

# PV System Components

- PV modules each containing many PC cells. Connected in series or parallel **arrays**.
- Charge Controllers – Optimally charges a **storage battery** for an *off-grid* system, or...
- Grid-tie Inverters – Most residential apps. Converts solar DC to AC synchronized with utility power, to push power back into the grid.
- Balance of System (BOS)  
Panel-mounting hardware and structures, electrical connection hardware, overcurrent protection, disconnect switchgear, grounding hardware

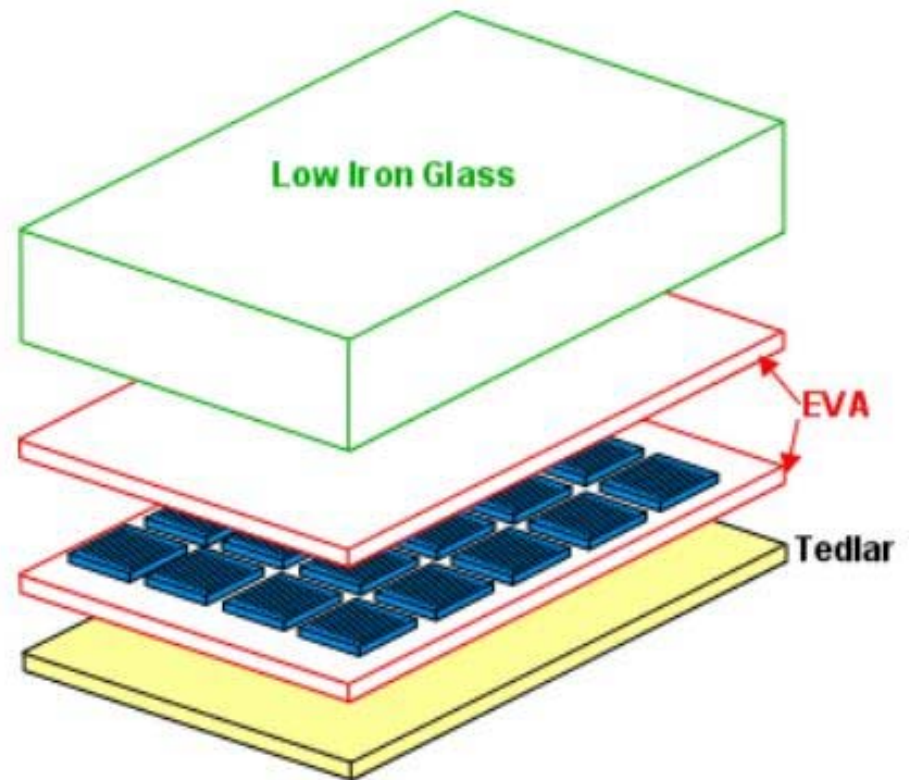


# Photovoltaic Cells

- Each *individual cell* in a PV array is essentially a 'large area' diode that *produces current in the reverse-bias direction due to incident light*
- Single-crystal Silicon PV cells, 156 mm diameter:
  - open circuit voltage  $\sim$  0.6 volts
  - 3-7 Watts per cell
- A panel typically has between 60 and 96 cells in series, to provide 36-57 volts at 3-7 amps
- PV arrays use several panels in series to produce up to 600 volts at 3-7 amps

# Solar Modules

- A simplified silicon PV module sandwich:
  - Transparent top surface (glass)
  - Encapsulant (EVA - ethyl vinyl acetate)
  - Rear layer (Tedlar or similar UV-durable protective cover)
  - Frame

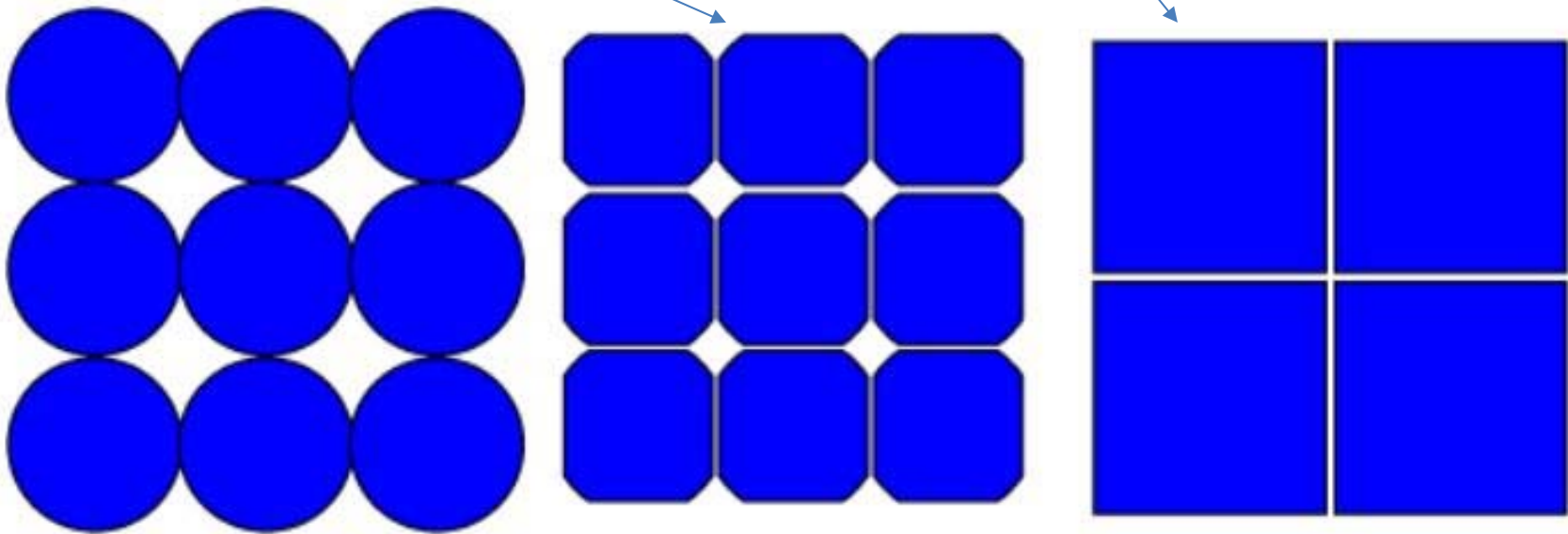


# Solar Modules

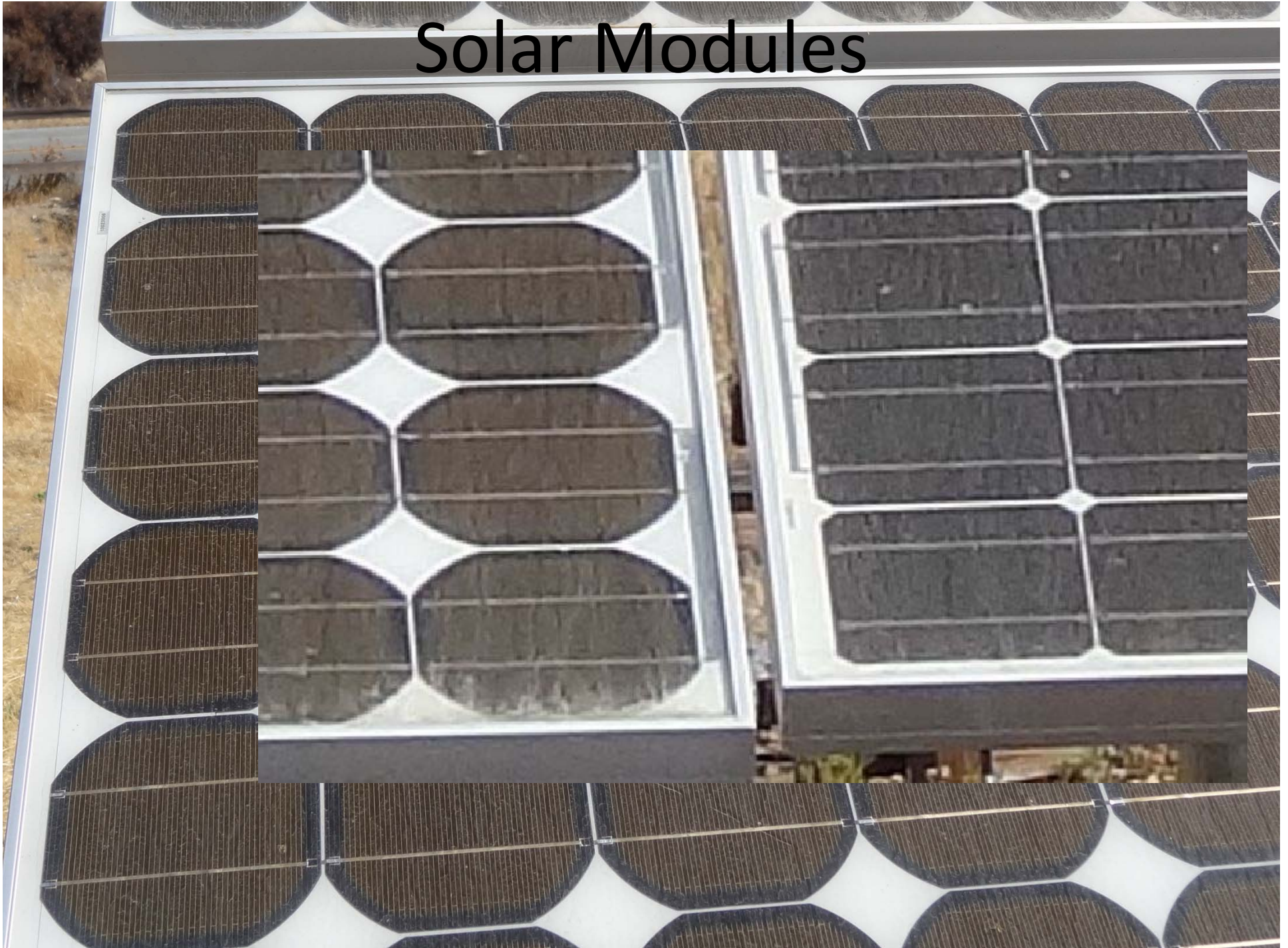


# Some Solar Cell Shapes

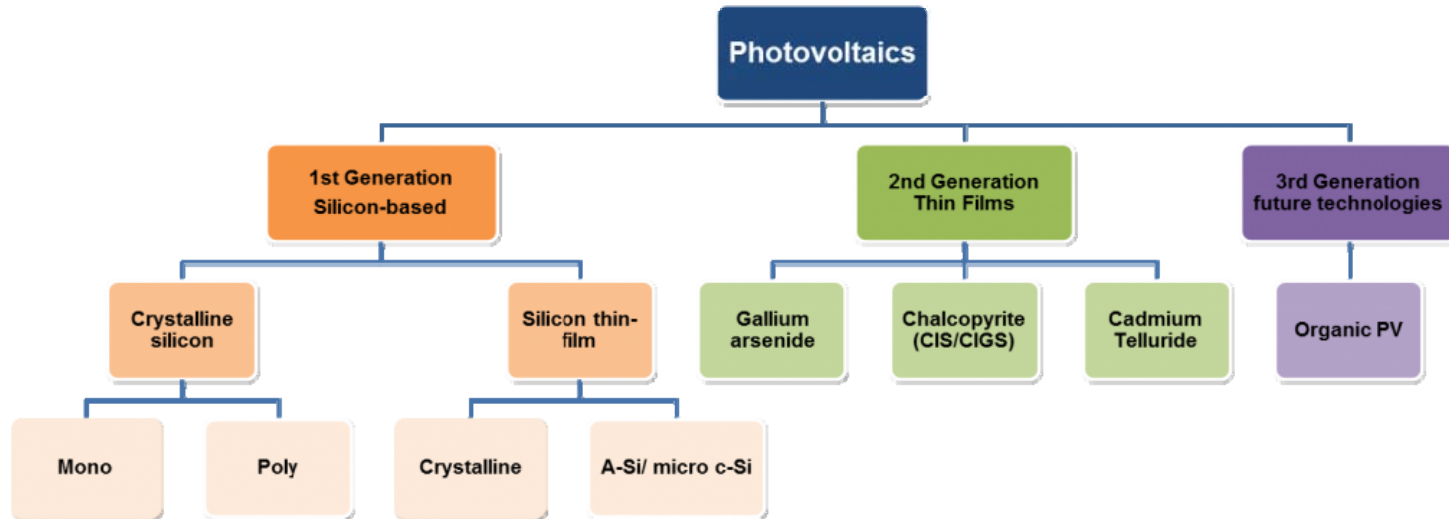
- Monocrystalline from round ingots (to achieve higher packing density edges are cut off)
- Polycrystalline material cast in square blocks



# Solar Modules



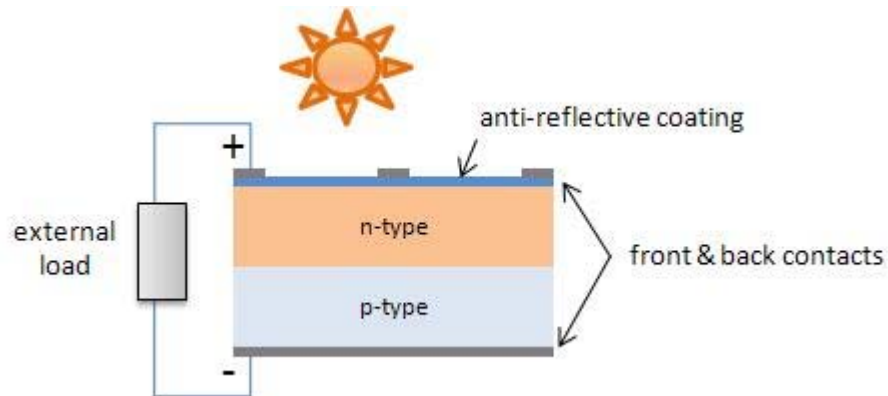
# Photovoltaic (PV) Technologies



- Silicon Monocrystalline
- Silicon Polycrystalline
- Amorphous Silicon (aSi)
- Cadmium telluride (CdTe)
- Copper Indium Gallium Selenide (CIGS)
- Gallium Arsenide
- Organic PV

# Silicon - Monocrystalline or single-crystal

- Made from the same pure-silicon crystal growth process used for production of wafers for integrated circuits

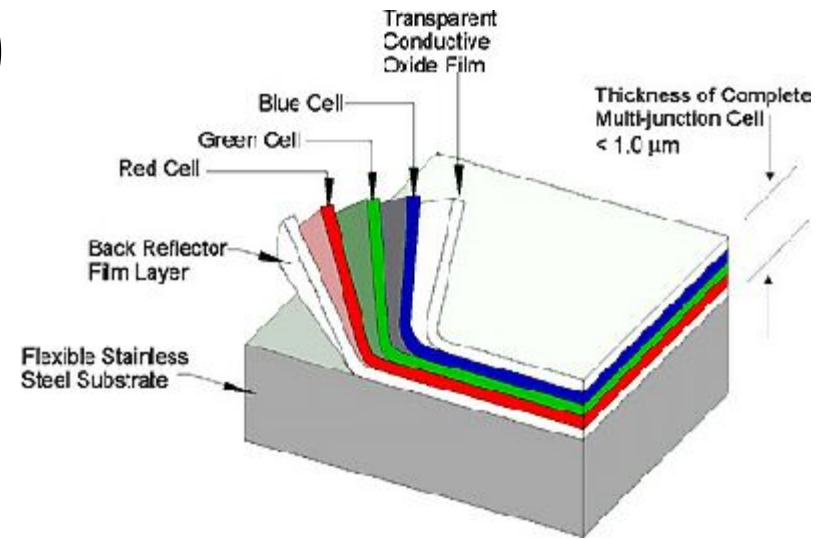


- Highest power and efficiency
- Most expensive per cell
- About 25% of the world-wide PV market



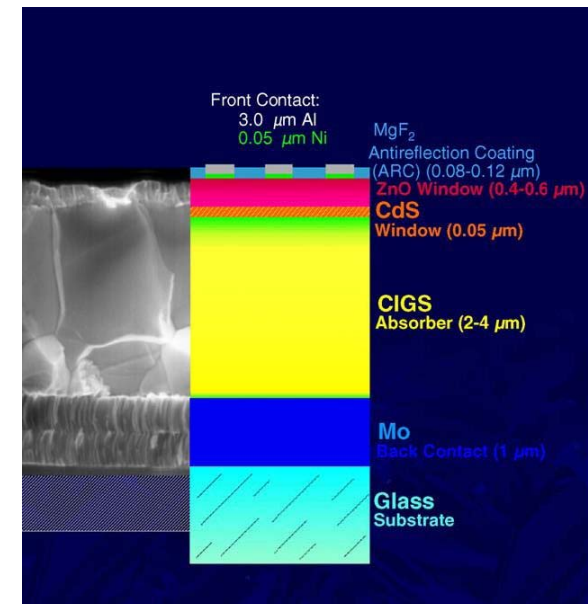
# Silicon Polycrystalline (multicrystalline)

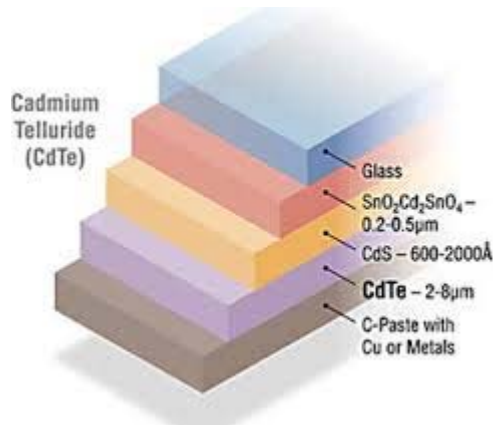
- Uses cast silicon instead of single crystal
- Can be recognized by a visible grain (cell usually square)
- Low cost, durable
- Easy to manufacture
- Efficiencies 12-18% (70%-80% of mono)
- Minimal hazardous materials – good end-of-life
- Greater efficiency reduction with temperature
- About 65% of the worldwide PV market, strong market competition



# CIGS (Copper Indium Gallium Selenide)

- Solyndra, Nanosolar, Miasole
- Most common thin-film and flexible panel technology
- Manufacturing process is more difficult
- Medium efficiency, < 20%
- Less sensitive to temperature effects than Silicon
- Lower environmental concerns than CdTe
- Current cost is high





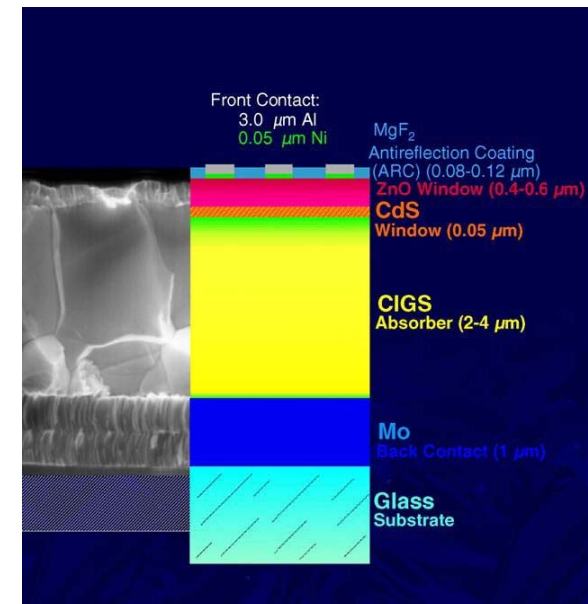
# Cadmium Telluride

- First Solar, Advanced Solar Power, GE Solar
- Most often used for *thin-film* PV cells
- Moderate cost materials
- Medium conversion efficiency, typically 16%
- Can easily be made into flexible panels
- Manufacturing process is relatively easy and low-cost
- Cadmium is abundant, but not so sure about Telluride
- Cadmium and CdTe are extremely toxic: end-of-life issues



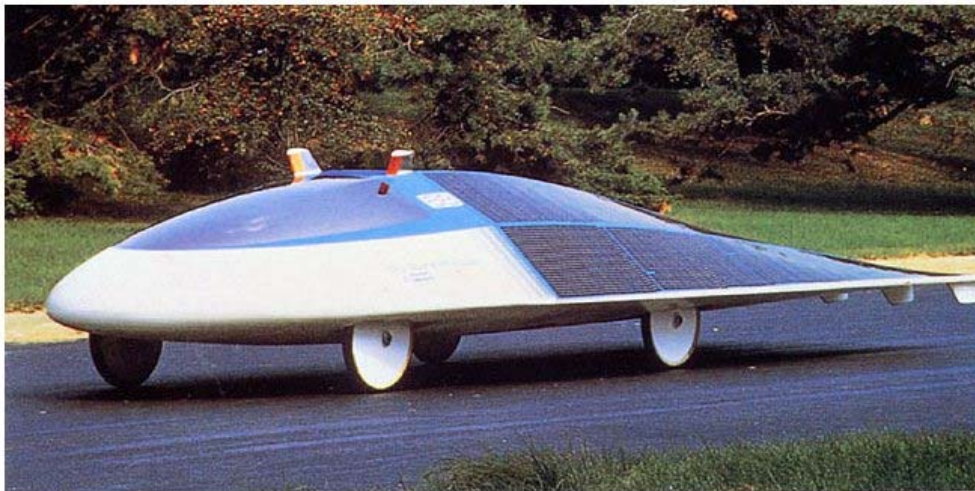
# CIGS (Copper Indium Gallium Selenide)

- Solyndra, Nanosolar, Miasole
- Most common thin-film and flexible panel technology
- Manufacturing process is more difficult
- Medium efficiency, 15 - 18%
- Less sensitive to temperature effects than Silicon
- Lower environmental concerns than CdTe
- Current cost is high



# Gallium Arsenide

- A compound semiconductor – see periodic table next slide
- Most efficient – holds world record for single-layer cell efficiency: 28.8%
- Most expensive PV technology
- Used in applications where cost is not a factor, e.g., spacecraft, 1987 GM SunRaycer
- Not in use for residential or utility solar PV



# Periodic Table of Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18														
1 <b>H</b> Hydrogen 1.00794	Atomic # Name Symbol Atomic Mass																2 <b>He</b> Helium 4.002602														
3 <b>Li</b> Lithium 6.941	4 <b>Be</b> Beryllium 9.012182	<div style="display: flex; justify-content: space-between;"> <div style="width: 20%;"> <p><b>C</b> Solid</p> <p><b>Hg</b> Liquid</p> <p><b>H</b> Gas</p> <p><b>Rf</b> Unknown</p> </div> <div style="width: 60%; border: 1px solid black; padding: 5px;"> <p style="text-align: center;"><b>Metals</b></p> <div style="display: flex; justify-content: space-between;"> <div style="width: 15%; background-color: #FFD700; padding: 2px;">Alkali metals</div> <div style="width: 15%; background-color: #FFD700; padding: 2px;">Alkaline earth metals</div> <div style="width: 15%; background-color: #FFDAB9; padding: 2px;">Lanthanoids</div> <div style="width: 15%; background-color: #FFDAB9; padding: 2px;">Actinoids</div> <div style="width: 15%; background-color: #FFDAB9; padding: 2px;">Transition metals</div> <div style="width: 15%; background-color: #FFDAB9; padding: 2px;">Poor metals</div> </div> </div> <div style="width: 20%; border-left: 1px solid black; padding-left: 5px;"> <p style="text-align: center;"><b>Nonmetals</b></p> <div style="display: flex; justify-content: space-between;"> <div style="width: 15%; background-color: #90EE90; padding: 2px;">Other nonmetals</div> <div style="width: 15%; background-color: #90EE90; padding: 2px;">Noble gases</div> </div> </div> </div>																5 <b>B</b> Boron 10.811	6 <b>C</b> Carbon 12.0107	7 <b>N</b> Nitrogen 14.0067	8 <b>O</b> Oxygen 15.9994	9 <b>F</b> Fluorine 18.9984032	10 <b>Ne</b> Neon 20.1797	11 <b>Na</b> Sodium 22.98976928	12 <b>Mg</b> Magnesium 24.3050	13 <b>Al</b> Aluminum 26.9815386	14 <b>Si</b> Silicon 28.0855	15 <b>P</b> Phosphorus 30.973762	16 <b>S</b> Sulfur 32.065	17 <b>Cl</b> Chlorine 35.453	18 <b>Ar</b> Argon 39.948
19 <b>K</b> Potassium 39.0983	20 <b>Ca</b> Calcium 40.078	21 <b>Sc</b> Scandium 44.955912	22 <b>Ti</b> Titanium 47.887	23 <b>V</b> Vanadium 50.9415	24 <b>Cr</b> Chromium 51.9961	25 <b>Mn</b> Manganese 54.938045	26 <b>Fe</b> Iron 55.845	27 <b>Co</b> Cobalt 58.933195	28 <b>Ni</b> Nickel 58.6934	29 <b>Cu</b> Copper 63.546	30 <b>Zn</b> Zinc 65.38	31 <b>Ga</b> Gallium 69.723	32 <b>Ge</b> Germanium 72.64	33 <b>As</b> Arsenic 74.92160	34 <b>Se</b> Selenium 78.96	35 <b>Br</b> Bromine 79.904	36 <b>Kr</b> Krypton 83.798														
37 <b>Rb</b> Rubidium 85.4678	38 <b>Sr</b> Strontium 87.62	39 <b>Y</b> Yttrium 88.90585	40 <b>Zr</b> Zirconium 91.224	41 <b>Nb</b> Niobium 92.90638	42 <b>Mo</b> Molybdenum 95.95	43 <b>Tc</b> Technetium (97.9072)	44 <b>Ru</b> Ruthenium 101.07	45 <b>Rh</b> Rhodium 102.90550	46 <b>Pd</b> Palladium 106.42	47 <b>Ag</b> Silver 107.8682	48 <b>Cd</b> Cadmium 112.411	49 <b>In</b> Indium 114.818	50 <b>Sn</b> Tin 118.710	51 <b>Sb</b> Antimony 121.760	52 <b>Te</b> Tellurium 127.60	53 <b>I</b> Iodine 126.90447	54 <b>Xe</b> Xenon 131.293														
55 <b>Cs</b> Caesium 132.9054519	56 <b>Ba</b> Barium 137.327	57-71		72 <b>Hf</b> Hafnium 178.49	73 <b>Ta</b> Tantalum 180.94788	74 <b>W</b> Tungsten 183.84	75 <b>Re</b> Rhenium 186.207	76 <b>Os</b> Osmium 190.23	77 <b>Ir</b> Iridium 192.217	78 <b>Pt</b> Platinum 195.084	79 <b>Au</b> Gold 196.966569	80 <b>Hg</b> Mercury 200.59	81 <b>Tl</b> Thallium 204.3833	82 <b>Pb</b> Lead 207.2	83 <b>Bi</b> Bismuth 208.98040	84 <b>Po</b> Polonium (209.9824)	85 <b>At</b> Astatine (209.9871)	86 <b>Rn</b> Radon (222.0176)													
87 <b>Fr</b> Francium (223)	88 <b>Ra</b> Radium (226)	89-103		104 <b>Rf</b> Rutherfordium (261)	105 <b>Db</b> Dubnium (262)	106 <b>Sg</b> Seaborgium (266)	107 <b>Bh</b> Bohrium (264)	108 <b>Hs</b> Hassium (277)	109 <b>Mt</b> Meitnerium (268)	110 <b>Ds</b> Darmstadtium (271)	111 <b>Rg</b> Roentgenium (272)	112 <b>Uub</b> Ununbium (285)	113 <b>Uut</b> Ununtrium (284)	114 <b>Uuq</b> Ununquadium (289)	115 <b>Uup</b> Ununpentium (288)	116 <b>Uuh</b> Ununhexium (282)	117 <b>Uus</b> Ununseptium	118 <b>Uuo</b> Ununoctium (294)													

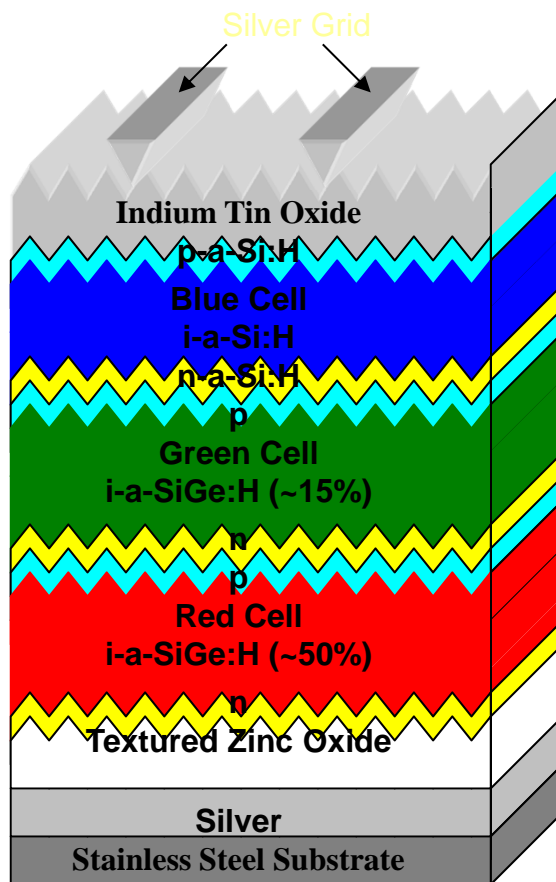
For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

Design and Interface Copyright © 1997 Michael Dayah (michael@dayah.com). <http://www.ptable.com/>



57 <b>La</b> Lanthanum 138.90547	58 <b>Ce</b> Cerium 140.116	59 <b>Pr</b> Praseodymium 140.90765	60 <b>Nd</b> Neodymium 144.242	61 <b>Pm</b> Promethium (145)	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.964	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 158.92535	66 <b>Dy</b> Dysprosium 162.500	67 <b>Ho</b> Holmium 164.93032	68 <b>Er</b> Erbium 167.259	69 <b>Tm</b> Thulium 168.93421	70 <b>Yb</b> Ytterbium 173.054	71 <b>Lu</b> Lutetium 174.9668
89 <b>Ac</b> Actinium (227)	90 <b>Th</b> Thorium 232.03806	91 <b>Pa</b> Protactinium 231.03588	92 <b>U</b> Uranium 238.02891	93 <b>Np</b> Neptunium (237)	94 <b>Pu</b> Plutonium (244)	95 <b>Am</b> Americium (243)	96 <b>Cm</b> Curium (247)	97 <b>Bk</b> Berkelium (247)	98 <b>Cf</b> Californium (251)	99 <b>Es</b> Einsteinium (252)	100 <b>Fm</b> Fermium (257)	101 <b>Md</b> Mendelevium (258)	102 <b>No</b> Nobelium (259)	103 <b>Lr</b> Lawrencium (262)

# Tandem, multi-layer or multi-junction cells



Schematic diagram of state-of-the-art a-Si:H based substrate n-i-p triple junction cell structure.

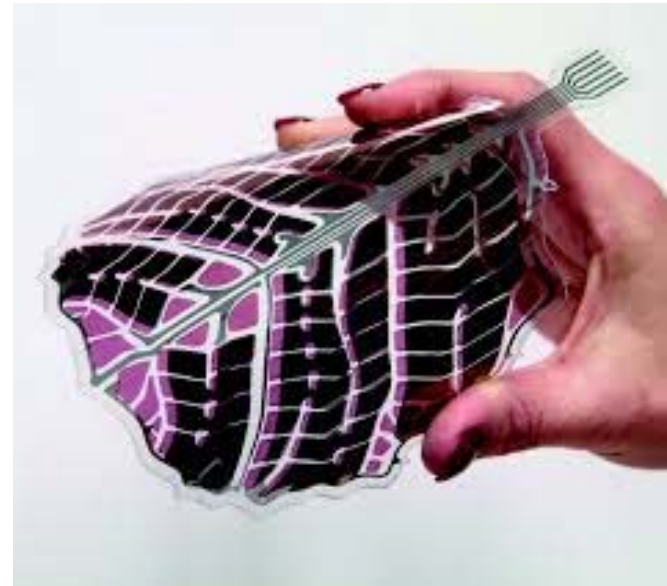
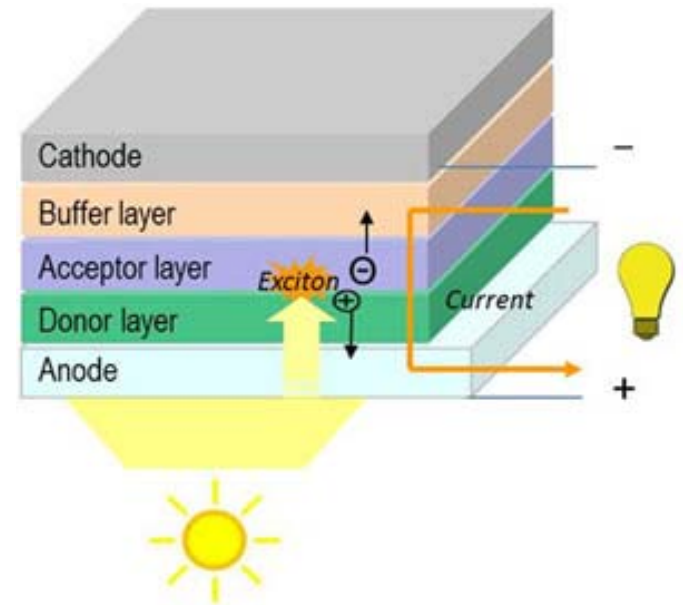
- Several cells on top of each other, each with optimal sensitivity to particular light wavelengths
- GaAs multilayer cells have efficiencies as high as 32%
- Used for the Mars Rovers



# Organic or Polymer Solar PV (OPV)

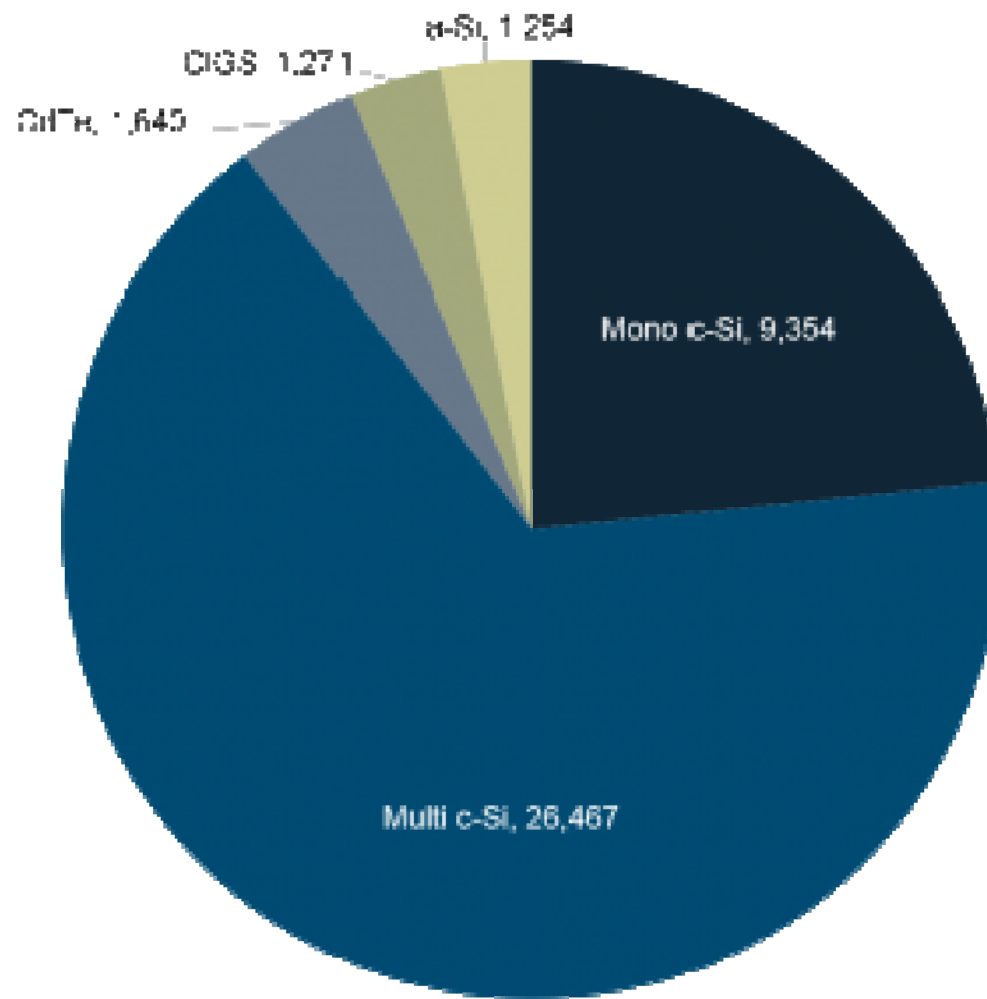
- Organic Photovoltaic (OPV) devices consists of one or several photoactive materials sandwiched between two electrodes
- Low manufacturing cost – possibly even printed by photolithography
- Flexible cells
- Low efficiency
- Can be any color or transparent
- Low efficiency, typically 1-2% for single layer, 4-5% with layers, but as high as 12% has been claimed:

<http://www.laserfocusworld.com/articles/2013/01/heliatek-opv-12-percent.html>

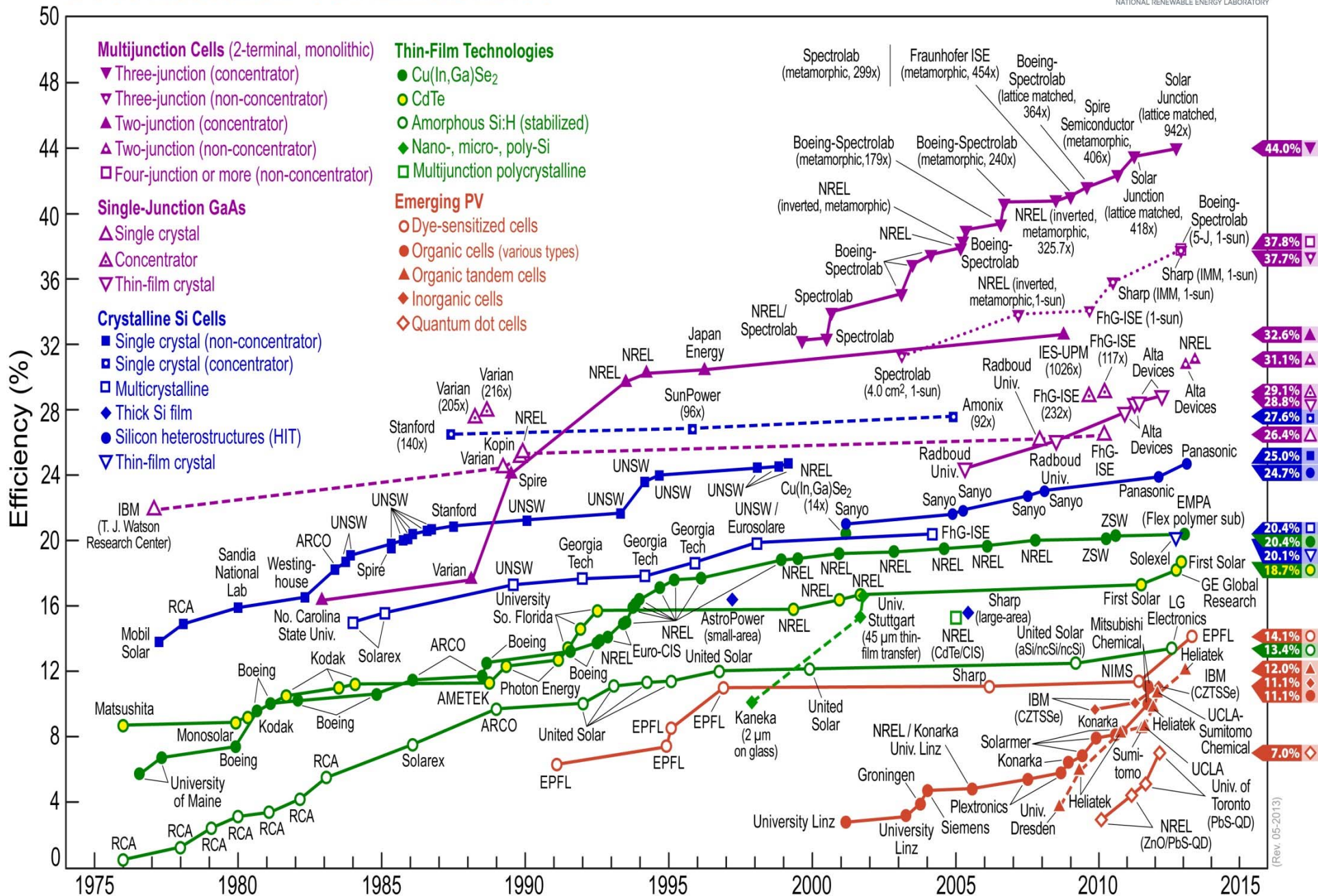




Global PV Module Production by Technology, 2013 (MW)



# Best Research-Cell Efficiencies



# Lots of competition to make the most efficient residential or utility PV modules

<http://www.solarcity.com/newsroom/press/solarcity-unveils-world%E2%80%99s-most-efficient-rooftop-solar-panel-be-made-america>

<http://us.sunpower.com/solar-panels-technology/facts/>

<http://cleantechnica.com/2015/05/01/3-solar-cell-efficiency-records-just-4-days/>

<http://solarlove.org/sharp-solar-cell-efficiency-record-another-one-44-4/>

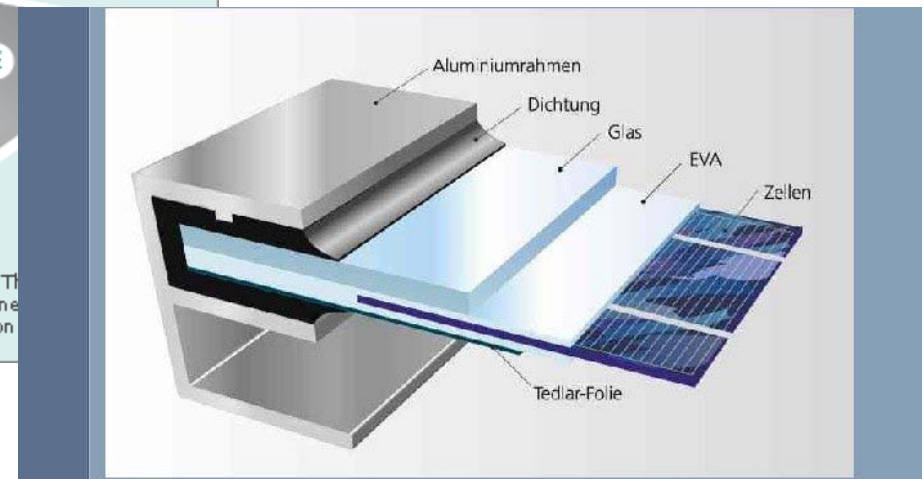
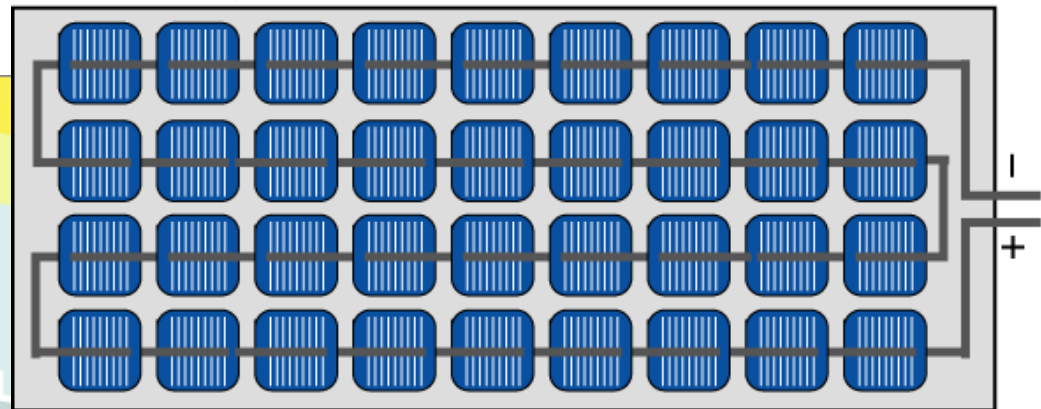
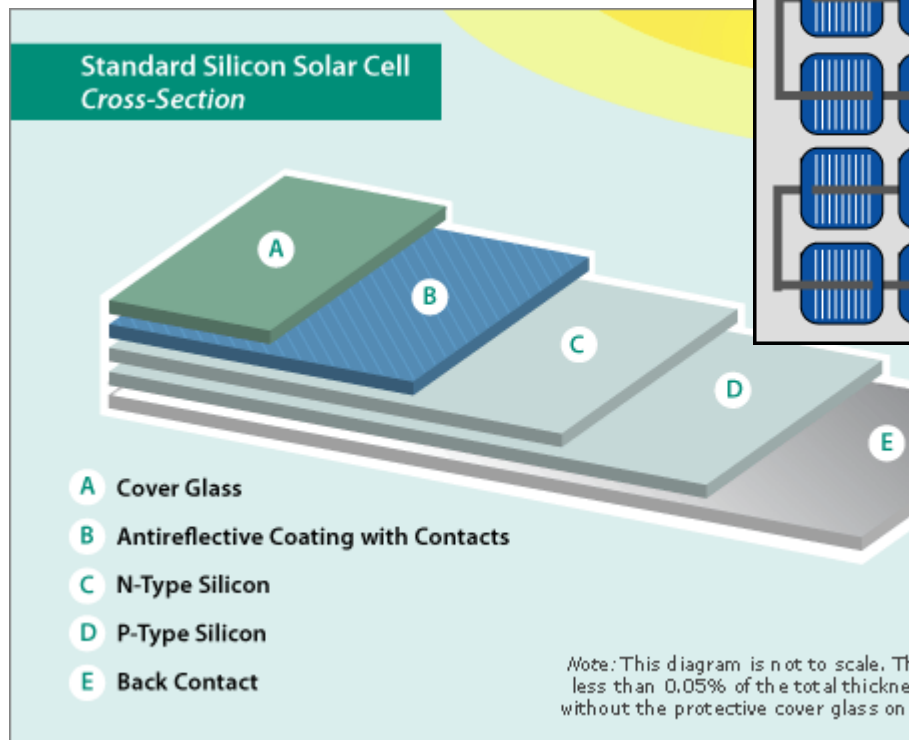
And the current highest efficiency claim using multilayer concentrator cells

<http://cleantechnica.com/2014/12/03/new-solar-cell-efficiency-record-set-46/>

# Solar Panel or Module

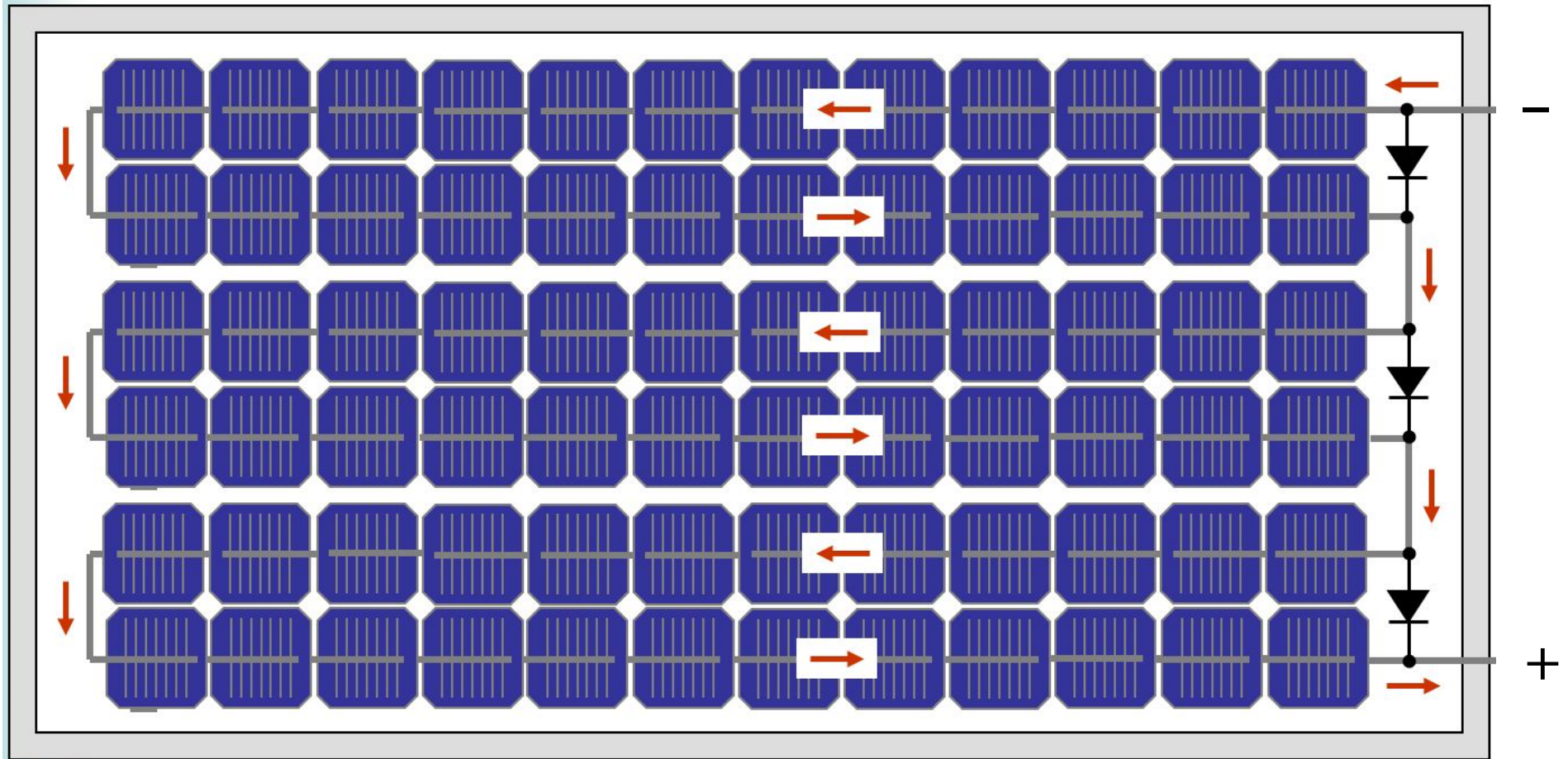
Many solar cells connected together to form a PV panel or module  
Usually in series, to achieve higher voltages rather than in parallel  
to achieve higher current

A typical module has 36 cells connected in series



# Connection of Cells in PV

72-cell PV Module with bypass diodes shown



# Solar Modules



**SunWize®**  
TECHNOLOGIES

MODEL: SW165 L  
Photovoltaic Module

UL  
26SN LISTED  
Photovoltaic Module  
E209345

SPECIFICATIONS RATED AT 1000W/m<sup>2</sup> SOLAR IRRADIANCE AND 25° C TEMPERATURE

MAXIMUM POWER	SHORT CIRCUIT CURRENT	RATED
165 WATTS	5.62A	4.95A

MAXIMUM SYSTEM OPEN CKT. VOLTAGE	OPEN CIRCUIT VOLTAGE	RATED
600V	42.0V	33.4V

FIRE RATING: CLASS C

SERIES FUSE: 12A

FIELD WIRING: COPPER ONLY, # 14 AWG MINIMUM INSULATED FOR 90° C MINIMUM

BYPASS DIODE: SEE INSTALLATION GUIDE

SERIAL NUMBER: 14/06/04 SW165 L 10023509 K

**SunWize®**  
TECHNOLOGIES

MODEL: SW 175  
Photovoltaic Module

UL  
26SN LISTED  
Photovoltaic Module  
E209345

SPECIFICATIONS RATED AT 1000W/m<sup>2</sup> SOLAR IRRADIANCE AND 25° C TEMPERATURE

MAXIMUM POWER	SHORT CIRCUIT CURRENT	RATED
175 WATTS	5.20 A	4.80 A

MAXIMUM SYSTEM OPEN CKT. VOLTAGE	OPEN CIRCUIT VOLTAGE	RATED
600V	43.90 V	36.50 V

FIRE RATING: CLASS C

SERIES FUSE: 12A

FIELD WIRING: COPPER ONLY, # 14 AWG MINIMUM INSULATED FOR 90° C MINIMUM

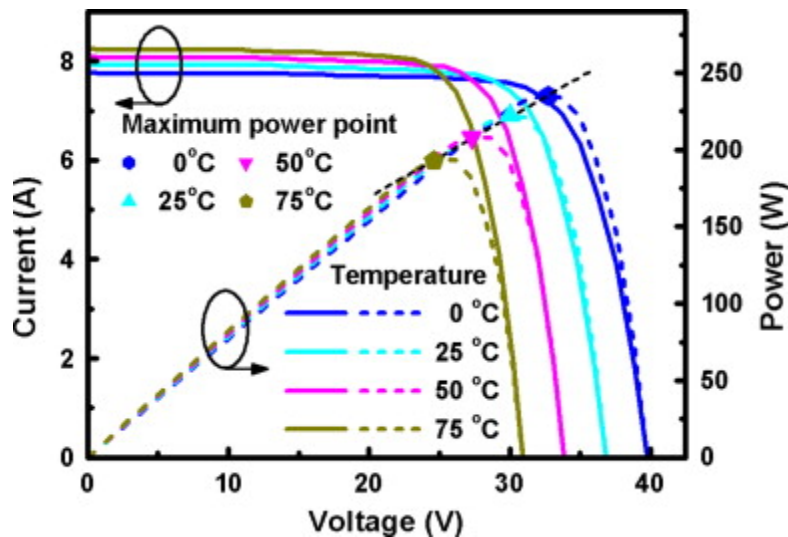
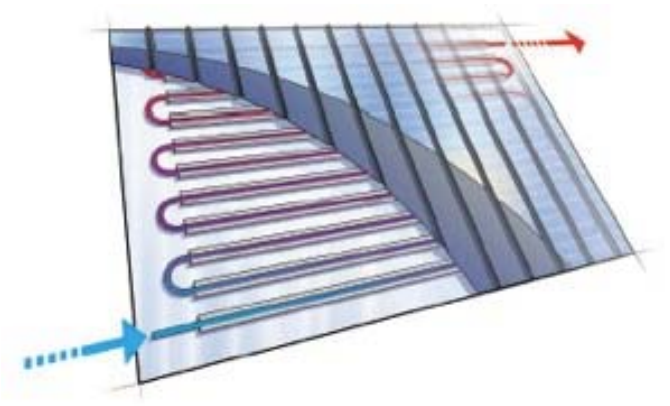
BYPASS DIODE: 8amp, 45 V

SERIAL NUMBER: 12/18/08 SW175 141913332 K

WARNING / ELECTRICAL HAZARD

# Combined PV and Thermal Solar

- Aka 'hybrid panels'
- Converts sunlight to electric power AND to heat for water heating or HVAC
- Cooling of water or coolant reduces temperature, improving PV efficiency



# Solar Shingles (BIPVs)

Aka Building-Integrated Photovoltaics.

Replace shingles on a composition, composite or ceramic tile roof.



Each is a solar panel producing about  $12 \text{ W} / \text{ft}^2$  but 13-63 W / shingle have been reported <https://pureenergies.com/us/how-solar-works/solar-shingles/>

Usually wired to adjacent shingles in series.

## **Silicon-based solar shingles**

Usually multicrystalline or amorphous, but some mono-crystalline, e.g., shingles made by SunPower advertised up to 22% efficiency, but were discontinued.

## **Thin-film solar shingles**

Use thin-film technologies such as CIGS or CdTe, laminated in thin films over conventional the shingles. Less efficient than Si, but less expensive.

## **Organic Solar PV shingles**

An obvious application of solar OPVs, but not yet commercial.



## Solar PV Skylights and Windows (another BIPV)



Since thin-film and organic solar technologies can be made nearly transparent, why not make windows or skylights or shade structures out of them?

Solar shade panels are being used in the Solar Cal Poly project

One variation is a *Transparent Luminescent Solar Concentrator* (TLSC)

# Solar PV Floors (YAPV\*)



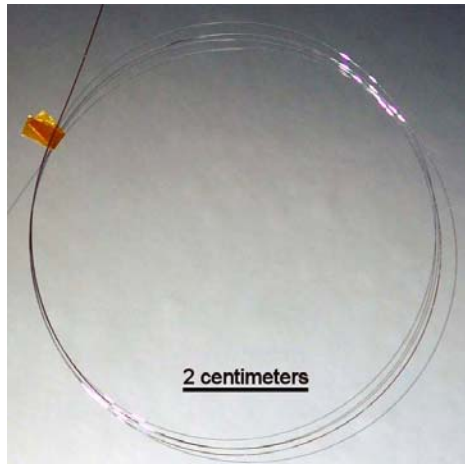
<http://www.onyxsolar.com/walkable-photovoltaic-roof.html>

Same attributes as other evolving applications of solar PV technologies.

Usually amorphous SI or CIGS, but OPVs may soon be available and could dominate the market due to super-low cost.

(\*Yet Another PV. Not really.)

# Solar PV Clothing (AYAPV)



Solar PV fiber (above) has been developed.  
<http://www.treehugger.com/solar-technology/silicon-based-fibers-could-make-fabric-solar-cells.html>



<http://wearablesolar.nl/>

Not just small PC cells attached to clothing

You know where this is headed...



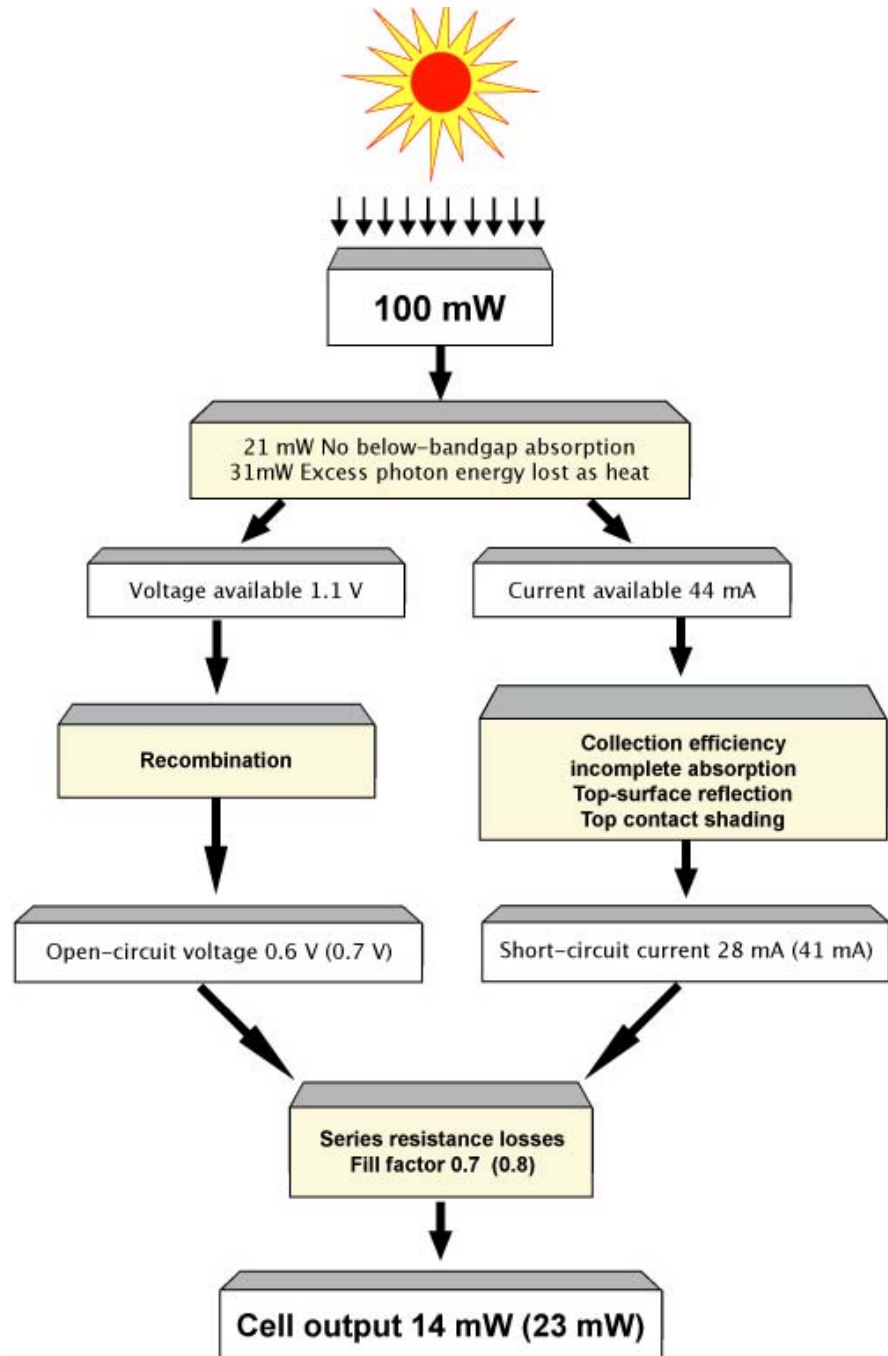
<http://solarenergy.net/News/2010042101-organic-photovoltaics-are-making-wearable-solar-possible/>

# Other Parts of Solar Modules

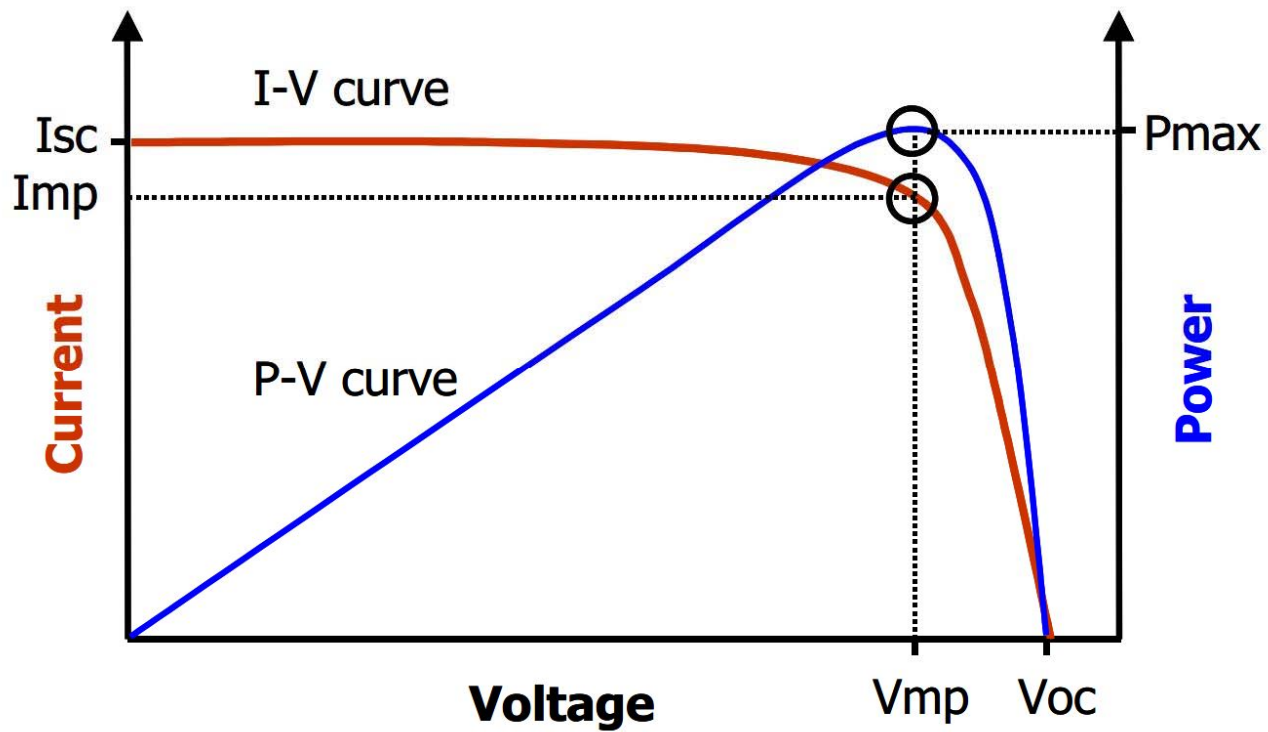
- Encapsulant
  - Provides good adhesion between PV cell, top and rear surfaces
  - Stable at high temperature and UV exposure
  - Usually EVA (ethyl vinyl acetate), many EVA formulations possible
  - Must be transparent at all usable wavelengths
  - Should have low thermal resistance (increase cell efficiency)
  - The ARCO Solar 'disaster' due to bad choice of encapsulant
- Rear Surface
  - Low Thermal resistance
  - Prevents water penetration from back
  - Tedlar common (UV-resistant polymer)
  - Bifacial modules
- Frame
  - Aluminum common
  - Provides support

# Power Losses in Solar Cells

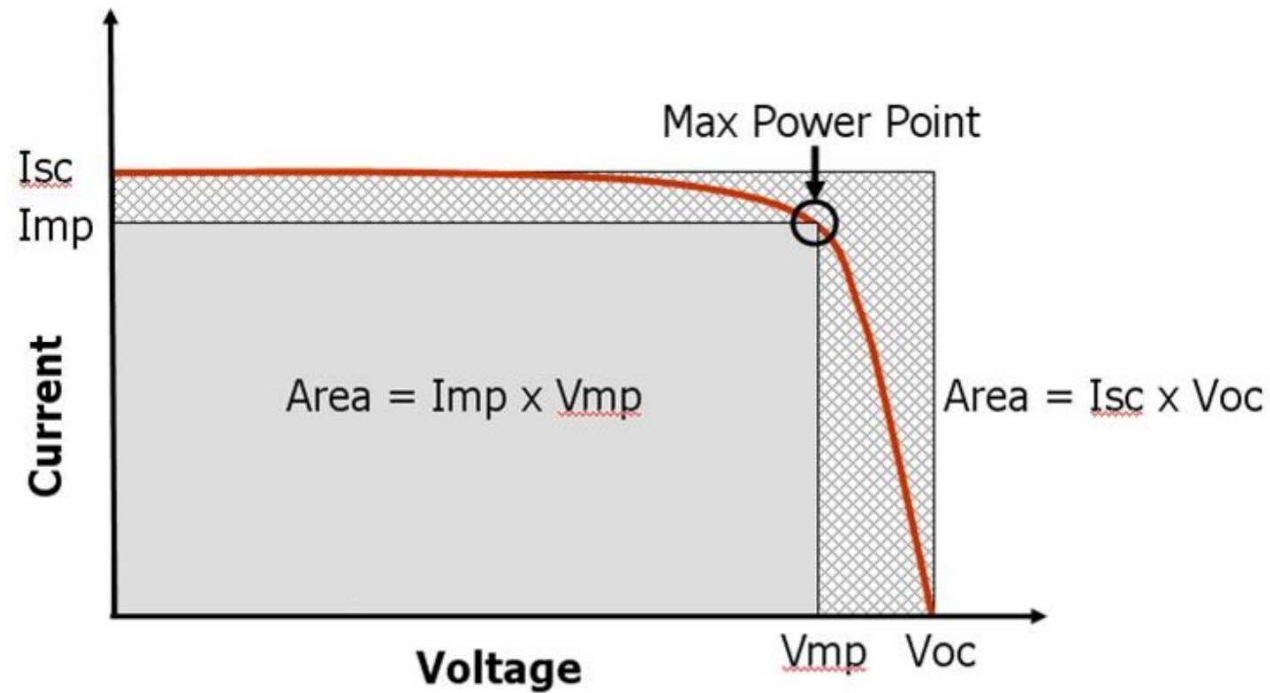
If a solar panel is 20% efficient, then where does the other 80% of the sunlight energy go?



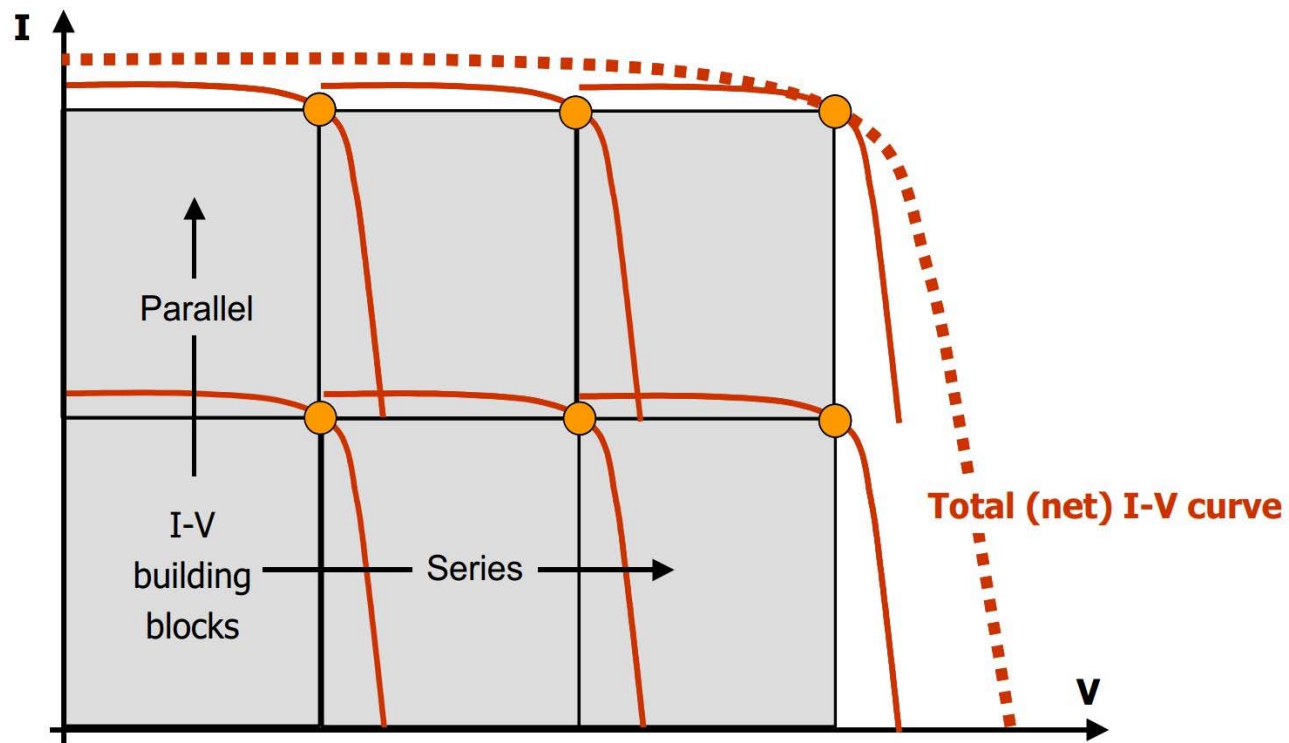
# IV Curve



# IV Curve - Fill Factor

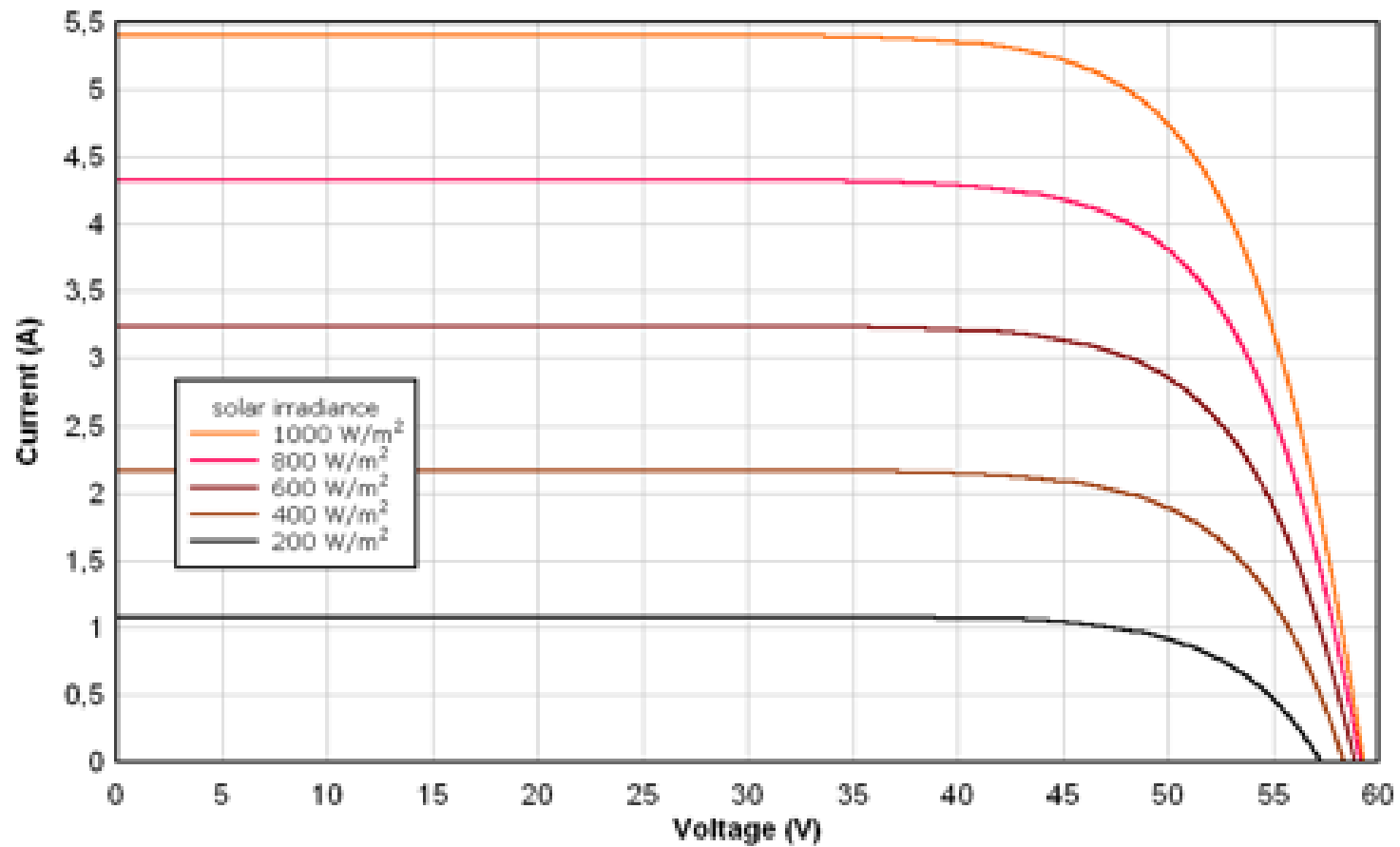


# IV Curve - Scaling





# IV Curve - Irradiance



# IV Curve - Temperature

