Lecture 6 – Solar Photovoltaics (I)

Dr. Yu Zhang

ECE, UC Santa Cruz

ECE180J

Outline

- PV Applications and History
- Conductor, Insulators, and Semiconductor
- Silicon: Doping and P/N-type
- Photon Energy and Band Gap
- PV Materials and Technologies

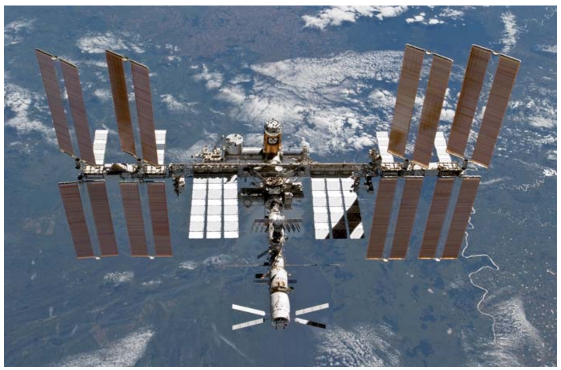
B3 Chap 4.1 – 4.6; B1 Chap 5

ECE 145 *Properties of Materials*

ECE 171 *Analog Electronics*

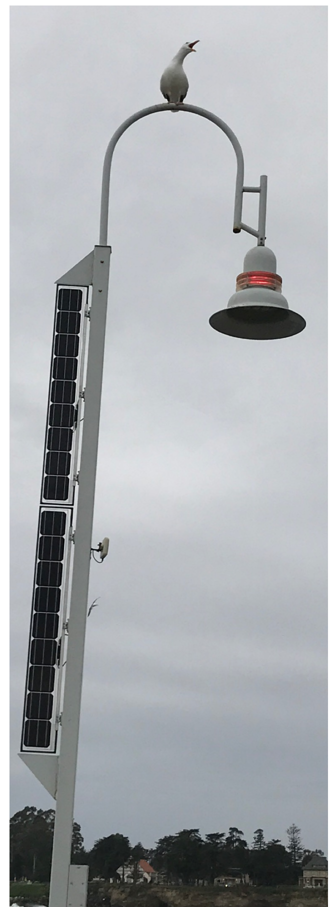
PV – Generation of Electricity from Light

- The net solar power input to the Earth is more than 8000 times humanity's current rate of use of fossil and nuclear fuels.
- Solar photovoltaic (PV) cells directly convert solar energy into electricity in a solid state device.



The Intl Space Station:
130 kW PV output

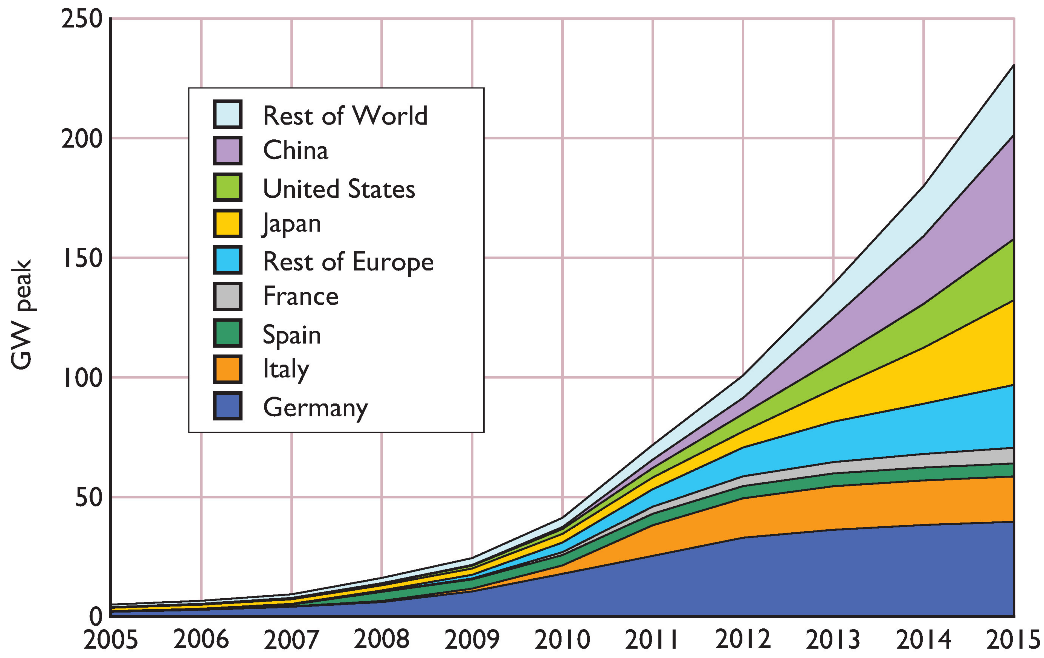
Solar car

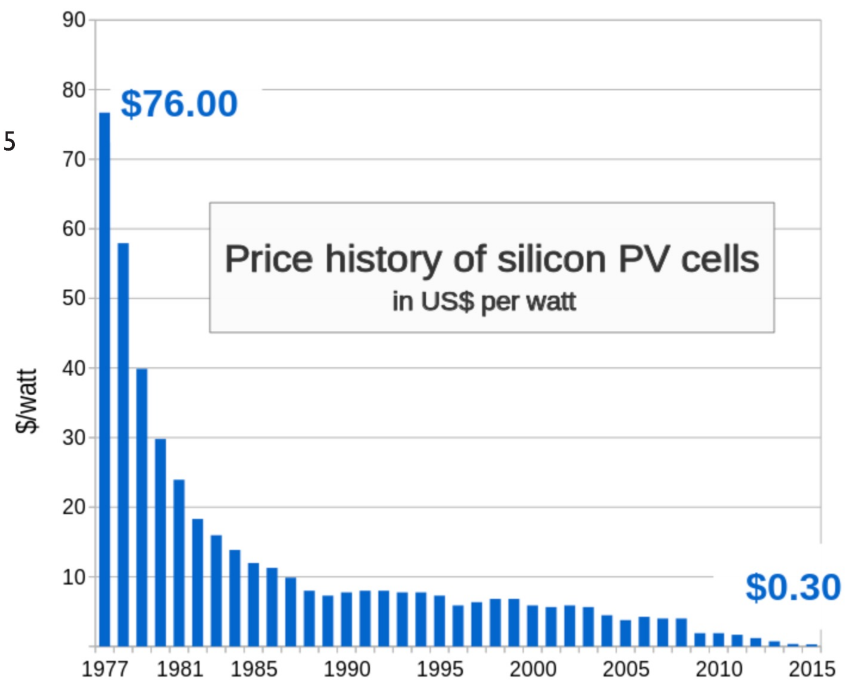


Sunseeker Duo

PlanetSolar

Development of PV





Source: Bloomberg New Energy Finance & pv.energytrend.com

PV Module Costs

Learning rate: the percent drop in cost for each doubling of installed capacity.

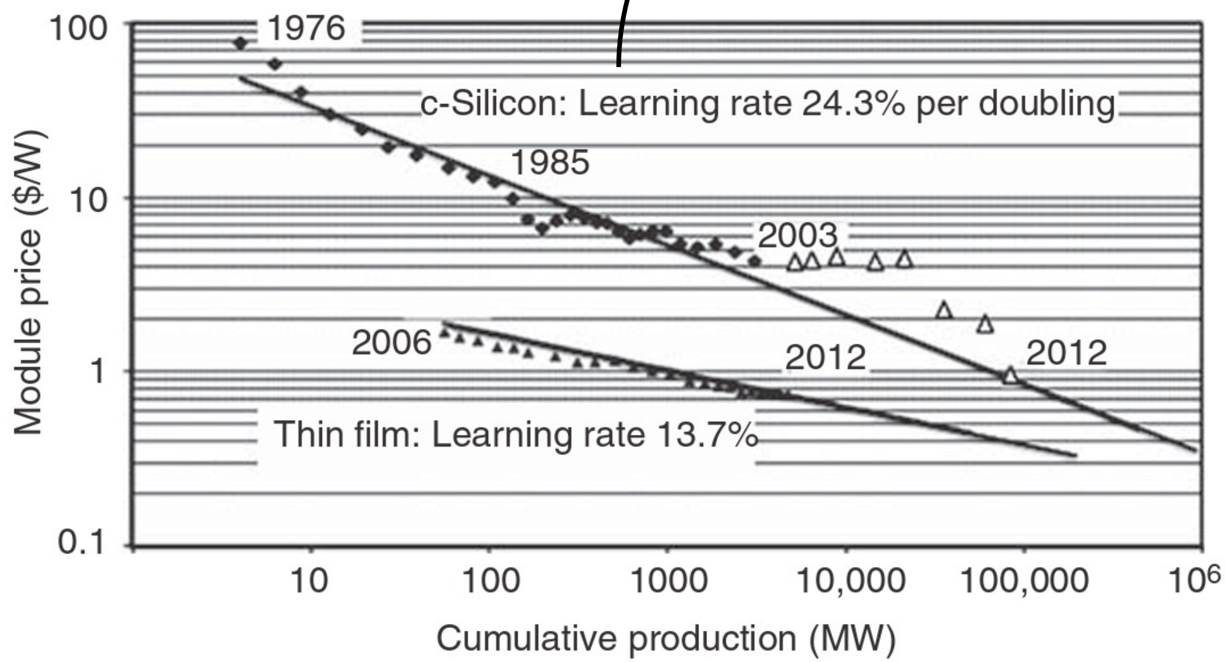
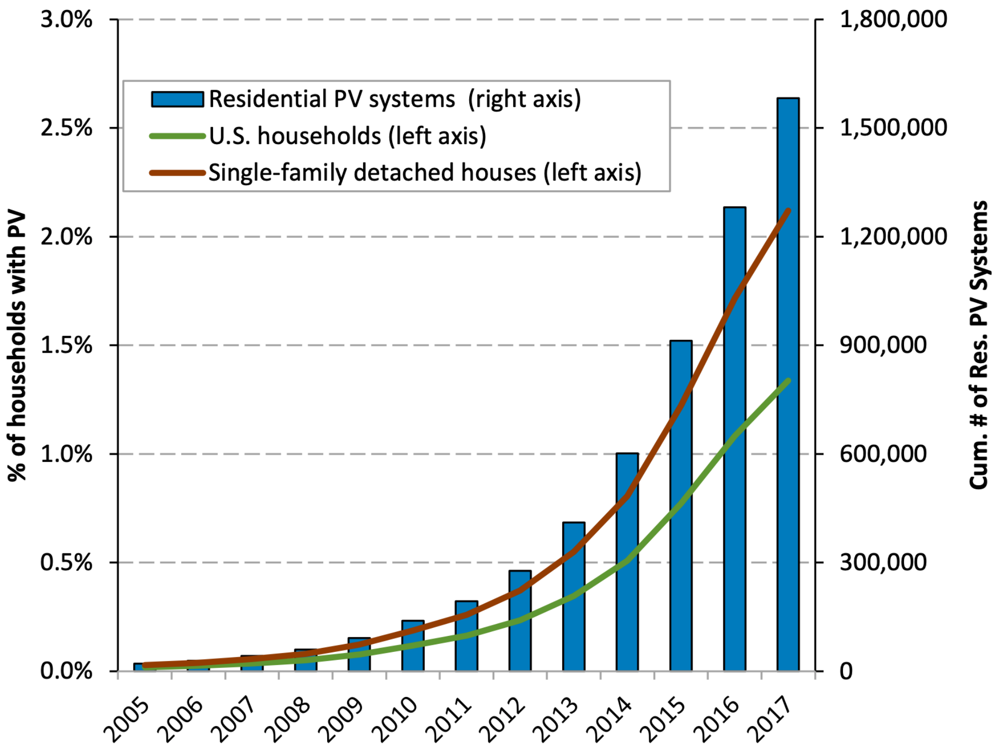


FIGURE 5.1 Photovoltaic module costs and cumulative production for both crystal silicon (c-Si) and thin-film technologies (Based on NREL data, 2012).

- DoE's goal: By 2020, installed costs of $1/Wp for utility scale systems, $1.25/Wp for commercial rooftop PV, and $1.50/Wp for residential rooftop.
- Wp (Watt-peak): the peak DC power delivered under idealized standard test conditions: Solar radiation of 1kW per square meter

US Residential PV Penetration



Sources: Res. PV Installations: 2000-2009, IREC 2010 Solar Market Trends Report; 2010-2017, SEIA/GTM Solar Market Insight 2017 Year-in-Review; U.S. Households U.S. Census Bureau, 2015 American Housing Survey; state percentages based on 2000 survey.

- Since 2005, when the investment tax credit was passed by congress, the residential PV market has grown by approximately 44% per year, or about 81X.
- At the end of 2017, there were approximately 1.6 million residential PV systems in the United States.
- Still, only 1.3% of households own or lease a PV system (or about 2.1% of households living in single-family detached structures).
- However, solar penetration varies by location. Hawaii, California, and Arizona have residential systems on an estimated 31%, 11%, and 9% of households living in single-family detached structures.

Source: NREL

CALIFORNIA BECOMES THE FIRST STATE TO MAKE SOLAR PANELS MANDATORY

The new standard will bring the state closer to meeting its climate goals.

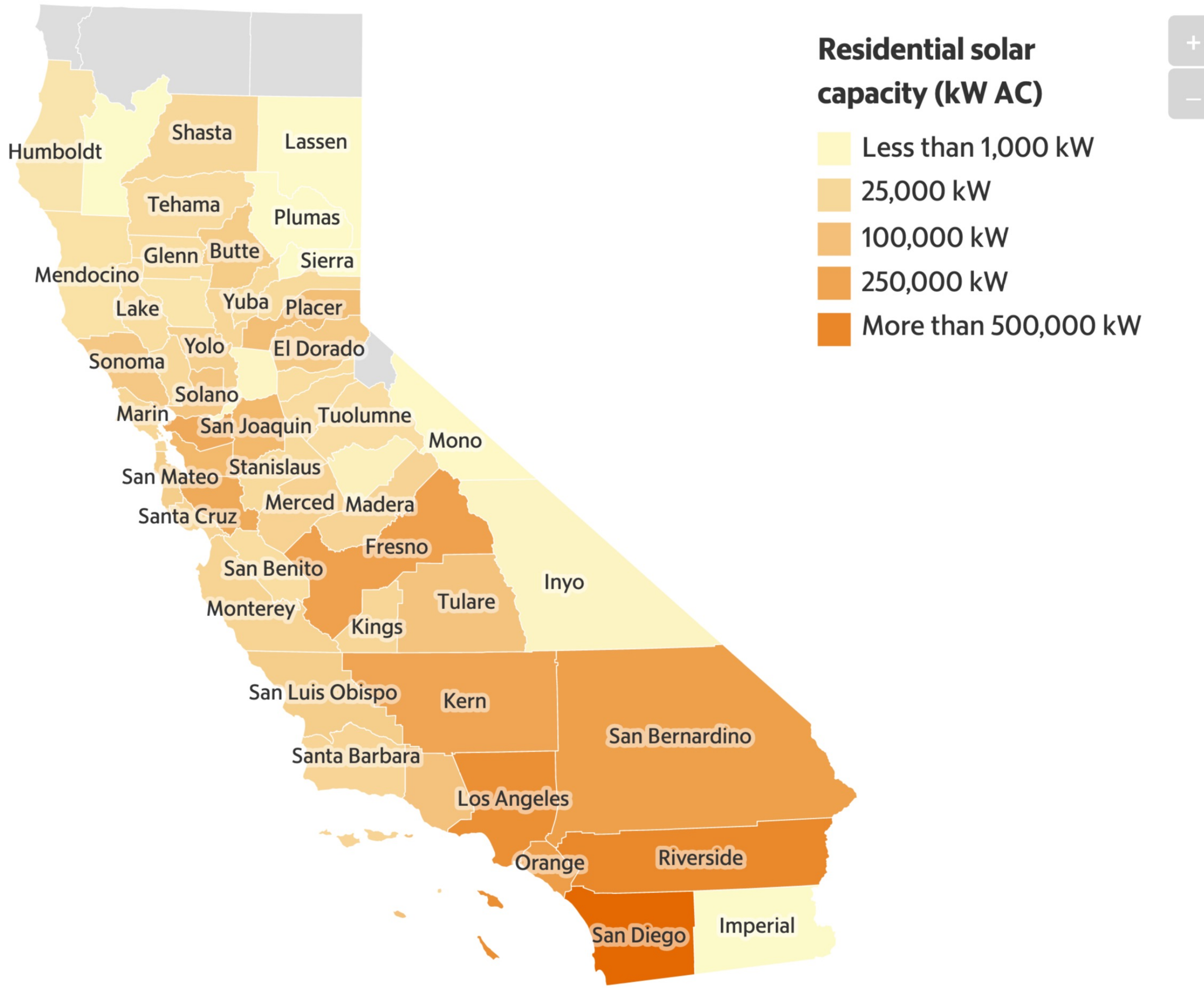
KATE WHEELING · MAY 9, 2018

Workers install solar panels on the roof of a home on May 9th, 2018, in San Francisco, California.
(Photo: Justin Sullivan/Getty Images)

Starting January 1st, 2020, virtually all new homes built in California will be equipped with solar panels.

- California law requires at least 50% of the state's electricity to come from noncarbon-producing sources by 2030.
- Solar power has increasingly become a driver in the growth of the state's alternative energy production.
- $10,000 additional upfront cost may be paid back by energy savings.

Residential Solar Capacity in CA



Figures reflect all net energy metering (NEM) interconnected solar photovoltaic (PV) systems in the Pacific Gas & Electric Co., Southern California Edison and San Diego Gas & Electric service territories as of June 30, 2019. No interconnected systems were reported in Alpine, Del Norte, Siskiyou or Modoc counties.

Map: Tim Sheehan | The Fresno Bee • Source: Go Solar Californnia • Get the data

At UCSC

Solar project advances campus sustainability

February 26, 2019
By Sarah Latham

SHARE THIS STORY:

Our campus will take a big step toward carbon neutrality next week when construction starts on a solar canopy on the East Remote parking lot that will generate up to 20 percent of our electrical demands.

This project—which we're calling "Slugs Go Solar"—will also include an energy storage system. The solar array and the storage system will give us more than three million kilowatt-hours (kWh) of electricity each year for at least two decades years, saving us a total of about $6 million on our energy bill.

Construction will start on a solar canopy—similiar to what's pictured here—on Friday at the East Remote parking lot.

Our 2017–2022 Campus Sustainability Plan calls on us to develop a plan to add four megawatts of solar photovoltaic to the campus—and this two-megawatt project gets us half way there. We continue to study additional opportunities to harness the sun's energy to support our mission of education and research.

Construction will begin on Friday and is scheduled to go through December 2019. The work will be done in phases, which—unfortunately and unavoidably—will temporarily reduce the number of available parking spaces at East

Brief History of PV

The photoelectric effect: the emission of electrons or other free carriers when electromagnetic radiation, like light, hits a material.

- 1839 - Edmond Becquerel observed the **PV effect** via an electrode in a conductive solution exposed to light.
- 1883 - Charles Fritts developed a solar cell using selenium (<1% efficiency).
- 1887 - Heinrich Hertz investigated ultraviolet light photoconductivity and discovered the photoelectric effect.
- 1904 - Wilhelm Hallwachs made a semiconductor-junction solar cell (copper & copper oxide).
- 1904 – Albert Einstein provided a theoretical explanation of the PV effect (Nobel prize)
- 1954 - Bell Labs announced the invention of the first practical silicon solar cell.

Edmond Becquerel (1820 – 1891), French physicist

Calvin S. Fuller at work diffusing boron into silicon to create the world's first solar cell

Solar Cell

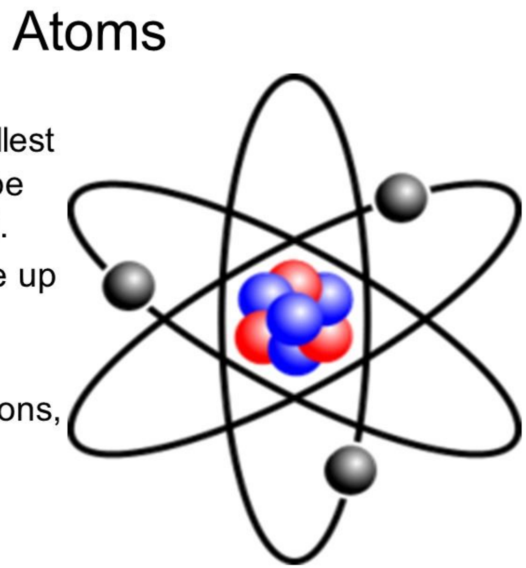
A conventional crystalline silicon solar cell (as of 2005). Electrical contacts made from busbars (the larger silver-colored strips) and fingers (the smaller ones) are printed on the silicon wafer.

- PV: A material or device that can convert the energy contained in photons of light into an electrical voltage and current.

- A photon with short enough wavelength and high enough energy can cause an electron in a PV material to break free of the atom that holds it.

- If a nearby electric field is provided, those electrons can be swept toward a metallic contact where they can emerge as current.

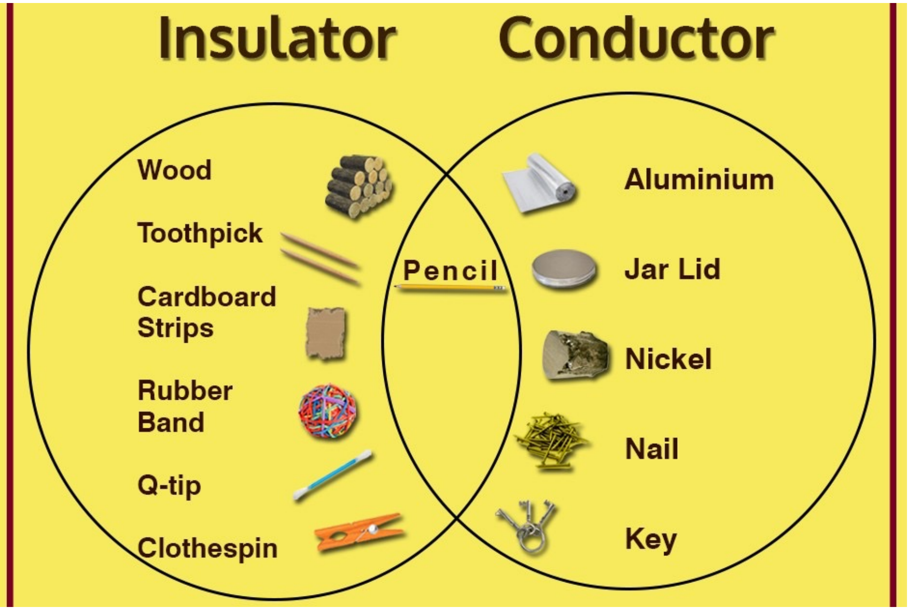
Conductors & Insulators



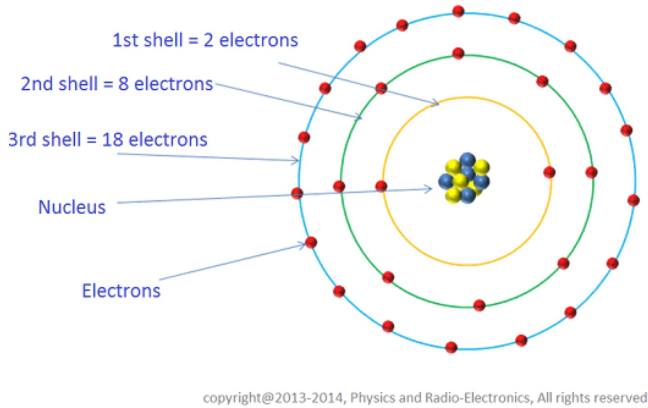
- Atom- The smallest particle that can be called an element.
- All matter is made up of atoms.
- Made up of Protons(+), Neutrons, and Electrons (-)

- The atomic nucleus consists of nucleons — protons and neutrons
- >99.94% of an atom's mass is in the nucleus
- The rest mass of the electron is 9.11×10^{-31} kg

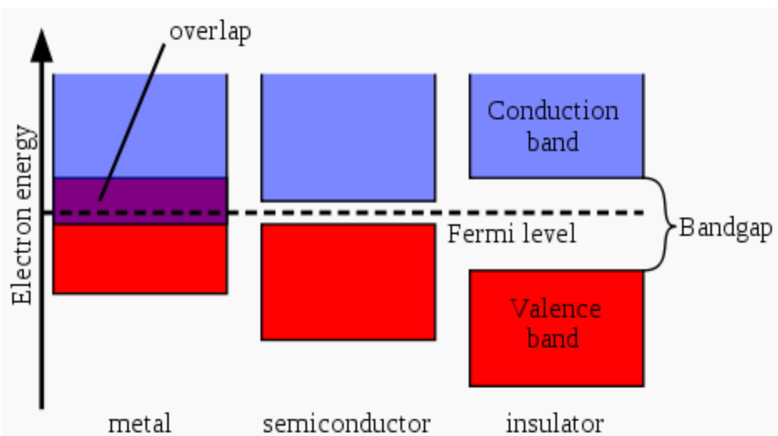
- Some materials are good *conductors* of electricity – such as (most metals) copper, gold
- Other materials are good electrical *insulators* – such as glass, rubber



Semiconductors



- Electrons are revolving around the nucleus in different orbits at a fixed distance from the nucleus.
- Electrons in first orbit (shell) have least energy while the outermost orbit highest energy.

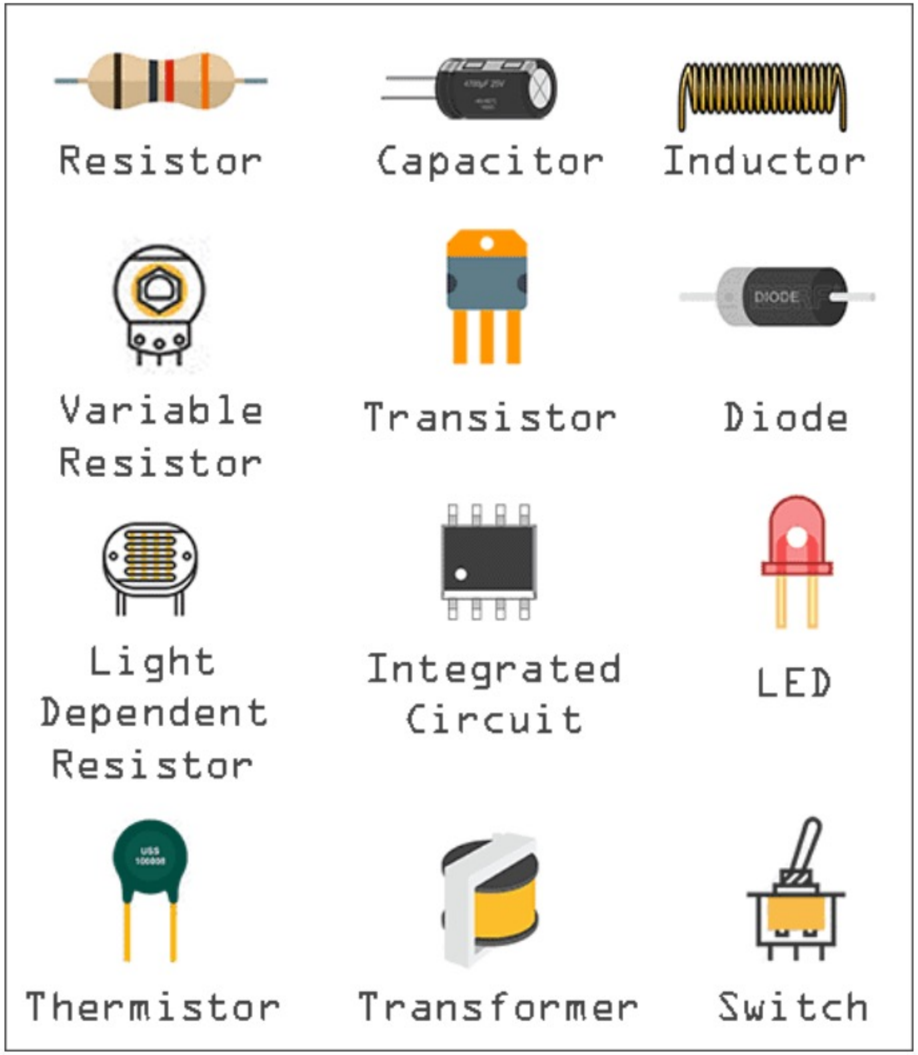


The closer the Fermi level is to the conduction band energy, the easier it will be for electrons in the valence band to transition into the conduction band.

- Fermi Level is the maximum energy point that an electron could reach at zero temperature.
- In solid-state physics, the valence band and conduction band are the bands closest to the Fermi level and determine the electrical conductivity.

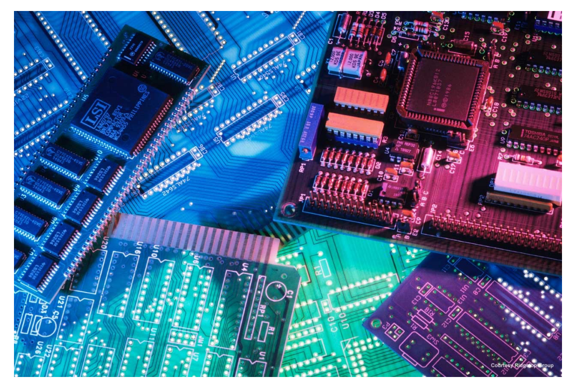
Electrons in conduction band have enough energy to move freely in the material → creates a current.

Semiconductor Devices



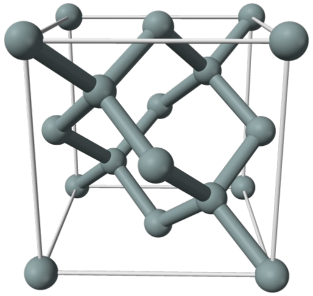
Semiconductors have a small band gap:

- Allows for a fraction of the valence electrons of the material to move into the conduction band given a certain amount of energy.
- Allows semiconductors to convert light into electricity in PV cells.



The Workhorse of the Semiconductor Industry

- The PV cell often is made almost entirely from silicon, the second most abundant element in the Earth's crust.
- Has no moving parts and can operate for an indefinite period without wearing out.
- Its output is electricity, probably the most useful of all energy forms.

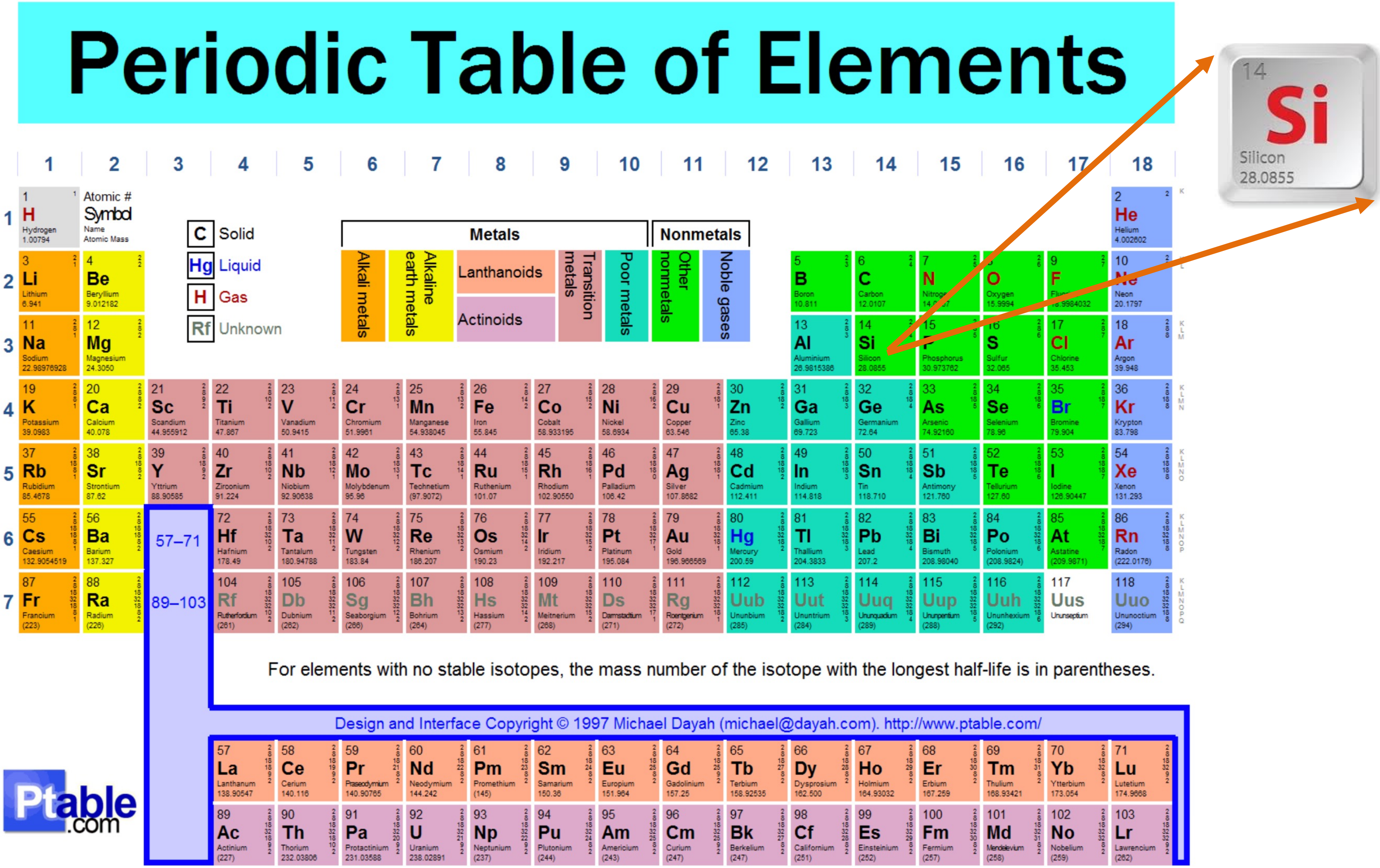


Silicon is an important element in high-technology semiconductor devices.
Many places in the world bear its name:

- Silicon Valley – CA
- Silicon Cape – Cape Town, South Africa
- Silicon Valley of China – Beijing, China
- Silicon Fen — Cambridge, England

Jöns Jacob Berzelius, discoverer of silicon

Silicon (cont'd)



Silicon – Atomic Structure

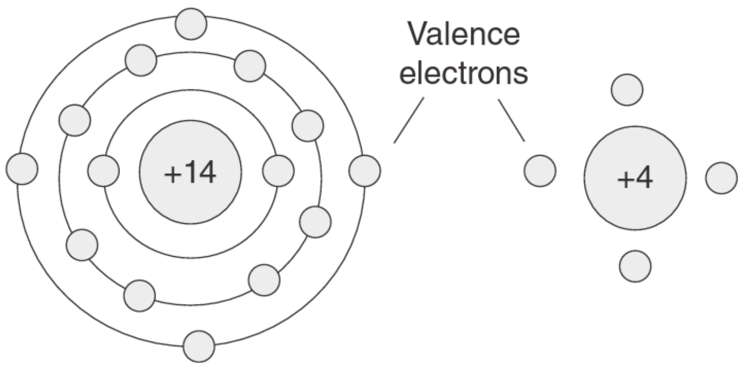
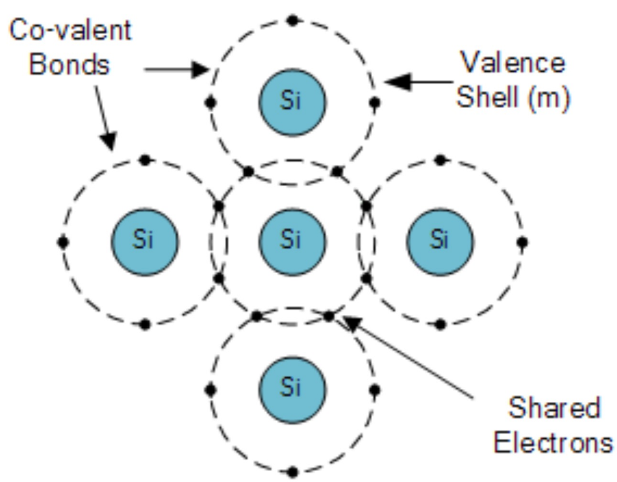


Figure: A simplified 2-D demonstration of a silicon atom, where 4 outer valence electrons are spinning around a nucleus with a +4 charge.

Consider a solid (like a semi-conductor) as any material in which the atoms are arranged in an ordered fashion (referred to as a crystal or a lattice).



Silicon Crystal Lattice

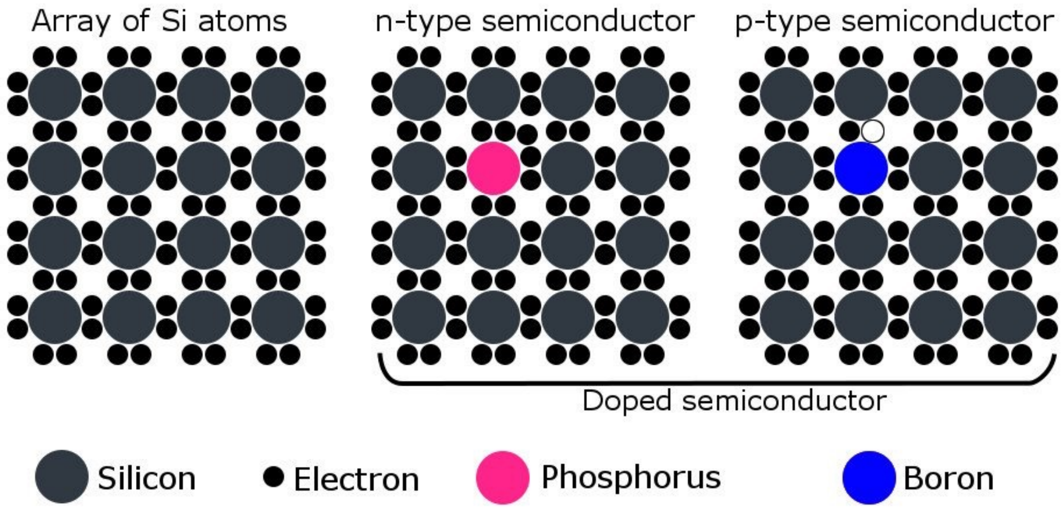
- Only the most outer 4 valence electrons can help bond with other atoms.
- In its solid form, each silicon atom normally shares one of its four valence electrons in a covalent bond with each of four neighboring silicon atoms.

Source: http://homework.uoregon.edu/pub/class/155/Canvas/semi.html

Doping

- Impurities and temperature can affect the Fermi level.
- Semiconductor atoms are closely grouped together in a crystal lattice and so they have very few free electrons to be good conductors.
- The ability of semiconductors to conduct electricity can be greatly improved by introducing donor or acceptor atoms to the crystalline structure, either producing more free electrons or more holes.
- This process is called “doping” and as the semiconductor material is no longer pure, these donor and acceptor atoms are collectively referred to as “impurities”.

P-type & N-type



PV cells consist of a junction between thin layers of two different types of semiconductor:
p-type (positive)
n-type (negative)

- **N-type:** Doped with phosphorus such that the doped material possesses a surplus of free electrons.
- **P-type:** Doped with boron causing the material to have a deficit of free electrons. Missing electrons are called 'holes', which can be considered equivalent to a positively charged particle.

P-type & N-type Comparison

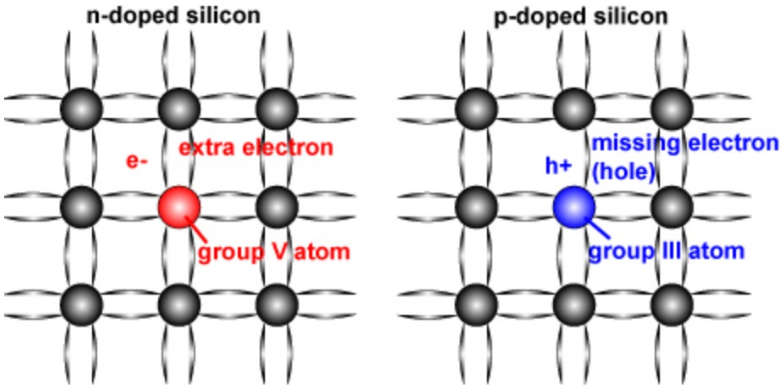


Fig: Schematic of a silicon crystal lattice doped with impurities to produce n-type and p-type semiconductor material.

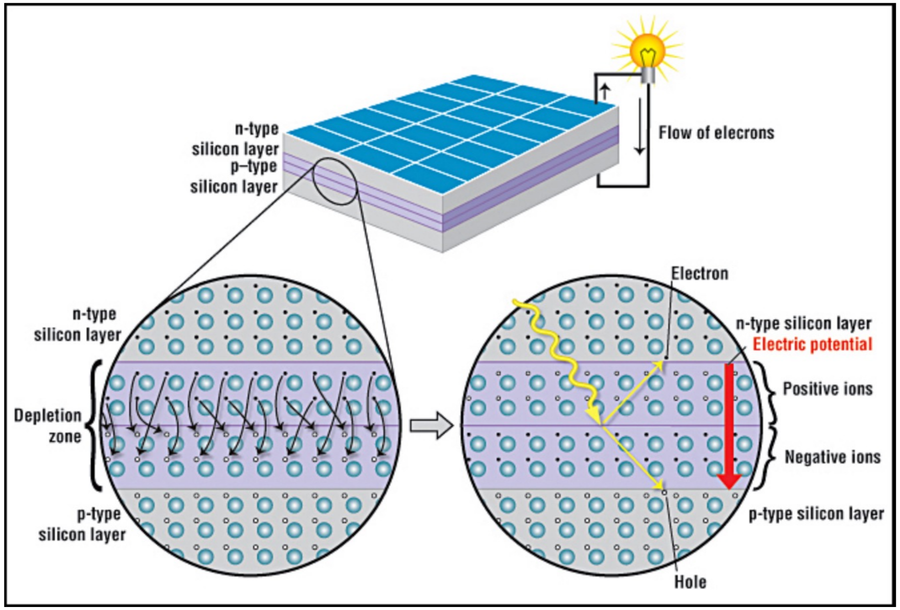
	N-type (negative)	P-type (positive)
Dopant	Group V (e.g. Phosphorous)	Group III (e.g. Boron)
Bonds	Excess Electrons	Missing Electrons (Holes)
Majority Carriers	Electrons	Hole
Minority Carriers	Holes	Electrons

TABLE 5.1 A Portion of the Periodic Table with the Most Important Elements for Photovoltaics Highlighted

I	II	III	IV	V	VI
		5 B	6 C	7 N	8 O
		13 Al	**14 Si**	**15 P**	16 S
29 Cu	30 Zn	**31 Ga**	32 Ge	**33 As**	**34 Se**
47 Ag	**48 Cd**	**49 In**	50 Sn	51 Sb	**52 Te**

Source: https://www.pveducation.org/pvcdrom/pn-junctions/doping

P-N Junction



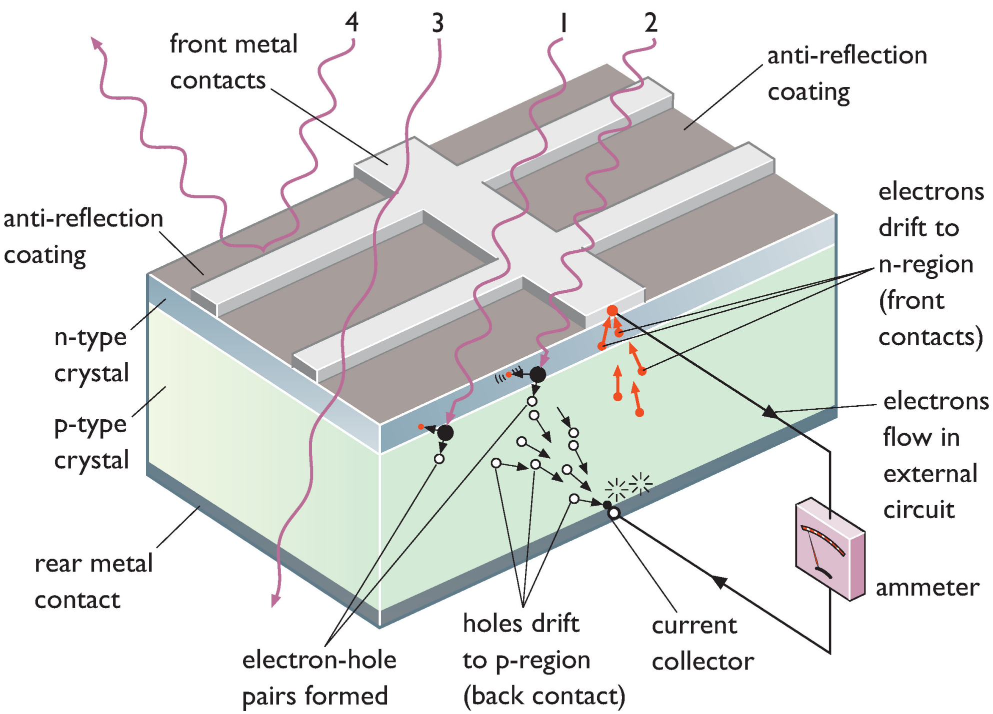
- The electrons on the n-type side of the junction move into the holes on the p-type side.
- When an equilibrium is reached, it creates the depletion zone, in which the electrons fill the holes and no mobile charge carriers are present.
- The p-type side of the depletion zone now contains negatively charged ions while the n-type side contains positively charged ions.

➢ The depletion zone creates an internal electric field that acts like a barrier that opposes the flow of electrons from n-side and holes from p-side.

➢ When sunlight strikes a solar cell, electrons are ejected, which results in the formation of “holes”. If this happens in the electric field, the field will move electrons to the n-type layer and holes to the p-type layer.

Source: https://www.acs.org/

Physical Principles of PV



- A photon of light with the appropriate amount of energy penetrates the cell and encounters a silicon atom 1. It dislodges one of the valence electrons and leaves behind a hole.

- The electron tends to migrate up into the n-type layer and the hole tends to migrate down into the layer of p-type layer.

- The electron then travels to a metallic current collector on the front surface of the cell, generates an electric current in the external circuit and then re-emerges in the layer of p-type silicon, where it can recombine with waiting holes.

Thickness of P/N Layers

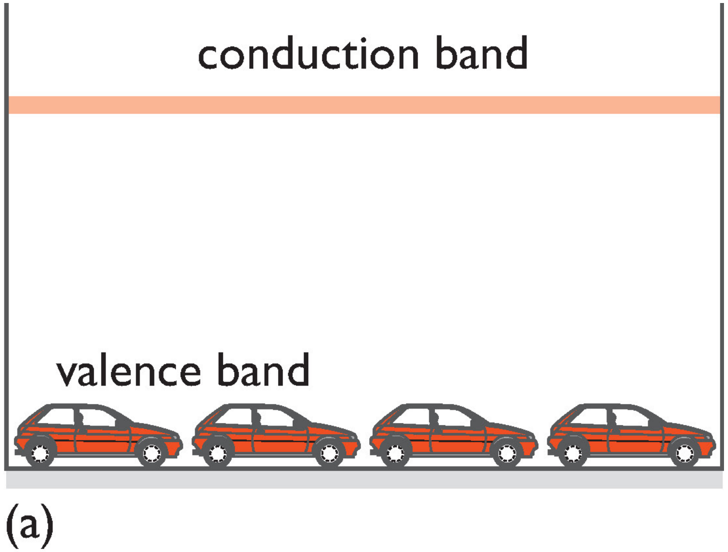
The difference in thickness of P/N layers can be correlated to

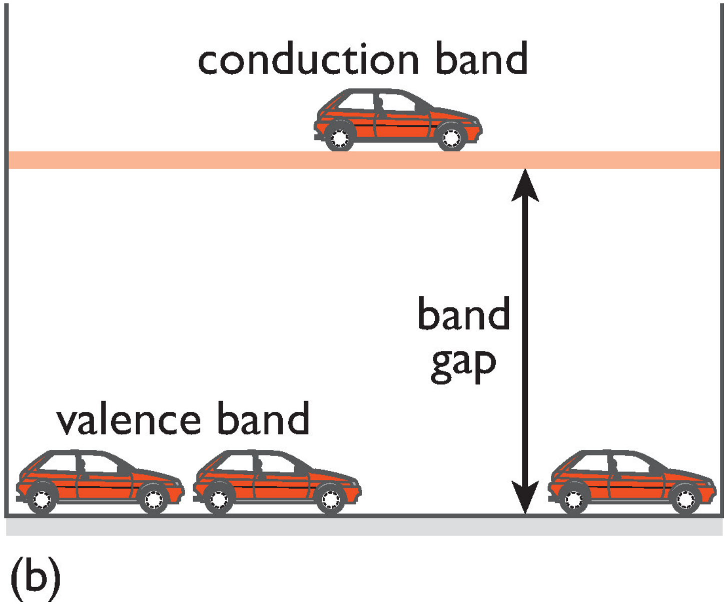
- mobility
- lifetime
- diffusion lengths of minority carriers

P-side minority carriers: electrons
N-side minority carriers: holes

Since the electrons have a higher mobility, lifetime and diffusion lengths than holes, so the electron-hole pair generated in a thick p-layer after photon interactions will have greater possibility of collection across the load terminals.

Conduction Processes





'Car-parking' analogy

1st floor → valence band
2nd floor → conduction band
cars → electrons

(a) 2nd floor is empty, but the 1st floor is full, no car can move

(b) a car is 'promoted' to the 2nd floor, and can then move around freely. This leaves a 'hole' that allows 1st floor cars to move around

Basic PV Cell Structure

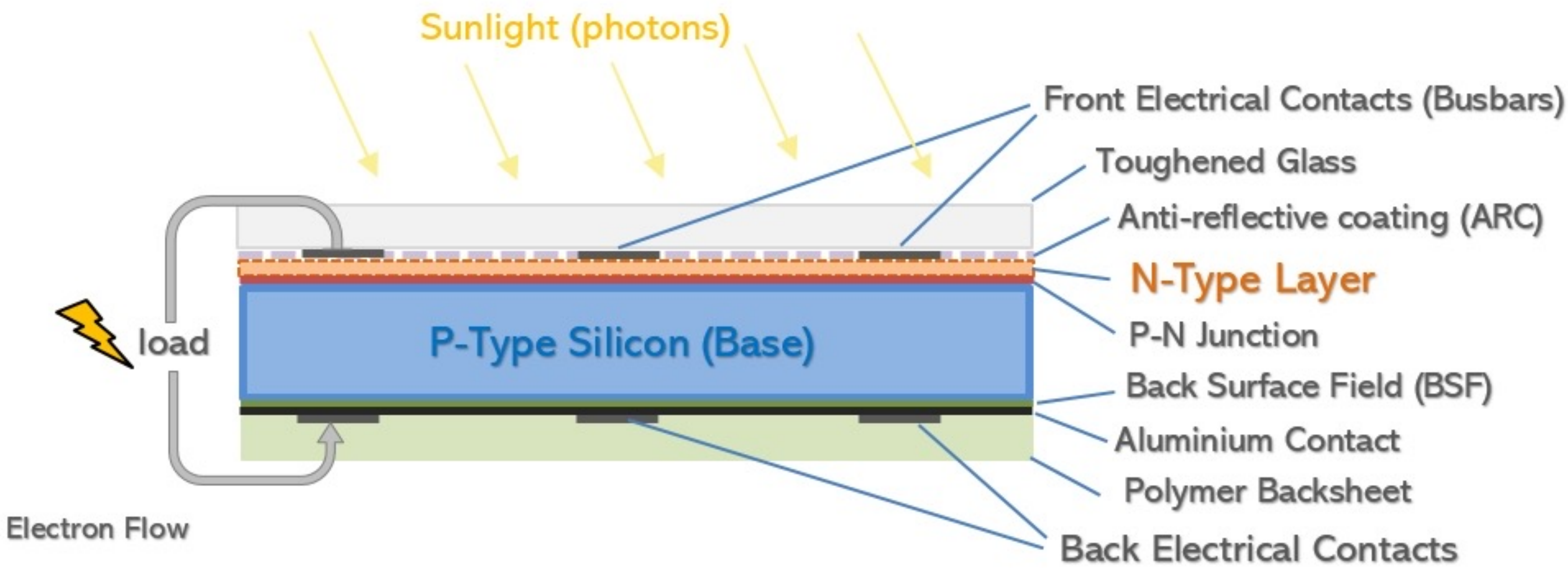


Fig: Basic construction diagram of a common P-type silicon cell – Mono/multi-crystalline

- The P-N junction creates an electric field which enables the flow of electrons when solar radiation passes through the cell.
- The PV effect is when light photons (energy) free the electrons from the silicon creating a flow of electricity.

Photon Energy & Band Gap

The energy of a photon of light: $\boxed{E = hf = hc/\lambda}$

$$\text{Planck's constant: } h = 6.626 \times 10^{-34} \ J \cdot s$$

$$\text{light speed: } c = 3 \times 10^{8} \ m/s \qquad \text{light wavelength: } \lambda$$

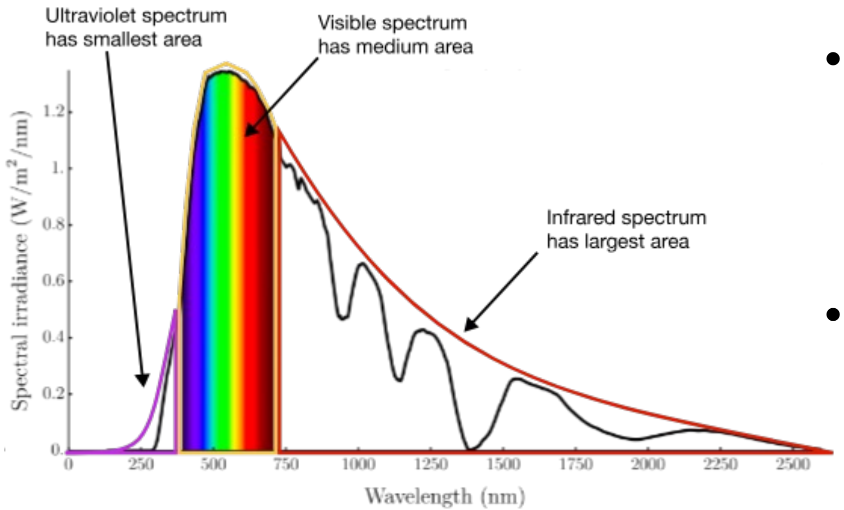
Energy at the atomic level is normally described by electron-volts (eV). 1 eV is the energy that an electron acquires when its voltage is increased by 1 V.

$$1 \ eV = 1.6 \times 10^{-19} \ J \longrightarrow \boxed{E_{(eV)} = 1241.5/\lambda_{(nm)}}$$

A photon of blue light (410nm): 3eV

A photon of infrared light (820nm): 1.5eV

PV Cell Efficiency Limits



- The entire spectrum of sunlight, from infrared to ultraviolet, covers a range of about 0.5 eV to about 2.9 eV.
- Solar cells are not 100% efficient ← semiconductors do not respond to the entire spectrum of sunlight.

- Photons with energy less than silicon's bandgap are not absorbed, which wastes about 18% of incoming energy.
- The energy content of photons above the bandgap will be wasted surplus re-emitted as heat or light. This accounts for an additional loss of about 49%.
- Thus about 67% of energy from the original sunlight is lost; i.e., only 33% is usable for generating electricity in an ideal solar cell.

- The useful electrical energy that a photon contributes to the cells is only equal to the band gap.

Band Gaps of Different Materials

TABLE 5.2 Band-Gap and Cut-off Wavelength Above Which Electron Excitation Does Not Occur

Quantity	Si	a-Si	CdTe	$CuInSe_2$	$CuGaSe_2$	GaAs
Band-gap (eV)	1.12	1.7	1.49	1.04	1.67	1.43
Cut-off wavelength (μm)	1.11	0.73	0.83	1.19	0.74	0.87

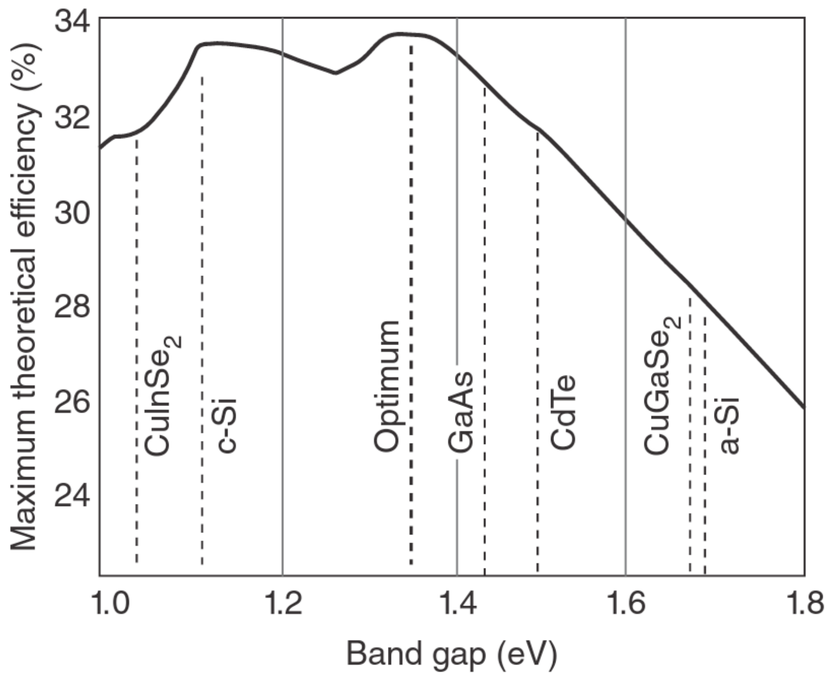
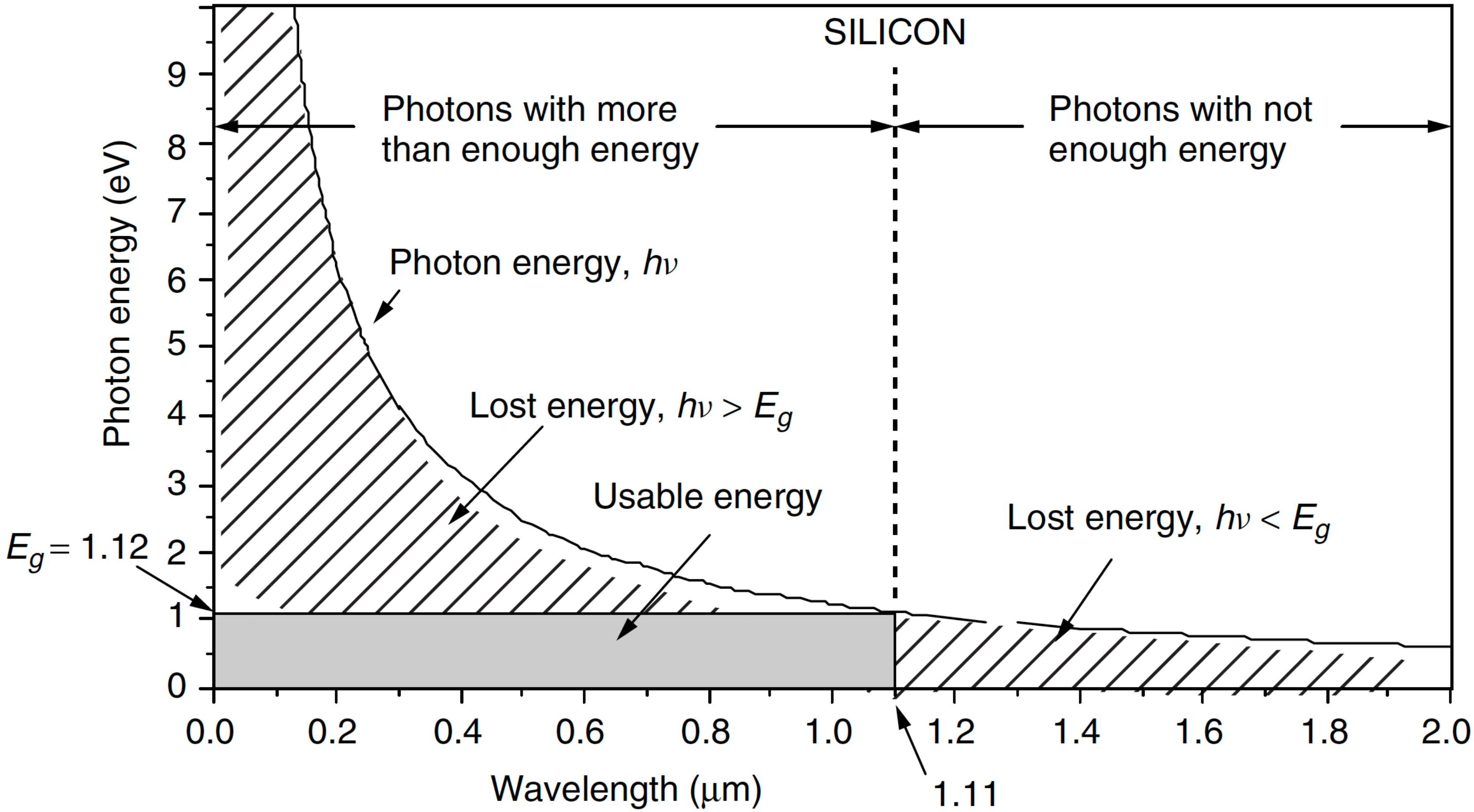


Fig: The Shockley-Queisser limit for solar cell efficiency (single-junction, unenhanced insolation)

Useful and Wasted Energy



- Photons with wavelengths above 1.11 μm don't have the 1.12 eV needed to excite an electron, and this energy is lost.
- Photons with shorter wavelengths have more than enough energy, but any energy above 1.12 eV is wasted.

Quiz

Q1. Blue light of wavelength 485 nm falls on a silicon photocell made from a semiconductor with bandgap is 1.35 eV. What is the maximum fraction of the light's energy that can be converted into electrical power?

Only the fraction of the incident energy equal to the bandgap energy can be converted to electrical power, the rest is lost as heat (the semiconductor hears up). Therefore, the efficiency is given as

$$\eta = \frac{E_g}{E_{485nm}} \times 100\% = \frac{1.35eV}{\frac{hc}{\lambda}} \times 100\% = \frac{1.35eV}{1241.5eV \cdot nm / 485nm} \times 100\% = 52.74\%$$

Q2. Find the maximum wavelength of the photon needed to cause an electron to jump from the valence to the conduction band in (a) silicon, band gap 1.1 eV; (b) cadmium selenide, band gap of 1.73 eV; (c) cadmium sulfide, band gap 2.42 eV.

Using $\lambda = \dfrac{hc}{E}$

(a) $\lambda = 1241.5eV \cdot nm / 1.1eV = 1128.64nm$

(b) $\lambda = 1241.5eV \cdot nm / 1.73eV = 717.63nm$

(c) $\lambda = 1241.5eV \cdot nm / 2.42eV = 513.02nm$

PV Cells & Modules

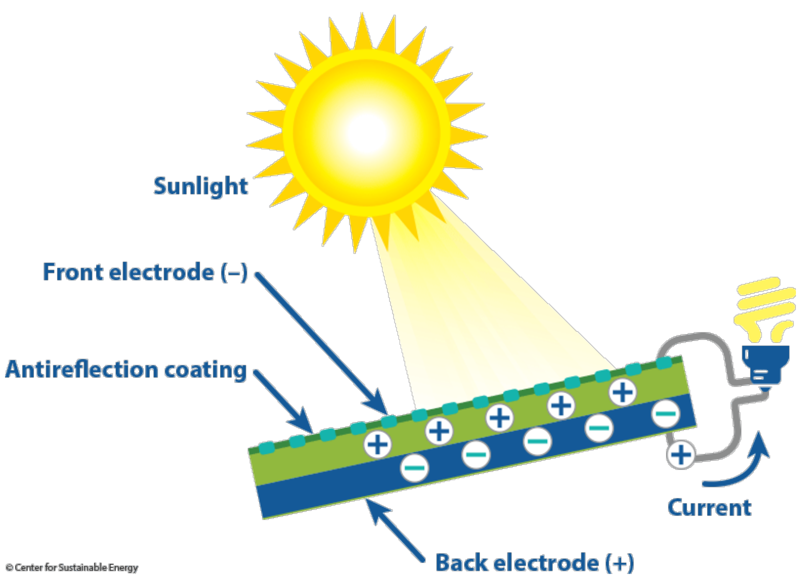
Q: How much voltage does a typical silicon PV cell produce?

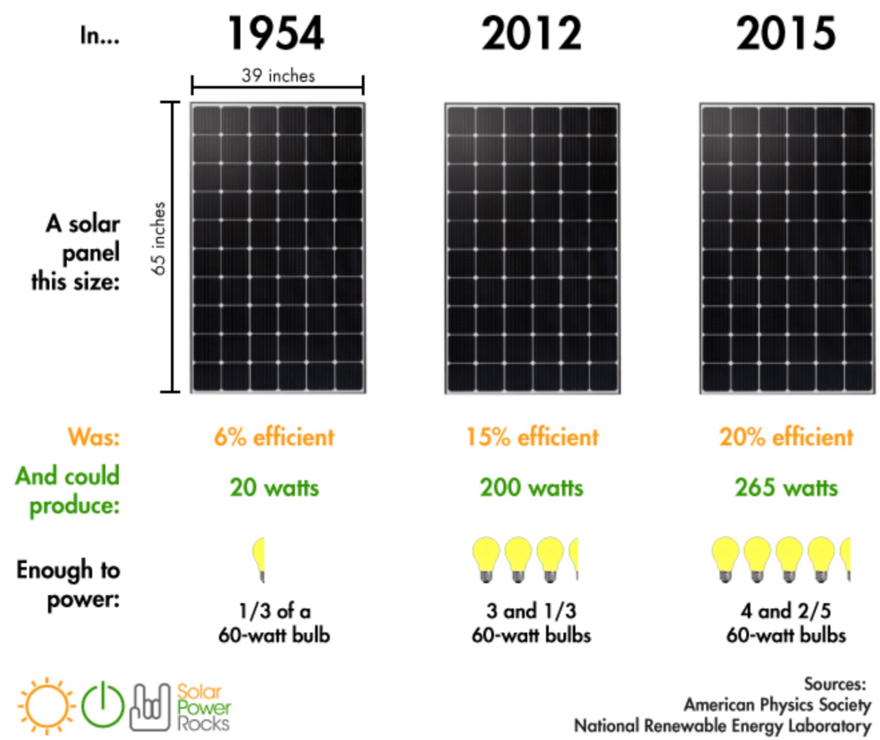
Answer:

• A typical silicon PV cell produces around 0.5 volts.

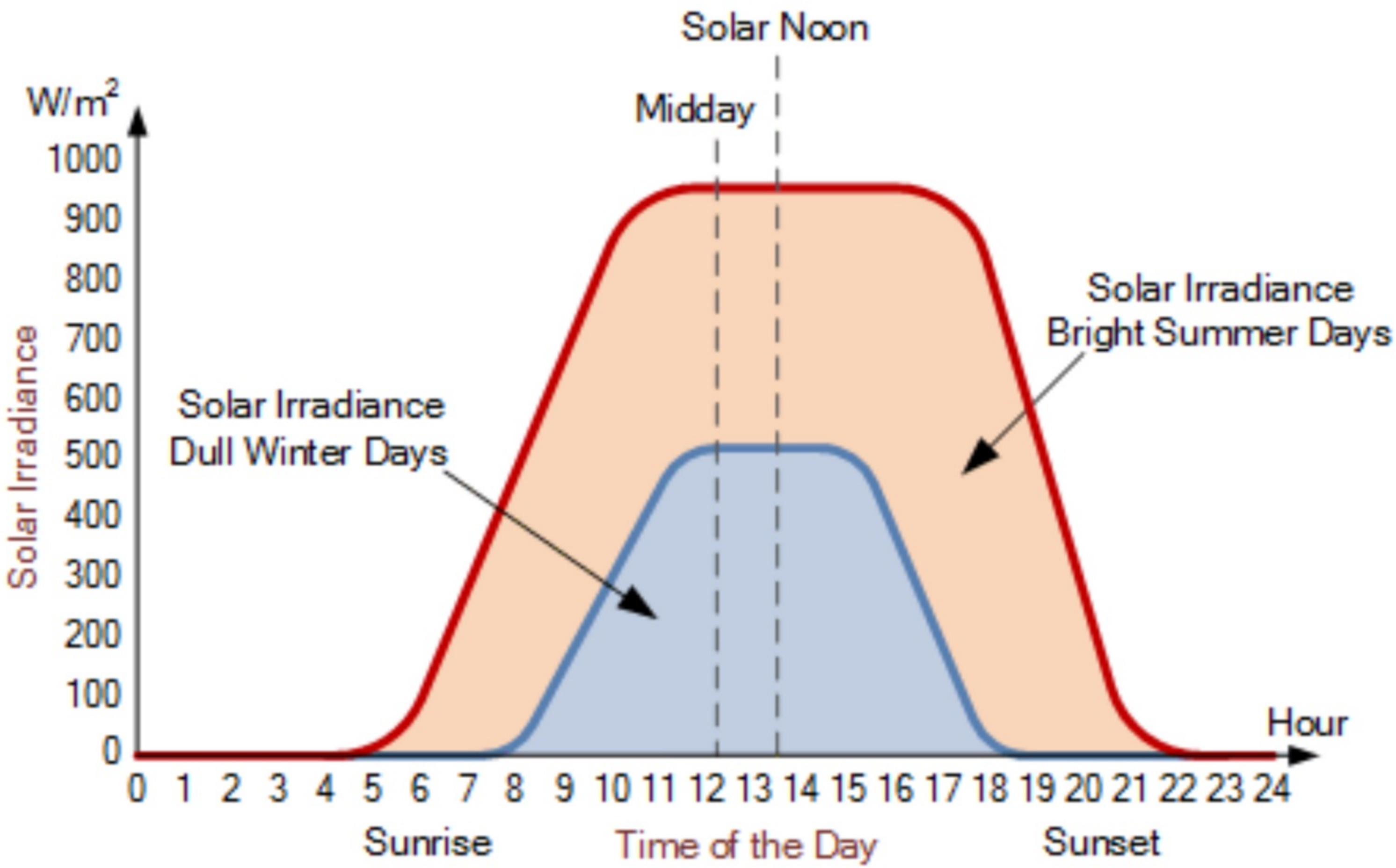
• 60-72 cells are combined (series-parallel mix) into PV modules.

• They are normally around 1.5 m^2 in area, and have a peak power output of 120-300 watts, depending on the design/tech.



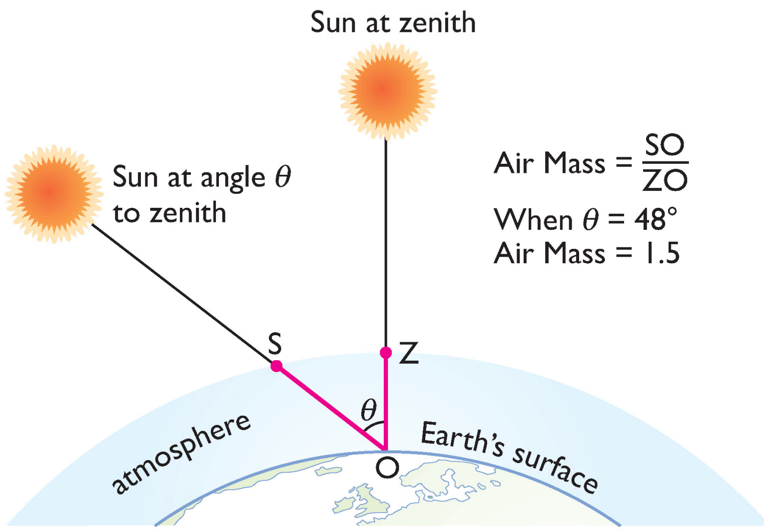


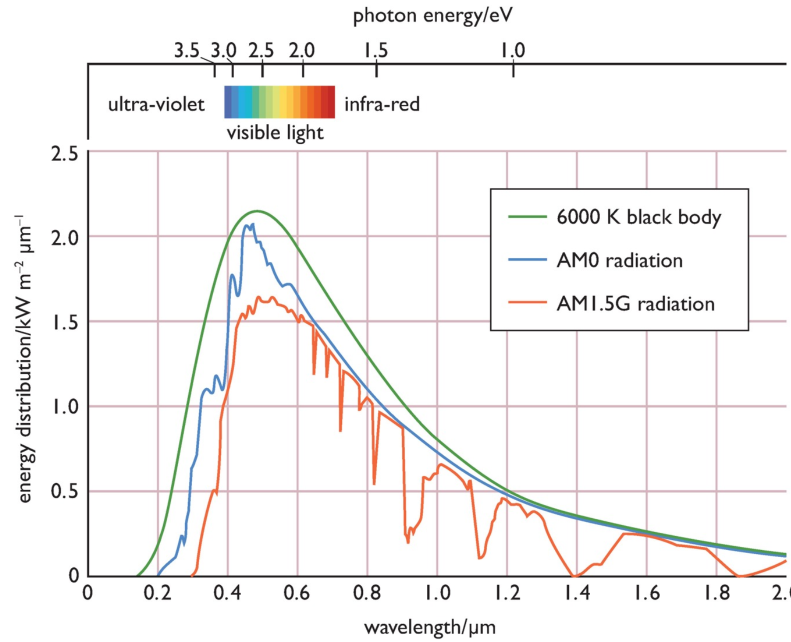
Standard Test Conditions for PV Cells



One “Full Sun” (1-sun) = 1kW/m^2

Standard Test Conditions (cont'd)





PV cell performance is dependent on solar radiation whose spectrum varies with the height of the Sun:

- AM0: solar radiation measured in space
- AM1: Sun directly overhead
- AM1.5: Sun at 48º angle
- 6K black body: Assuming Sun is an ideal 'black body' radiator with a surface temperature of 6000º K.

PV Industry

Two Categories:

- Crystalline silicon (c-Si), used in traditional wafer-based solar cells:
  - Monocrystalline silicon (mono-Si)
  - Multicrystalline silicon (multi-Si)
  - Ribbon silicon (ribbon-Si), has currently no market

- Not classified as crystalline silicon, used in thin-film & other solar cell tech:
  - Amorphous silicon (a-Si): low cost but relatively low efficiency
  - Nanocrystalline silicon (nc-Si): form of porous silicon
  - Protocrystalline silicon (pc-Si): distinct phase occurring during crystal growth
  - Other non-silicon materials, such as CdTe, CIGS
  - Multi-junction solar cells (MJ): multiple p–n junctions made of different semiconductor materials. Each material's p-n junction will produce electric current in response to different wavelengths of light

PV Tech Tree

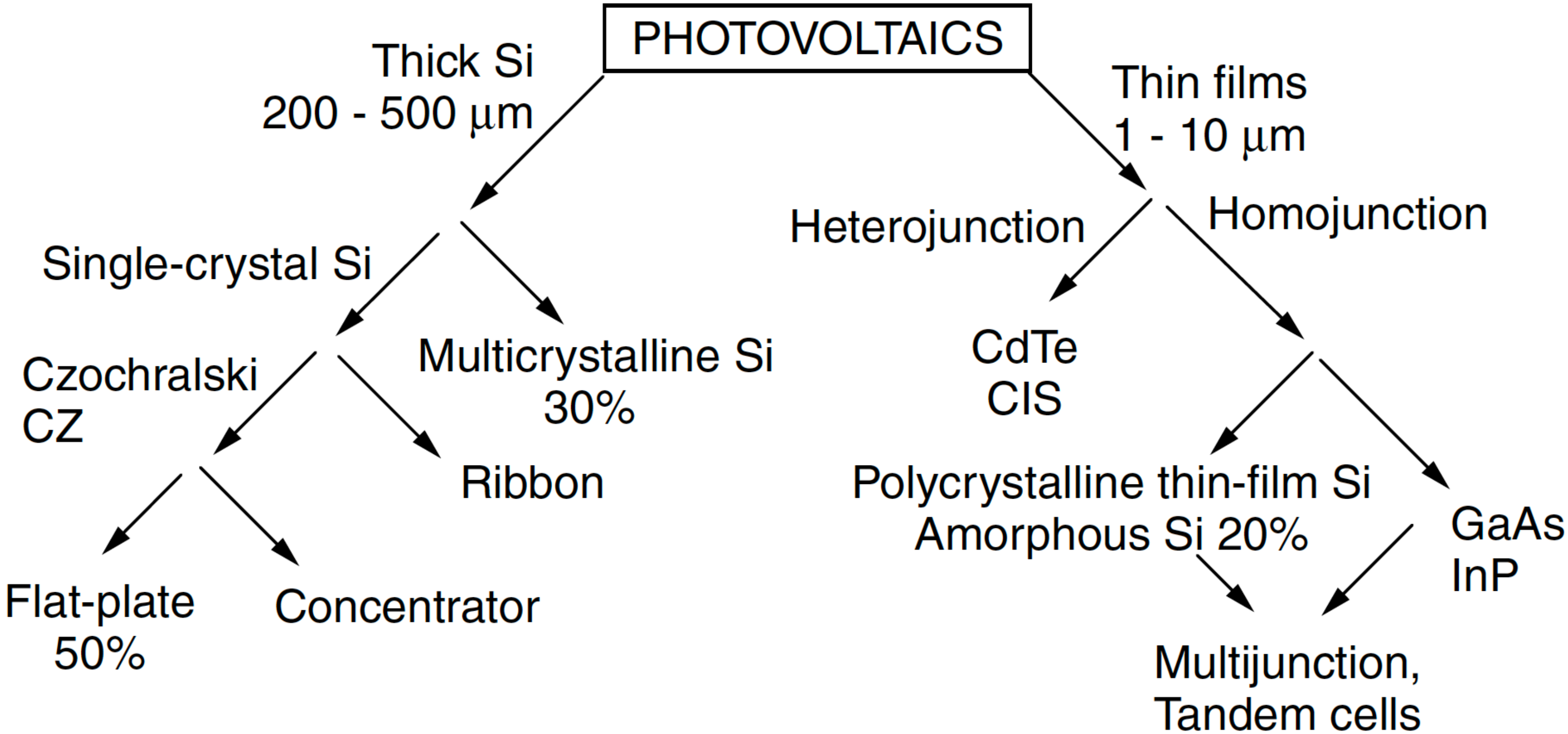
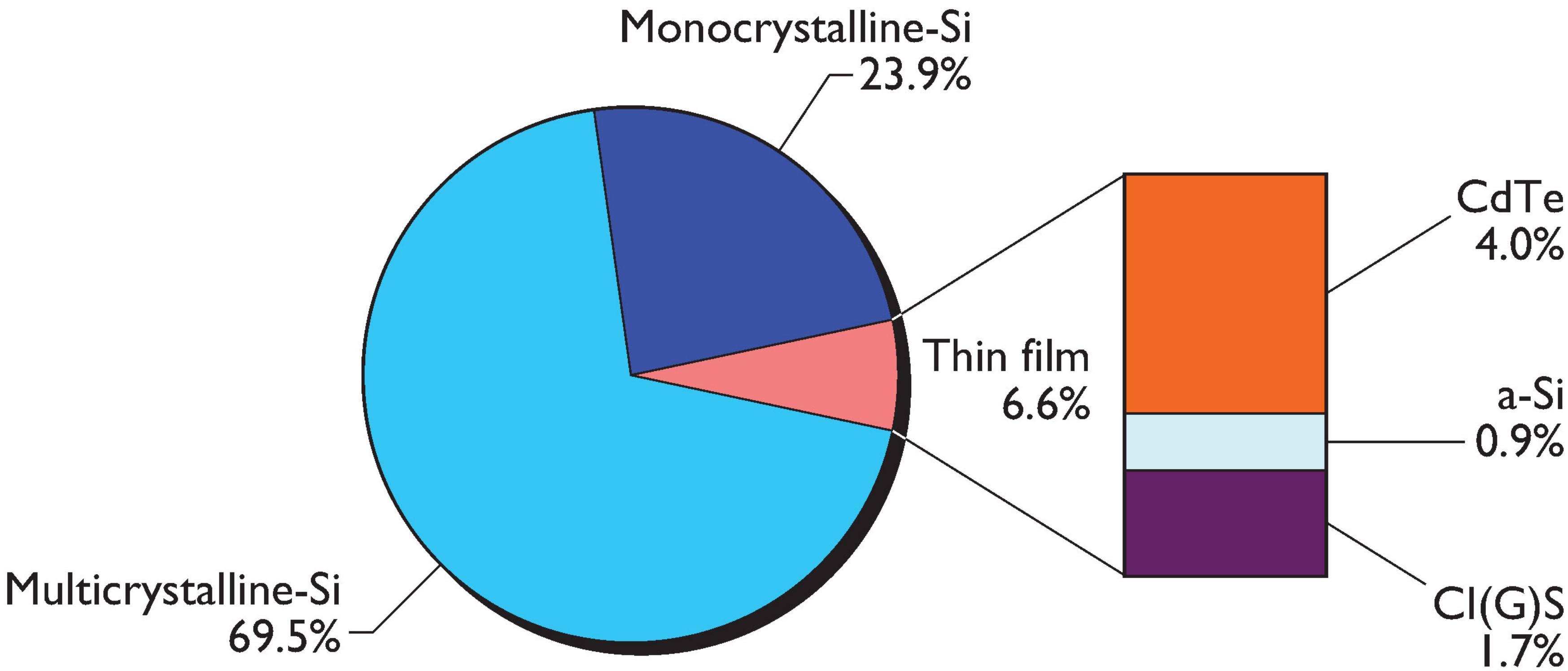


Fig: One way to organize various PV technologies

Global Production for Different PV Tech



Crystalline PV Cells

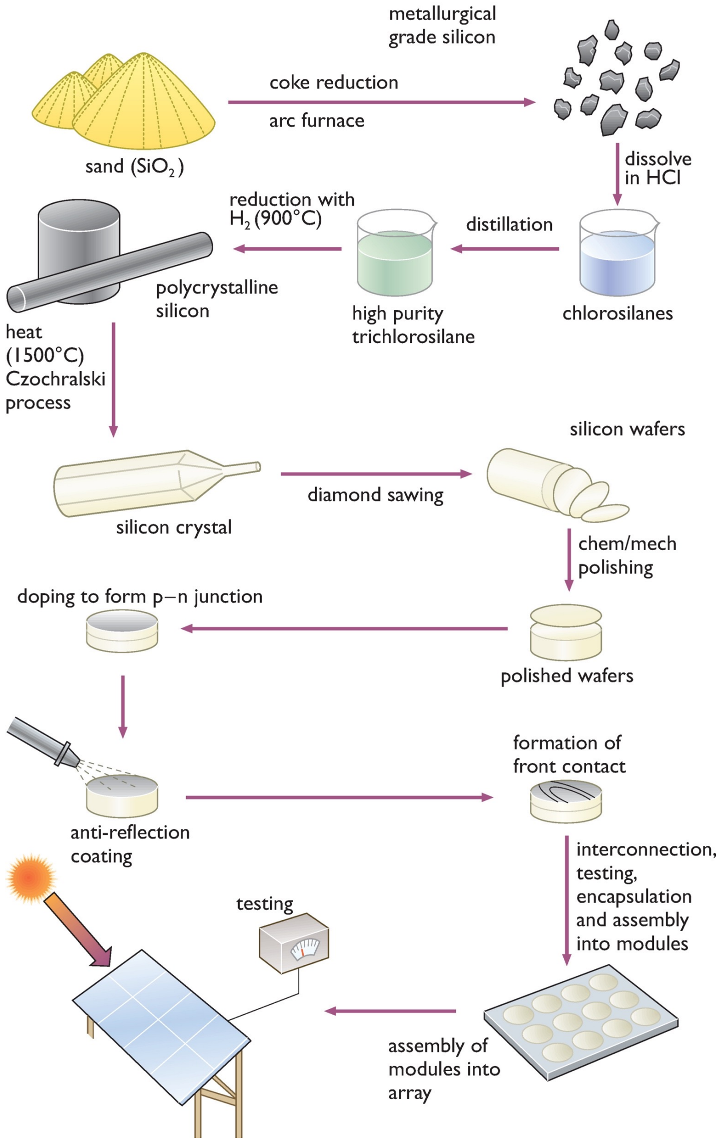
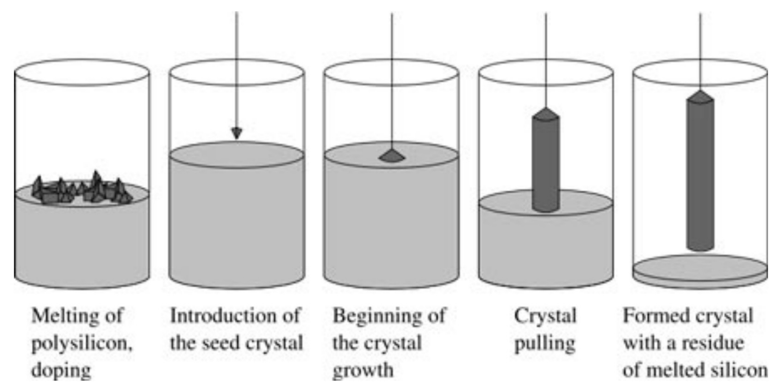


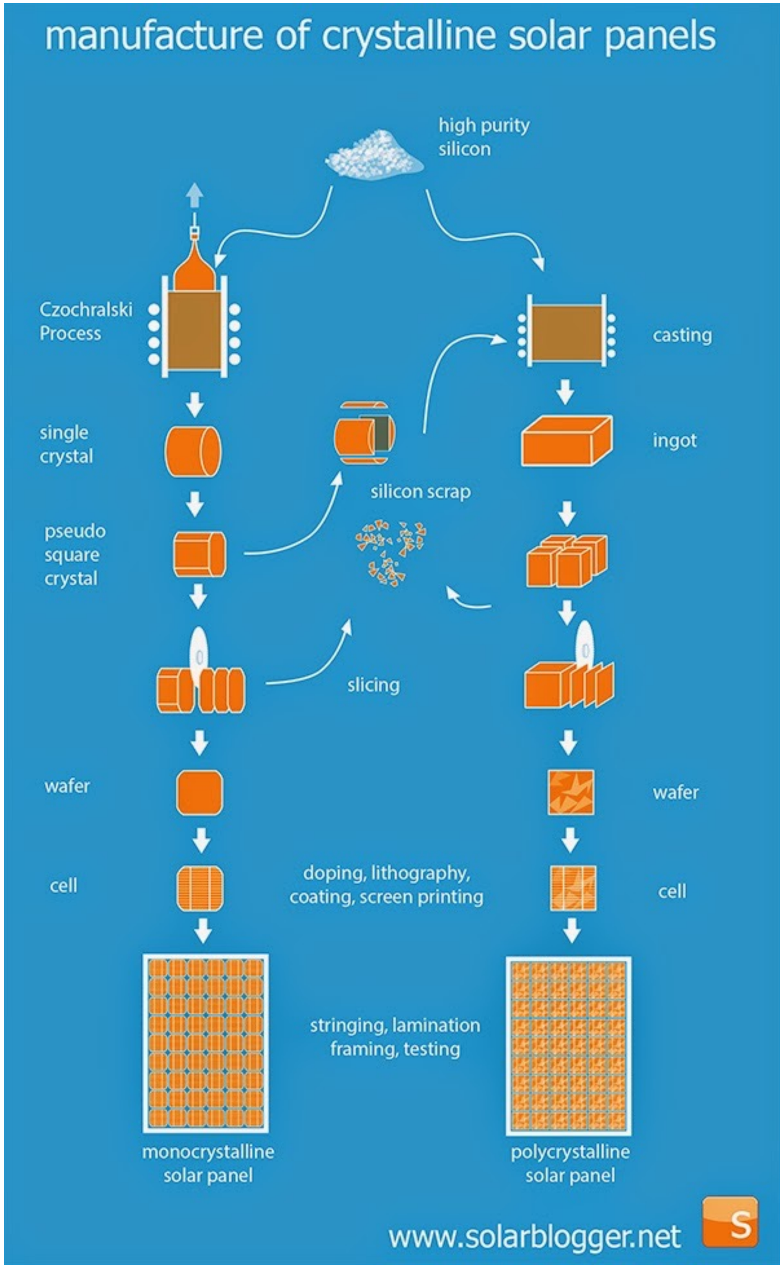
Fig: The process of monocrystalline silicon solar cell and module production

The most efficient cells are made from extremely pure monocrystalline: silicon with a single, continuous crystal lattice structure with no defects/impurities.

The **Czochralski process** (named after Polish scientist Jan Czochralski): A method of crystal growth used to obtain single crystals of semiconductors (e.g. silicon, germanium and gallium arsenide), metals, salts and synthetic gemstones.



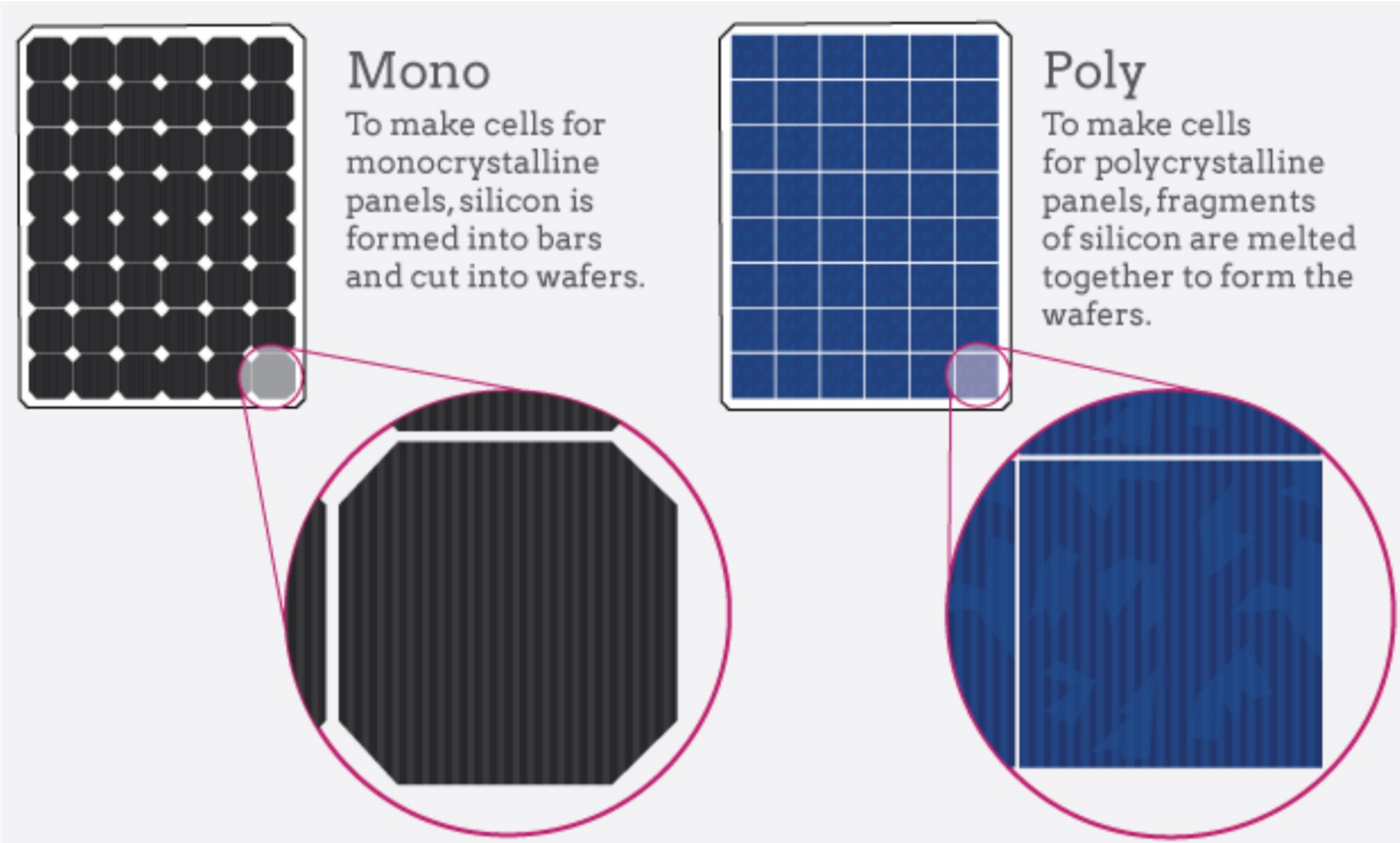
Mono vs Poly Crystalline



- **Monocrystalline** silicon is usually grown from a small seed crystal that is slowly pulled out of a molten mass of polycrystalline silicon (consists of small grains of monocrystalline).

- Polycrystalline (multicrystalline) cells are easier and cheaper to manufacture, but are less efficient.

Mono vs Poly Crystalline

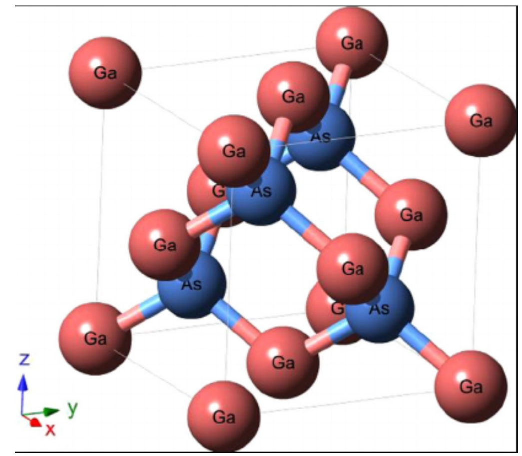


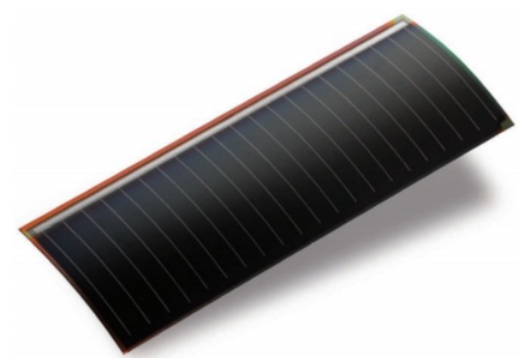
Picture source: https://www.civicsolar.com/

Other PV Materials - Gallium Arsenide Cells

Gallium arsenide (GaAs):

- structure similar to silicon
- consist of gallium and arsenic atoms
- more efficient than monocrystalline cells
- high light absorption coefficient (need only a thin layer)
- can operate at relatively high temperatures without substantial reduction in efficiency
- very expensive: i) gallium and arsenic not abundant; and ii) partly production process is not well developed
- often used when very high efficiency is required, regardless of cost – e.g., space PV applications.





Thin-film Silicon PV

Solar cells can also be made from very thin films of silicon, in a form known as amorphous silicon (a-Si), in which the silicon atoms are much less ordered

A-Si cells are cheaper to produce. Advantages in manufacturing process:

- ✓ operates at a much lower temperature, less energy required
- ✓ suited to continuous production
- ✓ allows quite large areas of cells to be deposited onto a wide variety of both rigid and flexible substrates, including steel, glass, and plastics.

A-Si cells are currently much less efficient than the mono/poly-crystalline silicon counterparts. They are already widely used as power sources for a variety of consumer products, where the requirement is for low cost rather than high efficiency.

Other Thin-film Silicon PV Tech

Based on compound semiconductors:

- Copper indium gallium diselenide (CIGS)
- Cadmium telluride (CdTe)

Categories	Technology	η (%)	V_{OC} (V)	I_{SC} (A)	W/m²	*t* (μm)
Thin film solar cells	a-Si	11.1	6.3	0.0089	33	1
	CdTe	16.5	0.86	0.029	–	5
	CIGS	20.5	–	–	–	

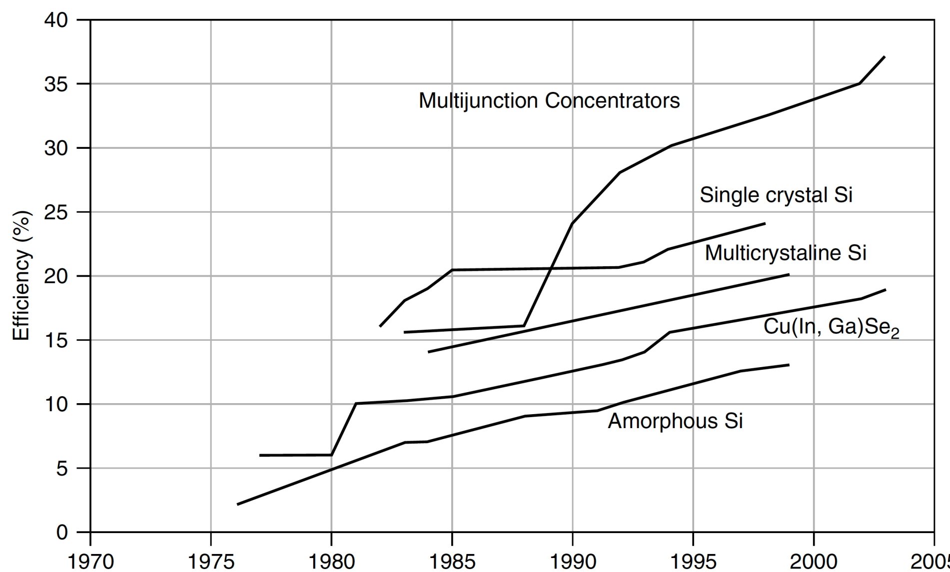


Figure 8.1 Best laboratory PV cell efficiencies for various technologies. (From National Center for Photovoltaics, www.nrel.gov/ncpv 2003).

Copper indium gallium (di)selenide (CIGS)

- CIGS is a I-III-VI_2 semiconductor material composed of copper, indium, gallium, and selenium. The material is a solid solution of copper indium selenide ("CIS") and copper gallium selenide.
- CIGS has a chemical formula of CuIn(1-x)Ga(x)Se2 where the value of x can vary from 0 (pure copper indium selenide) to 1 (pure copper gallium selenide).
- CIGS cells have the highest laboratory efficiencies of all thin-film devices, around 17%; modules over 10% are *commercially* available.
- CIGS has a bandgap varying continuously with x from about 1.0 eV (copper indium selenide) to about 1.7 eV (copper gallium selenide).

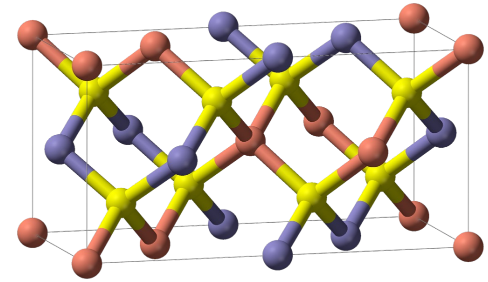


Fig a: CIGS unit cell. Red = Cu, yellow = Se, blue = In/Ga.

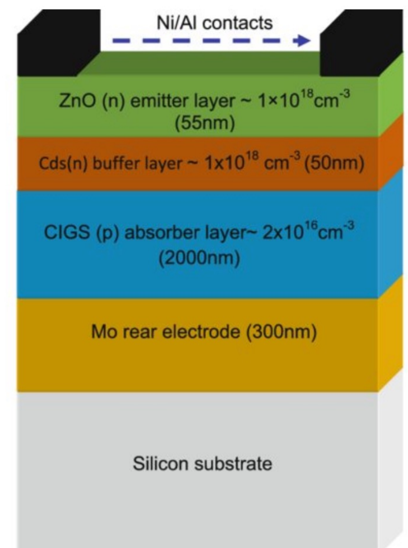
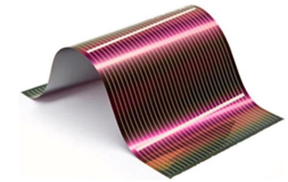


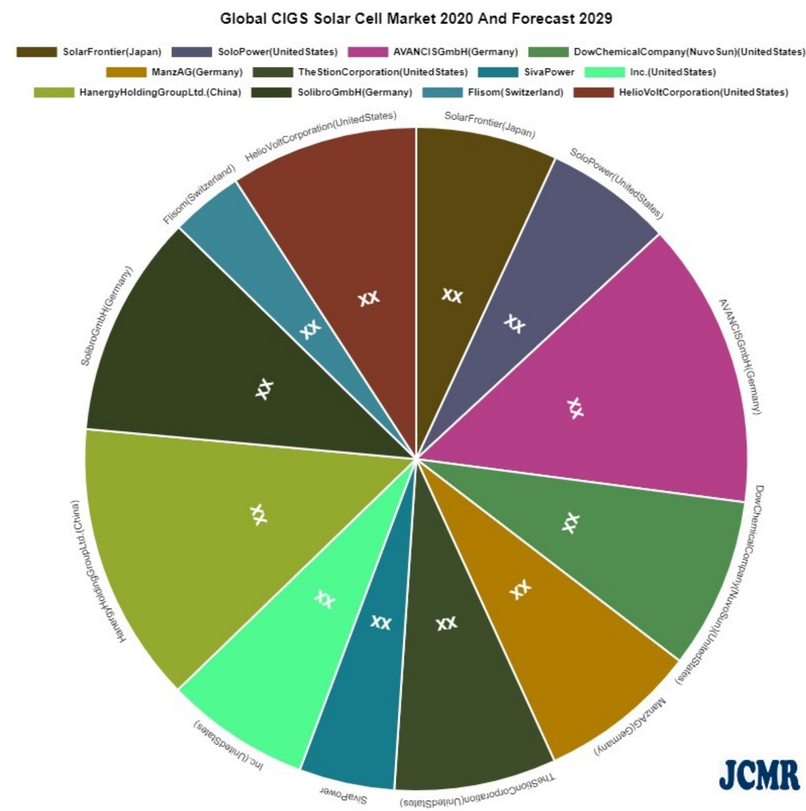
Fig b: Structure of the CIGS solar cell. ZnO = Zinc oxide, CdS = Cadmium sulfide, Mo = Molybdenum.

See more in https://www.hisour.com/copper-indium-gallium-selenide-solar-cells-39668/

Benefits of CIGS Solar Cells

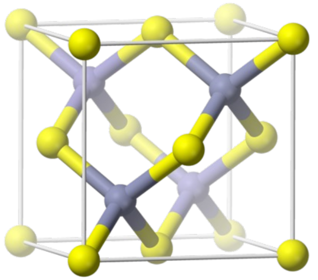


- High absorption: This direct-bandgap material can absorb a significant portion of the solar spectrum, enabling it to achieve the highest efficiency of any thin-film technology.
- Tandem design: A tunable bandgap allows the tandem CIGS devices.
- Protective buffer layer: The grain boundaries form an inherent buffer layer, preventing surface recombination and allowing for films with grain sizes of less than 1 micrometer to be used in device fabrication.

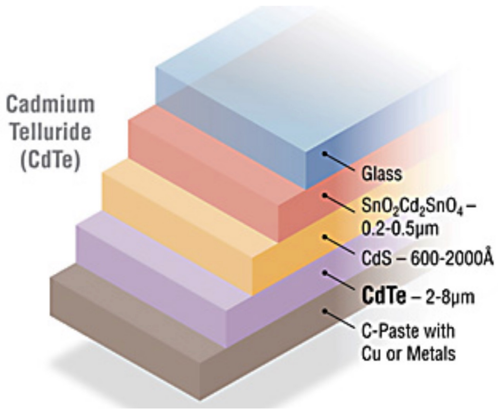


Source: https://www.energy.gov/eere/solar/copper-indium-gallium-diselenide

Cadmium Telluride (CdTe)



- CdTe-based PV is a thin-film technology: active layers are just a few microns thick (1/10 the diameter of a human hair).
- Transparent conducting oxide (TCO) layers (SnO_2/Cd_2SnO_4) are transparent to visible light and highly conductive to transport current efficiently.
- Intermediate layers such as CdS help in both the growth and electrical properties between the TCO and CdTe that acts as the primary photoconversion layer and absorbs most visible light.
- All three layers form an electric field that converts light absorbed in the CdTe layer into I & V.
- CdTe: relatively simple and inexpensive process. But cadmium is a highly toxic substance. Precautions need during manufacture/use/recycling.



See more in https://www.hisour.com/copper-indium-gallium-selenide-solar-cells-39668/

Multi-junction PV Cells

Multi-junction PV cells: there are layers of different p–n junctions, each 'tuned' to absorb light from a different part of the solar spectrum.

Prize-winning Tokai Challenger solar car:

• An array of more than 2000 Sharp triple-junction PV cells, with a peak power output of 1.8 kW and an efficiency of 30%, was used to power the electric motors

• It covered 2998 km in 29 hours 49 minutes at an average speed of 100.54 km/hour (62mph).