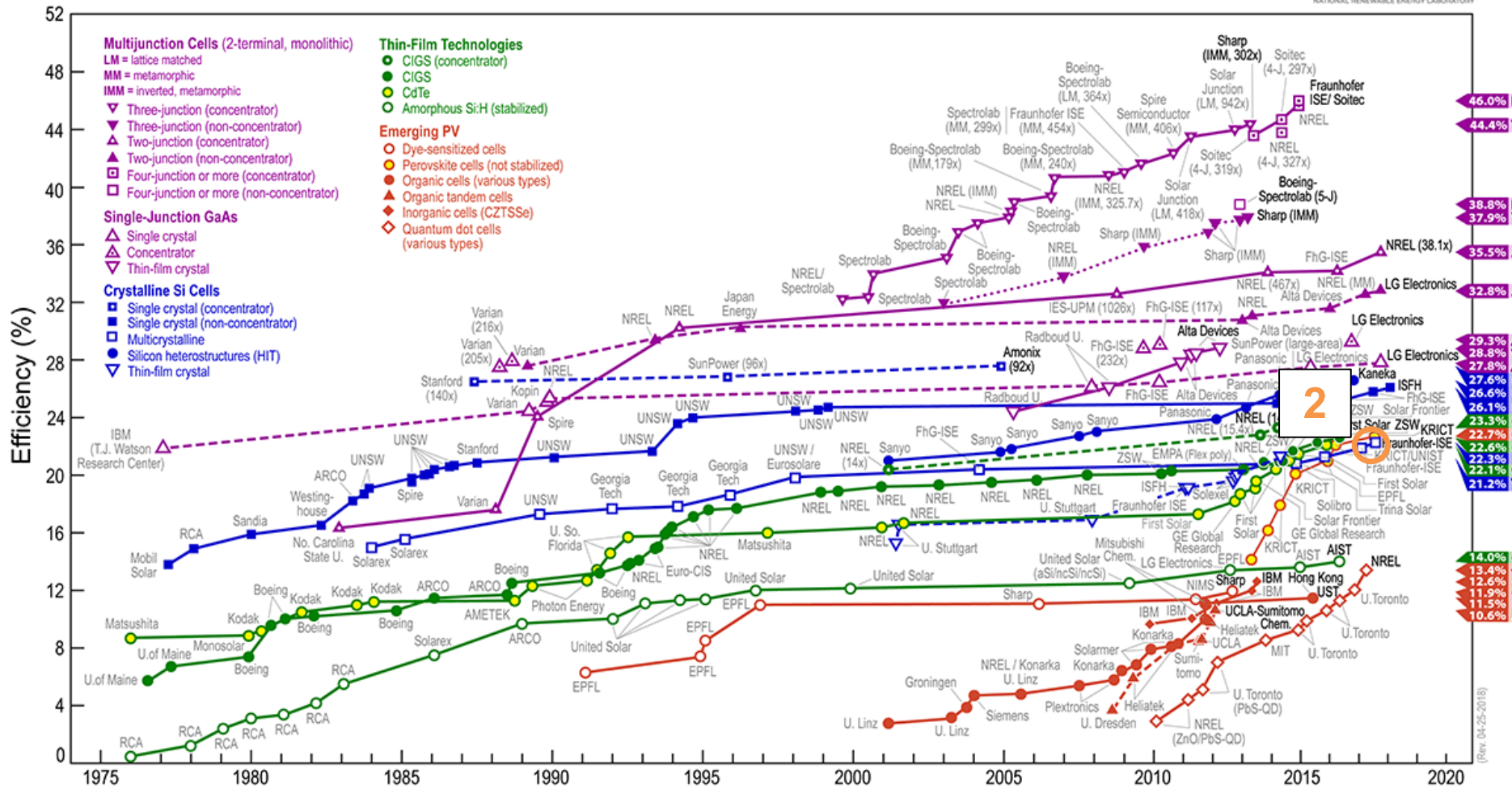
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Efficiency ~ 22%

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



Best Research-Cell Efficiencies



Lower Processing Costs

Deposition by chemical vapor deposition: $\text{SiH}_4 (\text{g}) \rightarrow \text{Si} (\text{s}) + 2\text{H}_2 (\text{g})$, 650 °C



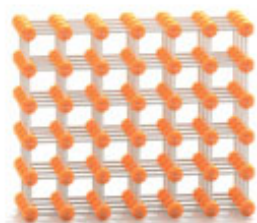
Grains

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

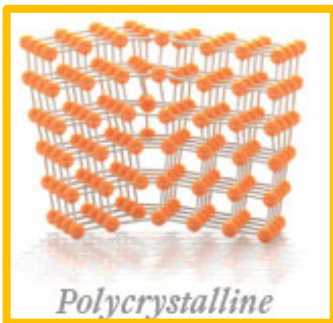
Image from: http://upload.wikimedia.org/wikipedia/commons/1/15/Polycrystalline-silicon-wafer_20060626_568.jpg

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

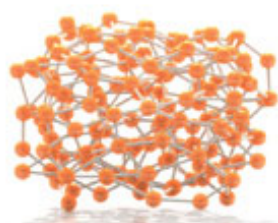
Crystallinity



Crystalline



Polycrystalline



Amorphous

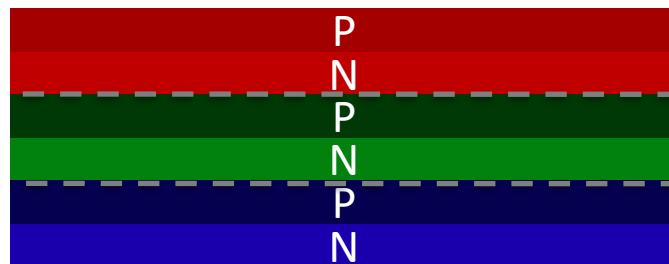
Image from: <http://spectrum.ieee.org/image/1838375>

Number of Junctions

Single-Junction:



Multi-Junction:



Small Bandgap
Medium Bandgap
Large Bandgap

Thick Crystal or Thin Film

Thin-Film

Semiconductor Thin Film
Substrate (Glass / Plastic)

Thick Crystal

Semiconductor Crystal

Composition

Periodic Table of Elements

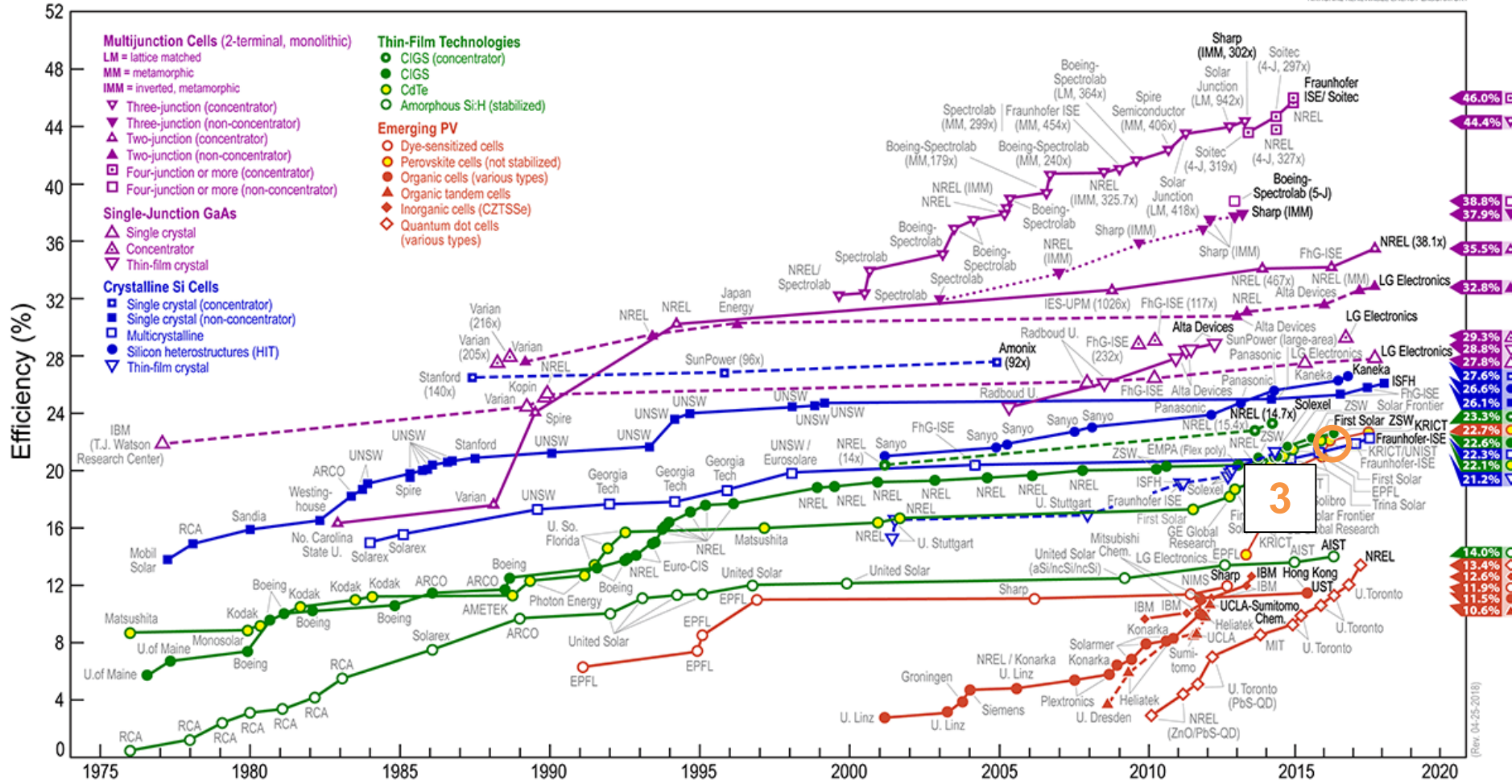
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Efficiency ~ 22-23%

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



Best Research-Cell Efficiencies



Lower Processing and Materials Costs: Vapor Deposited, Thin Films

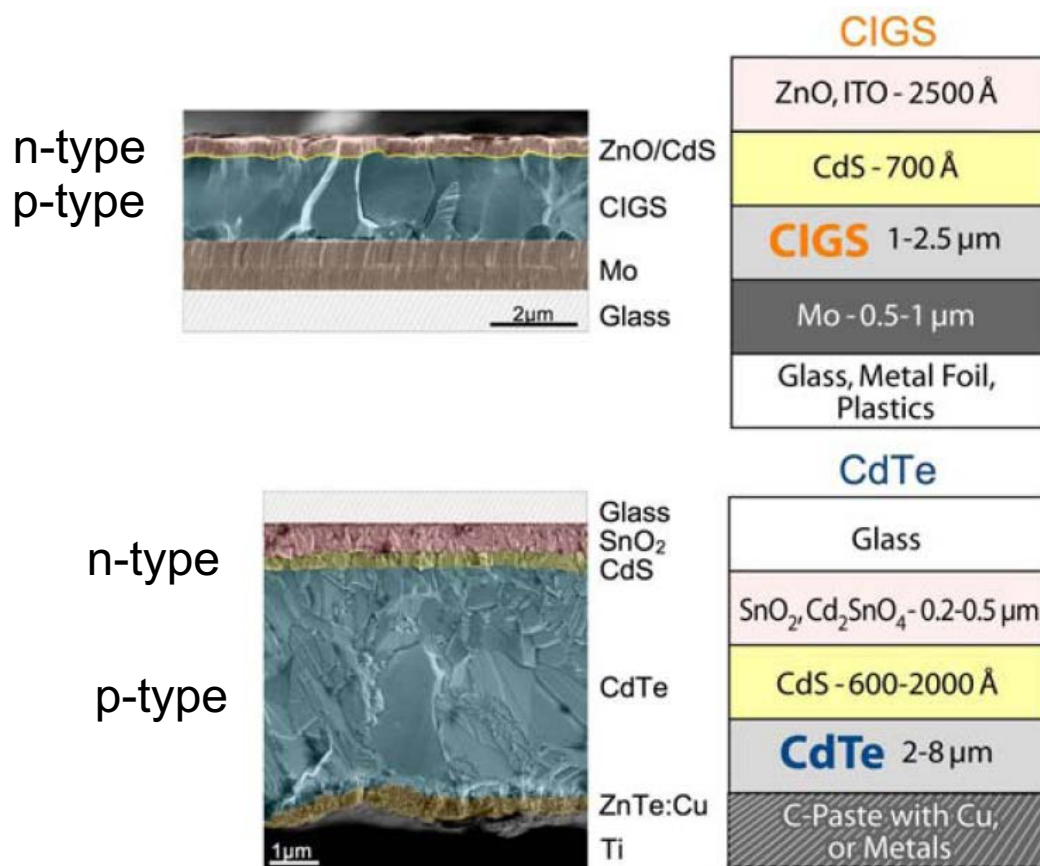
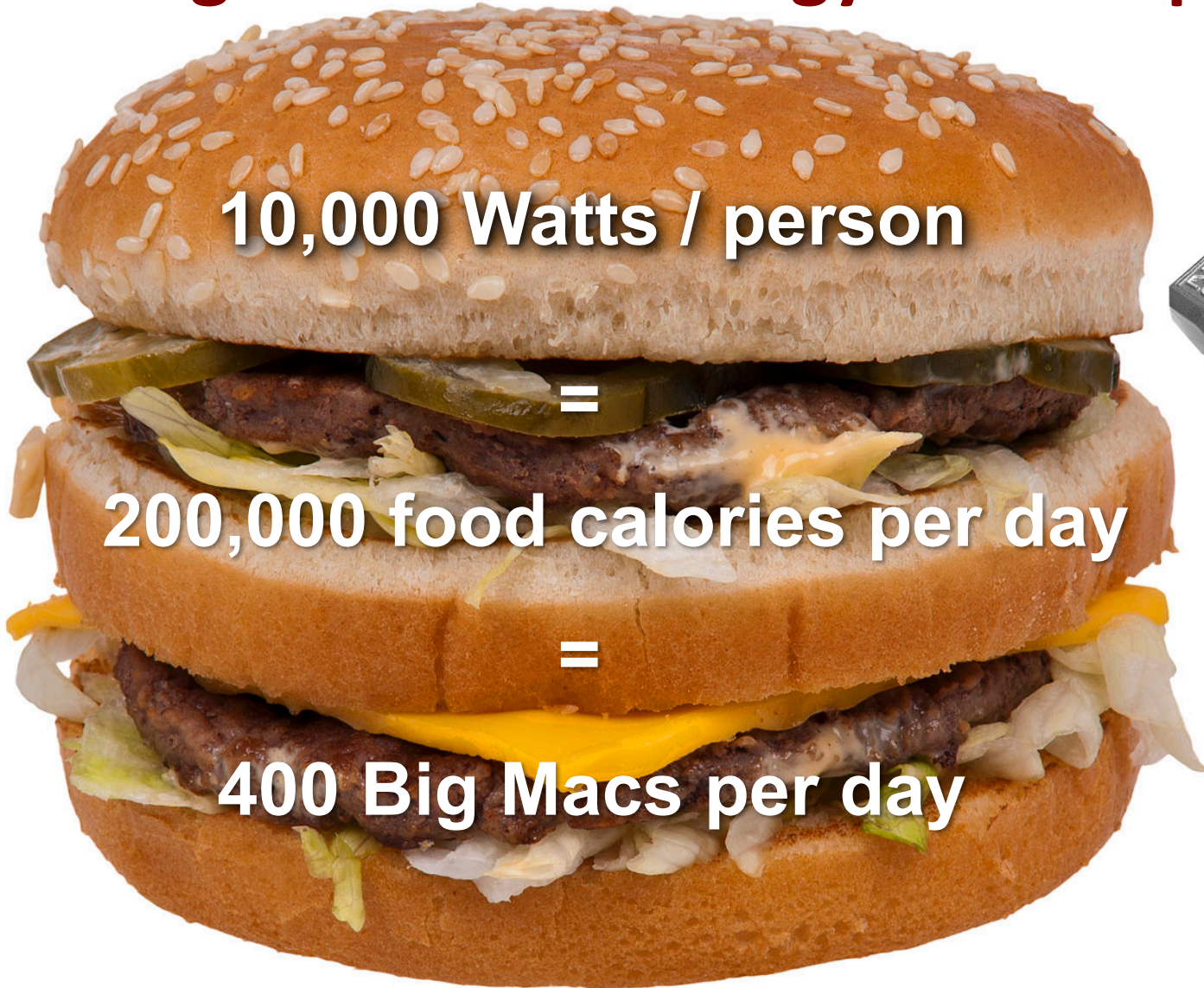


Fig. 1. CdTe and CIGS Device Structure

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



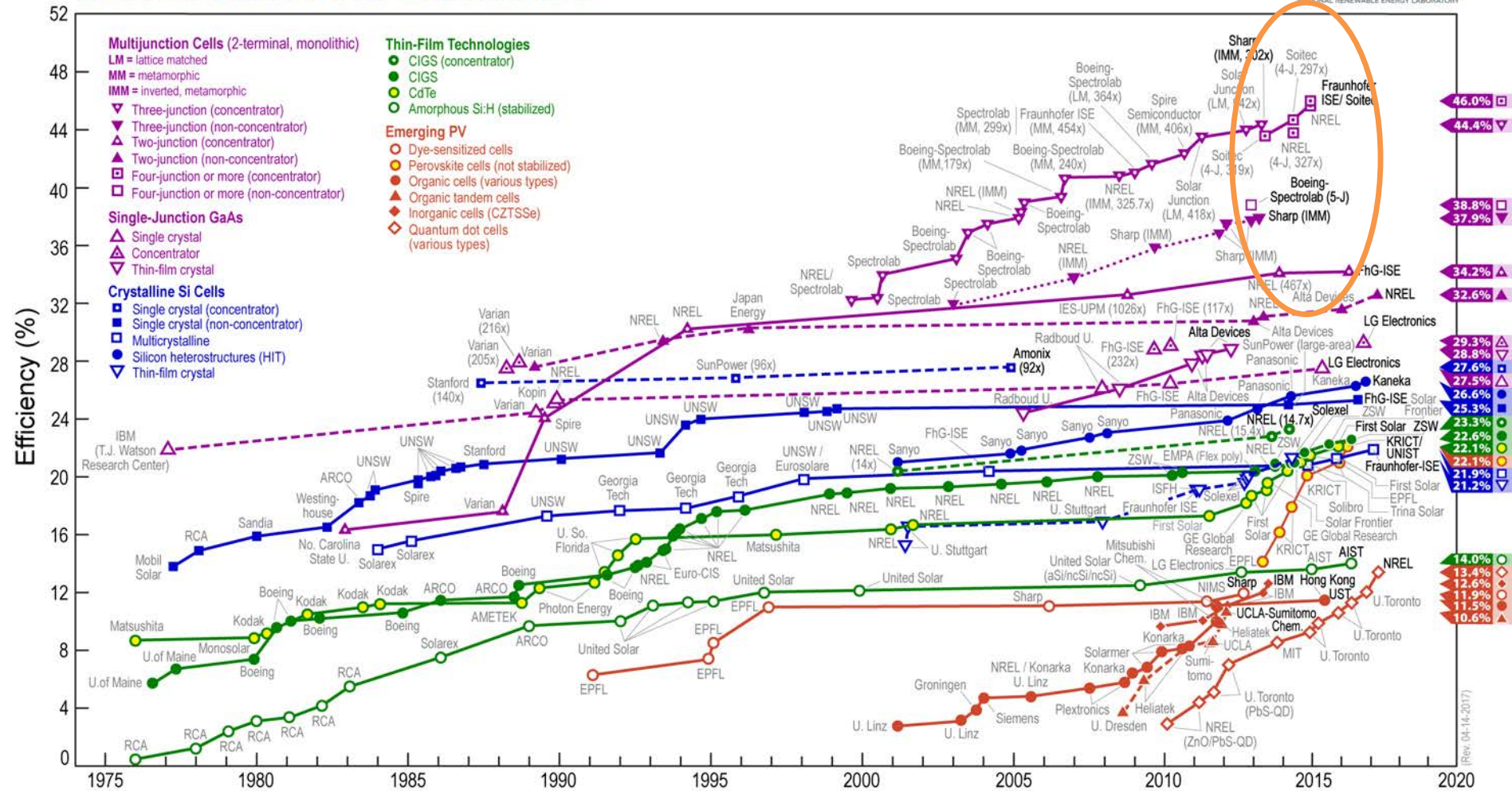
Other Types of Solar Cells

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%)

Best Research-Cell Efficiencies



Multi-Junction Solar Cells

Crystallinity

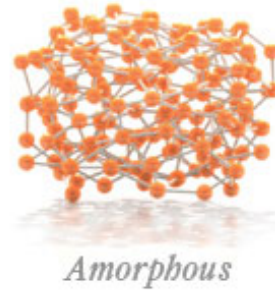
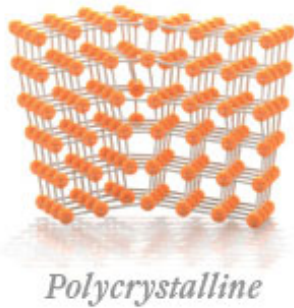
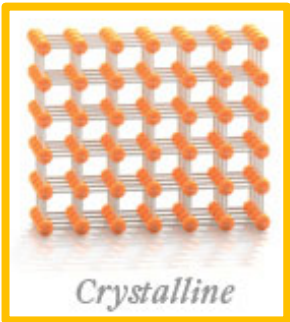


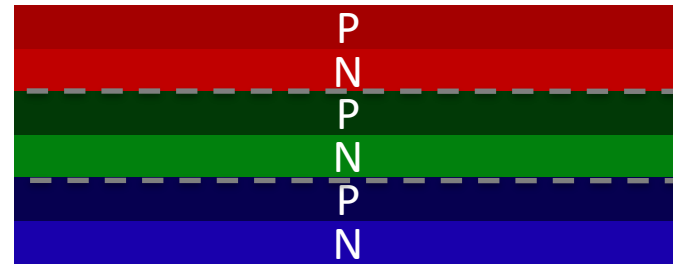
Image from: <http://spectrum.ieee.org/image/1838375>

Number of Junctions

Single-Junction:



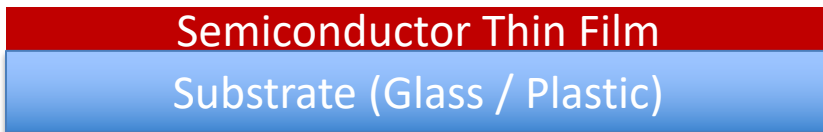
Multi-Junction:



Small Bandgap
Medium Bandgap
Large Bandgap

Thick Crystal or Thin Film

Thin-Film



Thick Crystal



Composition

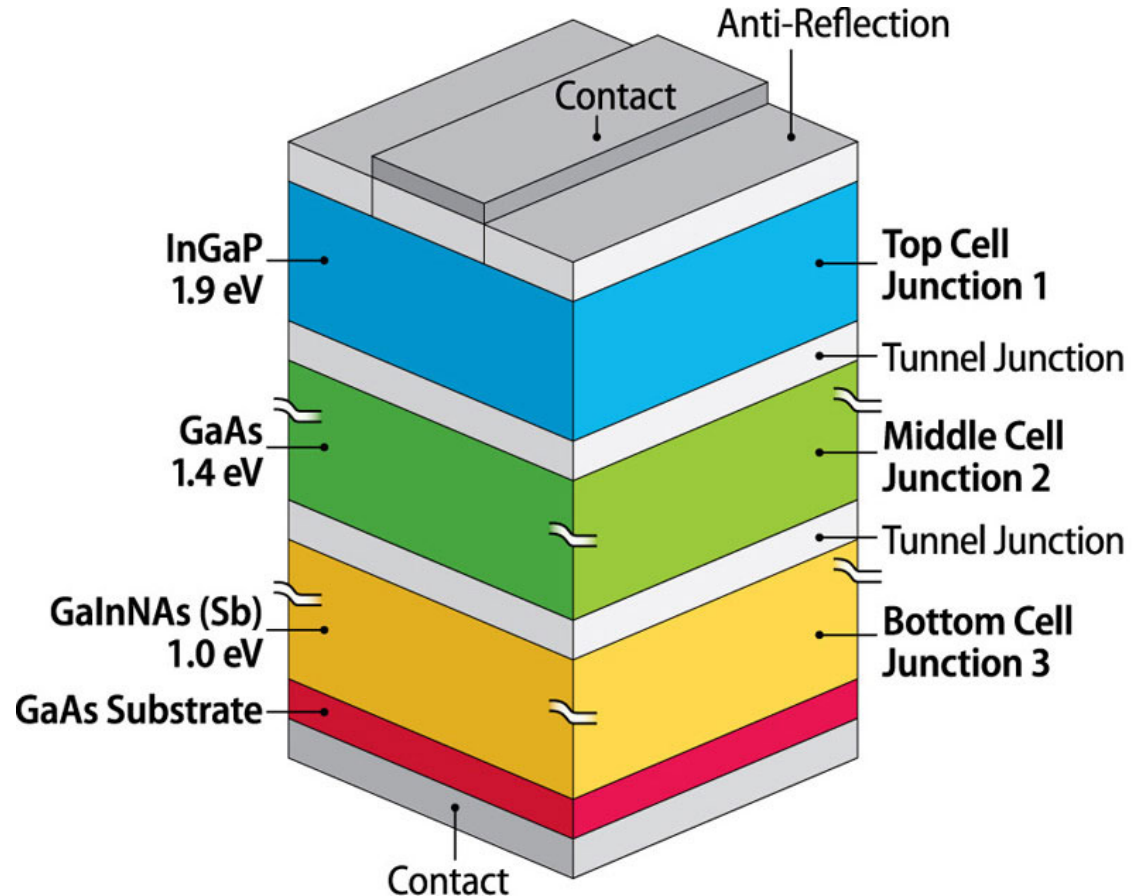
Periodic Table of Elements

For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

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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

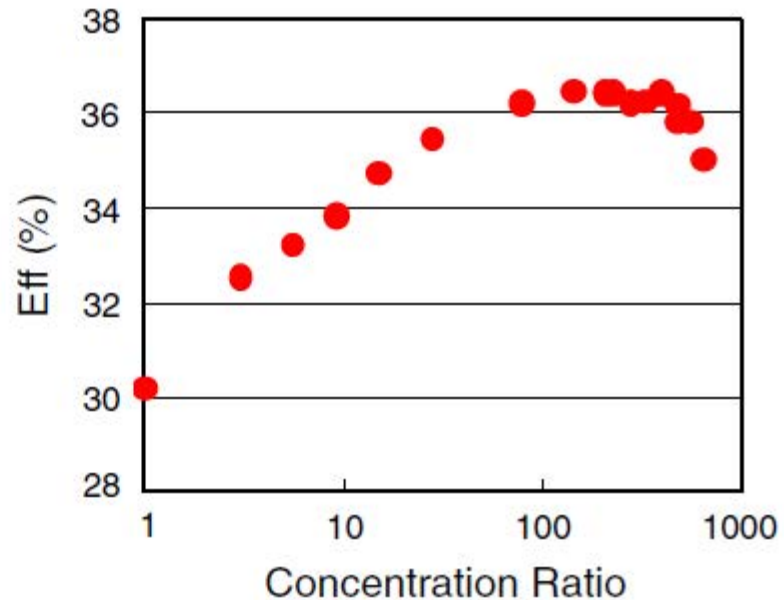
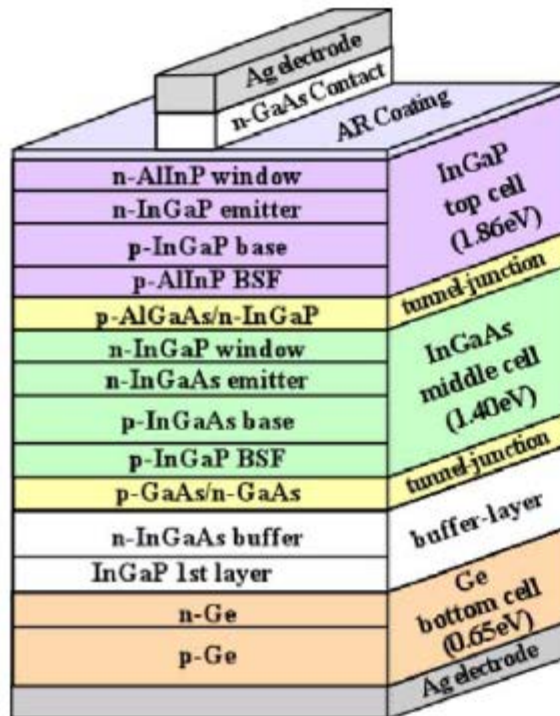


Fig. 5. A schematic cross section of a high-efficiency InGaP/InGaAs/Ge 3-junction solar cell and efficiency of a concentrator cell as a function of concentration ratio.

■ Higher efficiency but much higher cost!

Possible Solution: *Concentrators*

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

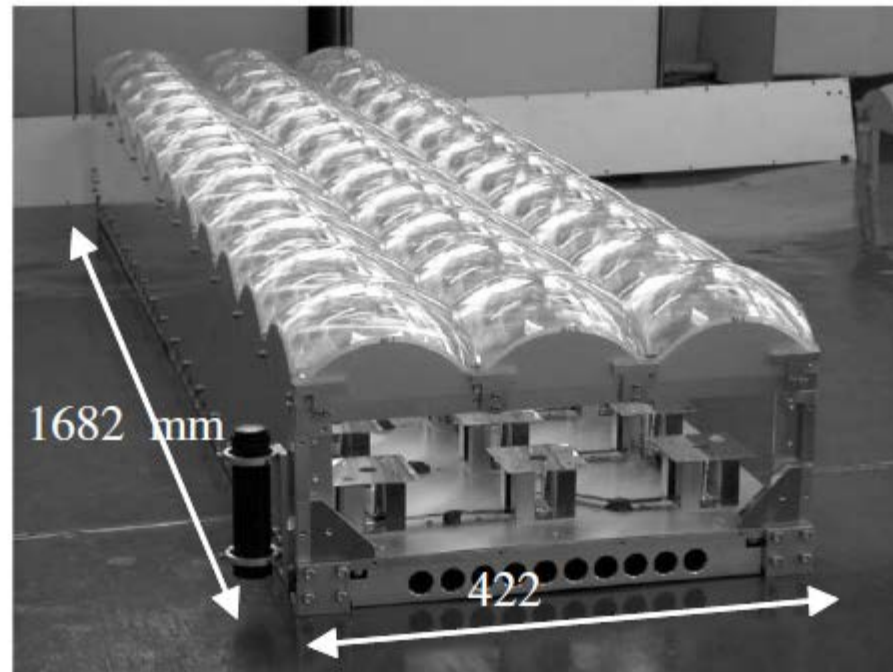
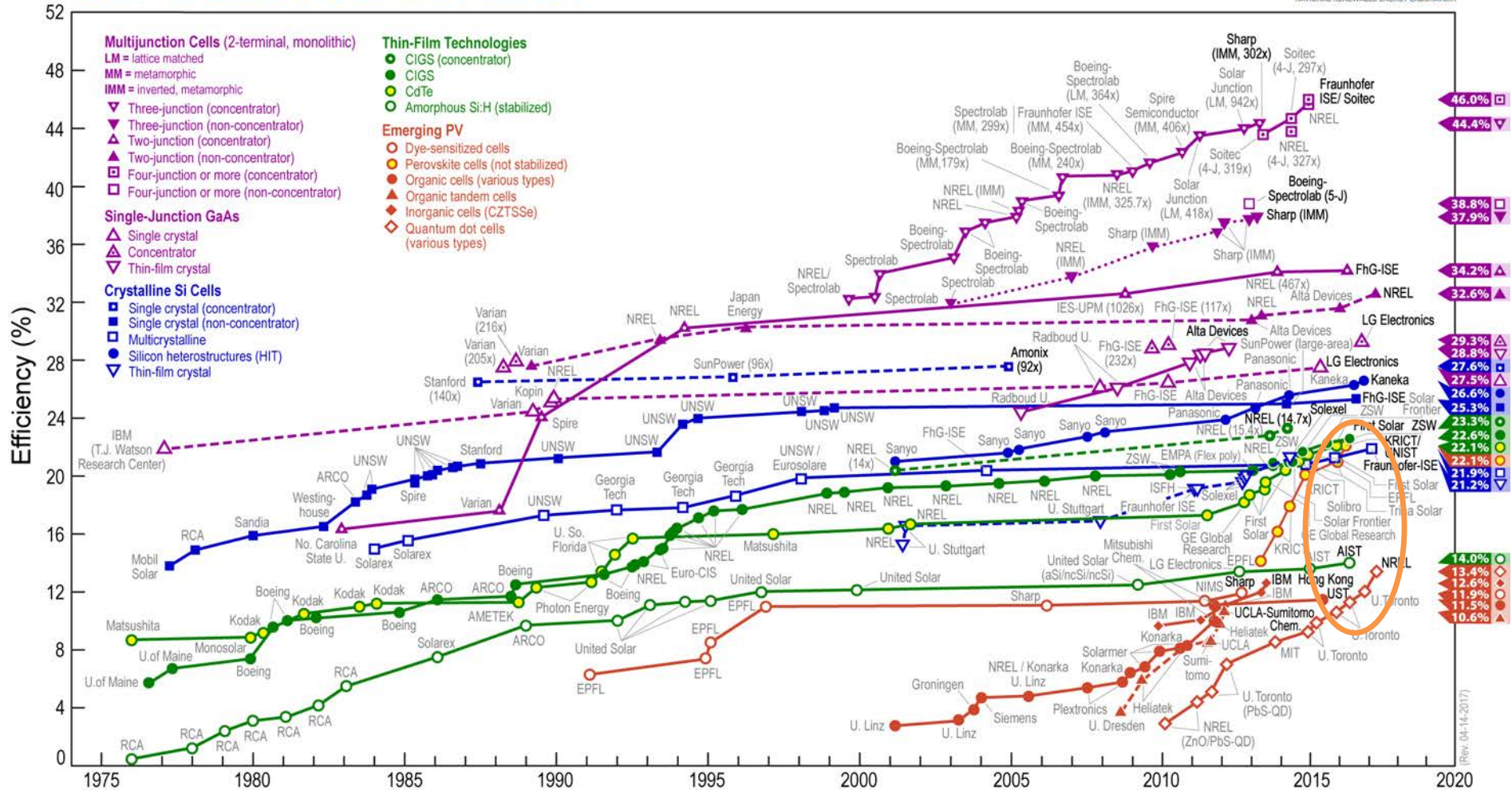


Fig. 6. 7000 cm^2 and $400\times$ concentrator module with the 36 receivers connected in series and dome-shaped Fresnel lens made by injection mold.

- Must track the sun to enable focusing → expensive.

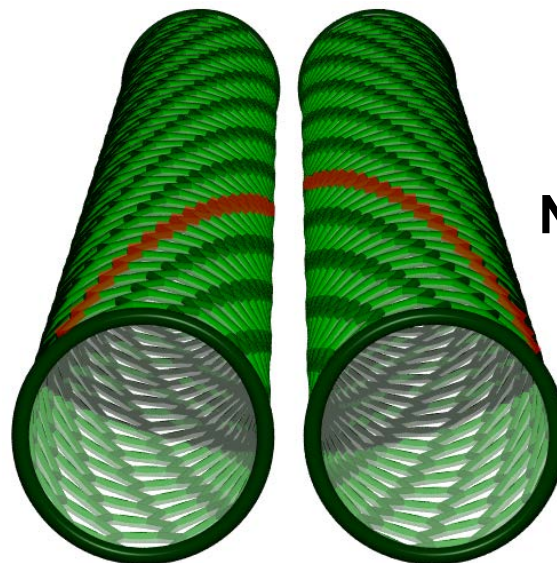
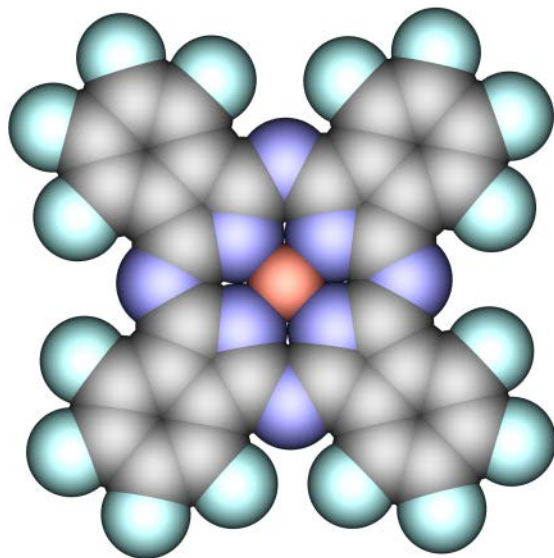
Highly Exploratory Cells

Best Research-Cell Efficiencies



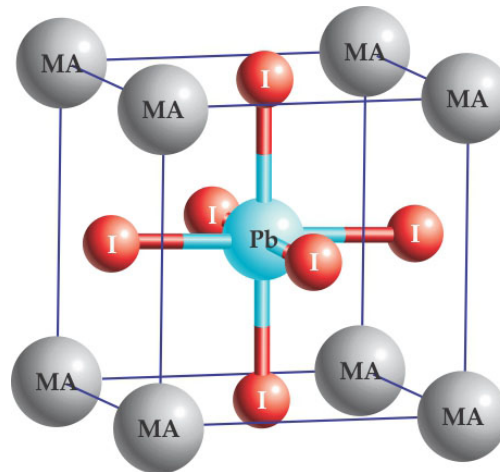
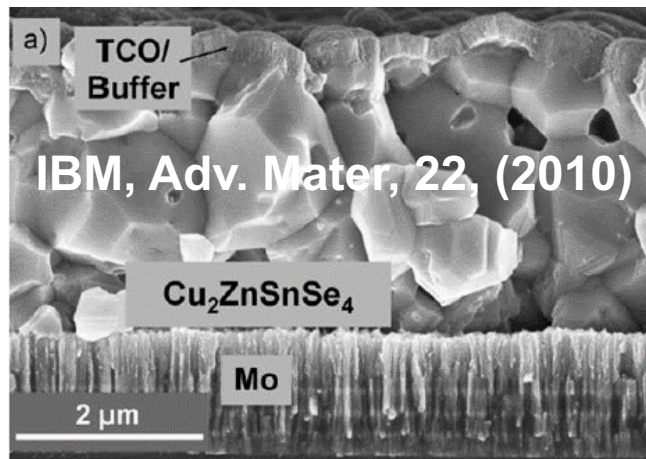
Highly Exploratory Cells: *New Materials*

Organic molecules & polymers



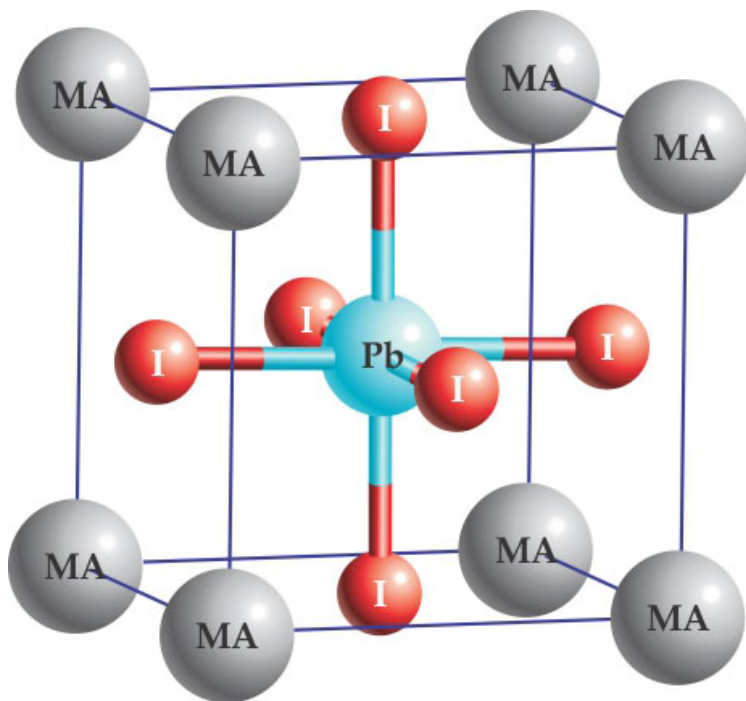
Nanotechnology
(quantum dots
and carbon
nanotubes)

New
inorganic
semi-
conductors

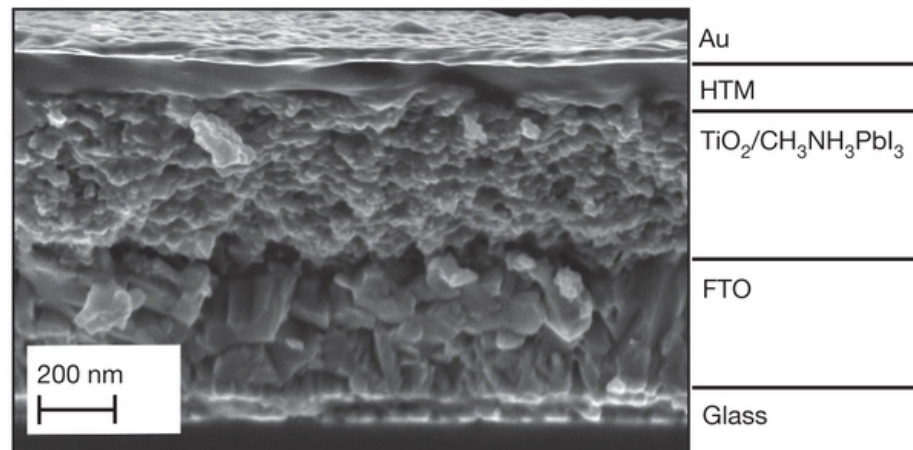


Inorganic/or
ganic hybrid
perovskites

Organic-Inorganic Hybrid Perovskites



MA = methylammonium



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

<http://scitation.aip.org/docserver/fulltext/pt.5.7058figure1.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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and Engineering**
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Madison, WI 53706
TEL 608-262-3863
michael.arnold@wisc.edu

