Today's Photovoltaic Solar Cells

John C. Bean

Outline

What is electricity? => The need for "electron pumps"

What is sunlight? How does light interact with various materials

How to make an electron pump (vs. a non energy producing "photoconductor")

- How to create free electrons & free holes by adding "donor" or "acceptor" impurities
  - Doing this side-by-side to form electron-pumping interfacial electric fields

Choosing solar cell material to milk the most power from sunlight – Shockley-Queisser Limit

- Silicon's idiosyncrasies => The impact of "indirect bandgap" & "traps"
- Today's diamond, gold, silver & bronze standards / Record solar cell efficiencies

Huge difference between average and peak solar cell output => My ½ x ½ x maybe ½ rule

Dealing with the possible loss of sunlight via reflection

A solar cell's lifetime energy output vs. lifetime energy input => E.R.O.I.

(Written / Revised: November 2019)

Today's Photovoltaic Solar Cells

"Photovoltaic" refers to the direct, single step conversion of **sunlight** into **electricity**

So, to start, both need to be explored in greater depth

What is electricity? That may sound like a very simple, or even dumb question

In which case: I've read an incredible number of "dumb" news stories

And "dumb" university press releases

And even occasional "dumb" comments from research scientists

Because they imply that:

"Electricity" = THING that can just ooze out of a lump of material

WRONG!

Electricity is not a thing – It is a process:

Of electrons being driven in a flow

*But why **CAN'T** we just squeeze electrons out (and then USE them)?*

From notes on **Electricity & Magnetism** (pptx / pdf / key) & **Magnetic Induction** (pptx / pdf / key):

Maxwell's 1st Equation says **Electric Fields** build in proportion to net charge

"Net charge" = Positive charge density – Negative charge density

Electric Force is then proportional to the strength of that electric field

So just a TINY ACCUMULATION of net charge => HUGE FORCE

For a second or two this may happen:

Then there's a snap as charge dissipates

joyerickson.wordpress.com/2012/08/05/pull-up-something-cool/

BOTTOM LINE:

On scales much greater than molecular dimensions

Nature will not LET you add or remove significant net charge!

(because the resulting HUGE force would then EXPEL that net charge)

*So "electricity" is instead all about **pumping** charge*

We **PUMP** charge in one end of something and out the other end:

"Something" = Generator, solar cell, battery . . .

That's WHY it's called electrical **current** = An analogy to incompressible water:

We pump water THROUGH pipes, but if we try to increase water IN pipes => Explosion!

Generators, solar cells, batteries, . . . are all CHARGE PUMPS

And pumps are judged on basis of the **flow** and **pressure** they can generate:

Water Power = Flow x Pressure which is analogous to:

Electrical Power = "Current" x "Voltage"

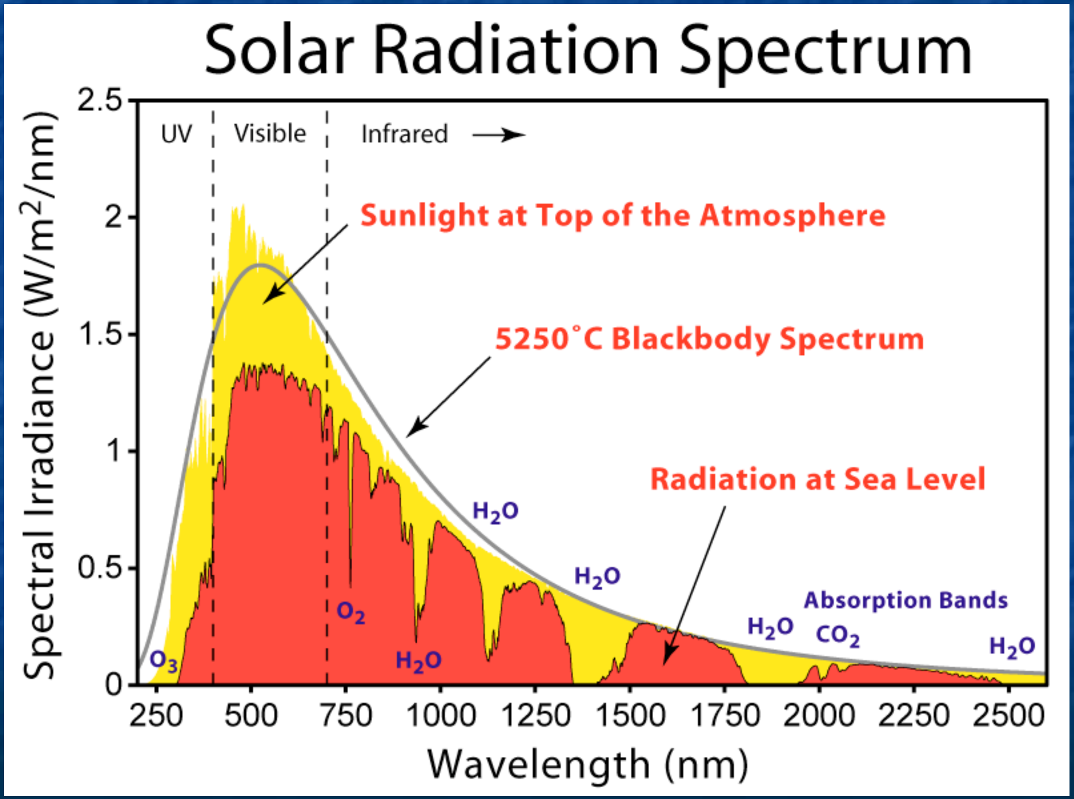
So what we are NOW looking for is a solar-powered electron pump!

Moving on to the 2nd key question: ***What is Sunlight?***

It is a very BROAD range of colors (a.k.a. "wavelengths")

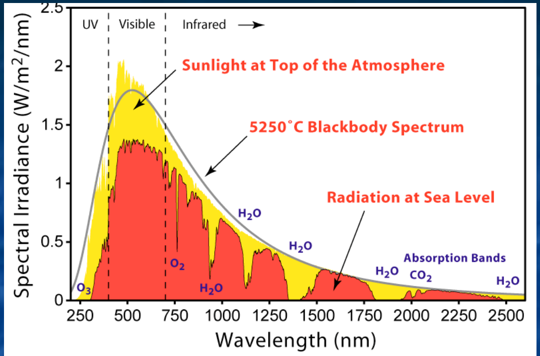
Resembling a "Black Body Spectrum" (= vibrating things randomly sharing energy)

Significant portions of which are absorbed in the atmosphere (yellow => red)



Source: en.wikipedia.org/wiki/Sunlight

How much power can sunlight provide?



Above the earth's atmosphere, total power is ~ 1350 Watts / square meter

This value is referred to as "AM0" (air mass zero)

But the atmosphere absorbs ~ 25% => ~ 1000 Watts / square meter

Referred to as "AM1.5" (air mass 1.5)

But that is the MAXIMUM solar power that can EVER reach the earth's surface

Because it is the value only when the sun is DIRECTLY overhead

Which happens only in certain locations, in certain seasons, once a day,

when there is no haze, fog, or clouds to absorb or redirect sunlight

How to convert light's wavelength into photon energy:

Start with fact that light's energy is proportional to its frequency:

$\text{Energy}_{\text{light}} = h\, f$ h = Plank's constant,   f = frequency (in Hz = cycles /sec)

Add in the fact that, in one cycle, light travels one wavelength (= "λ")

So velocity of light = $c = \lambda$ / (cycle time) = $\lambda\, f$

Plug second relationship into first relationship:

$\text{Energy}_{\text{light}} = h\, f = h\, (c / \lambda) = hc / \lambda$

Then, agree to express light energies in eV, and wavelengths in microns

Yielding relationship: **$\text{Energy}_{\text{light}}$ (in eV) = 1.24 / λ_{light} (in microns)**

A Joule = (1 coulomb of charge) (crossing a 1 Volt potential)

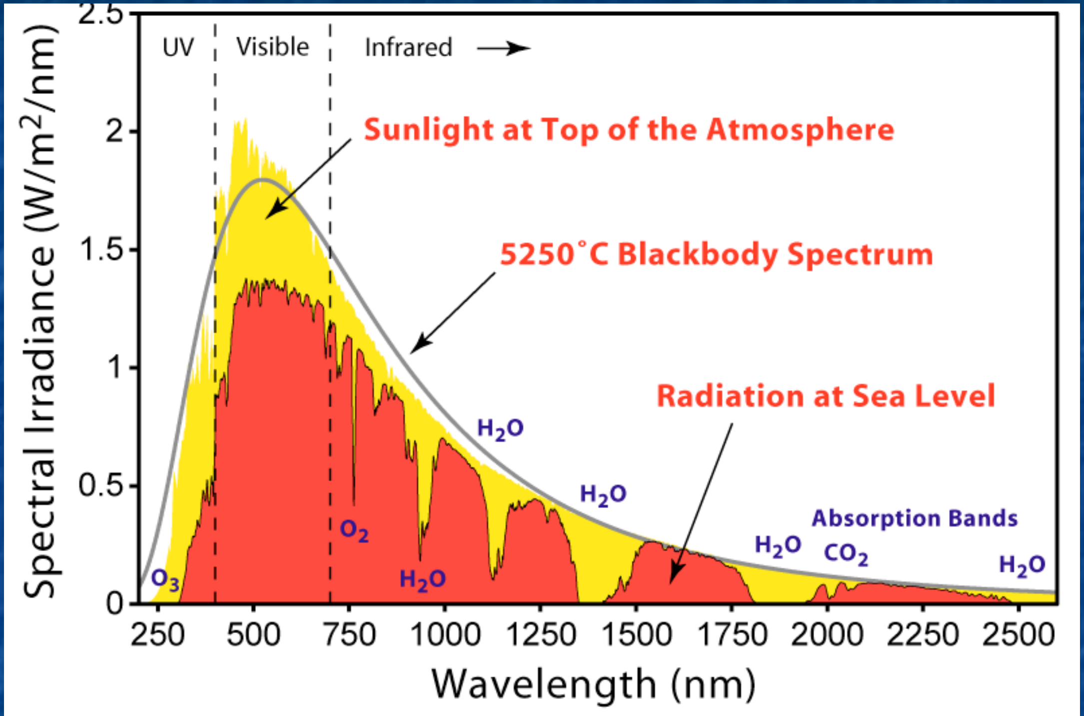
An eV = (1 electron charge) (crossing a 1 Volt potential) = 1.6×10^{-19} Joules

Using this to revise the scale of earlier sunlight plot:

From formula above (and fact that 1000 nm = 1 micron):

← Energy

Wavelength →



5 eV 2 eV 1 eV 0.5 eV

And calling out spectral ranges by their common names:

UV | Vis | Infrared

*We now need to know how these colors **interact with matter***

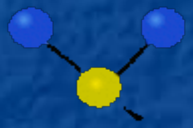
Because we want to exploit these interactions to CAPTURE the light's energy!

1) **INFRARED (IR) LIGHT**: 0.7 microns < Wavelength

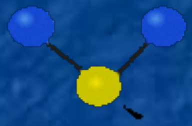
Energy < 1.7 eV

If absorbed by matter, IR => heat = atomic & molecular vibrations

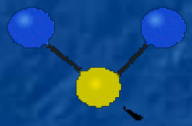
Symmetric Stretch



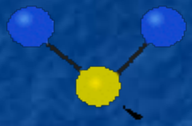
Asymmetric Stretch



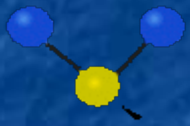
Scissoring



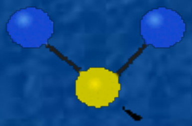
Rocking



Wagging



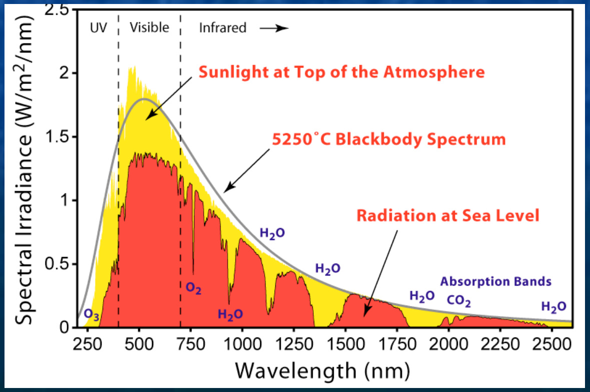
Twisting



Uniqueness of an atom/molecule's vibrational energies => absorption bands

=> "IR" spectroscopies used by chemists AND

to absorption bands seen in AM1.5 spectrum:



Animated GIFs from: en.wikipedia.org/wiki/Infrared_spectroscopy

IR vibrations may be amusing (and quite useful elsewhere)

But, in the context of solar photovoltaics, the important fact is that:

  Most IR light lacks the energy necessary to liberate electrons from atoms/bonds

    Thus most **Infrared** light **CANNOT DIRECTLY** produce electricity

But Infrared's heat energy CAN be transferred to (absorbed by) other things

  Especially if they are thick enough

    The captured heat can then be used to boil water

      Which, expanding, can drive the turbines of electrical generators

        = **Solar Thermal Energy** as described in subsequent note sets

    So **Infrared** light can **INDIRECTLY** produce electricity

As opposed visible light which CAN directly produce electricity:

1) **VISIBLE (Vis):** 0.4 microns < Wavelength < 0.7 microns

1.8 eV < Energy < 3 eV

Visible light **CAN** knock an electron free from an atom ("ionization")

Visible light **CAN** also knock one electron out of a covalent bond

That's probably why our eyes use visible light:

Infrared light just causes atoms in eye to vibrate

Vibrations CAN be transferred to other atoms (a.k.a. heat flow)

But it's hard to imagine a heat-directing "optical nerve fiber"

In contrast, **visible** light can liberate electrons/ions (producing => electrical flow)

What about ultraviolet light?

1) **ULTRAVIOLET (UV):** Wavelengths < 0.4 microns

3 eV < Energy

UV has MORE than enough energy to liberate electrons!

So we CAN ALSO use UV light to directly produce electricity

HOWEVER, UV light also has enough energy to **BREAK MANY ATOMIC BONDS**

Distinction: "Liberating" = Removing one of a covalent bond's paired electrons

Or extracting one electron from an unbonded pair (=> "free radical")

In both cases, pair can re-form later by capturing an electron

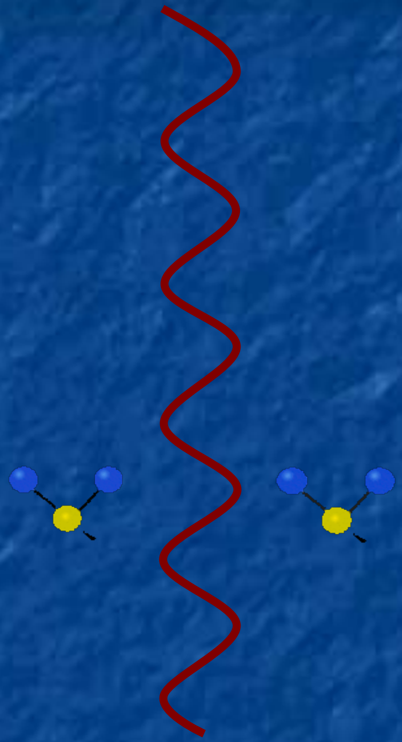
Whereas: "Bond breaking" = wiping out bond => changing molecular structure

Thus, over time, UV LIGHT can even DESTROY solar cell materials

= A particular problem for weakly bonded organic solar cell materials

Summarizing the different ways in which light interacts with matter:

Infrared



Vibrates a few atoms

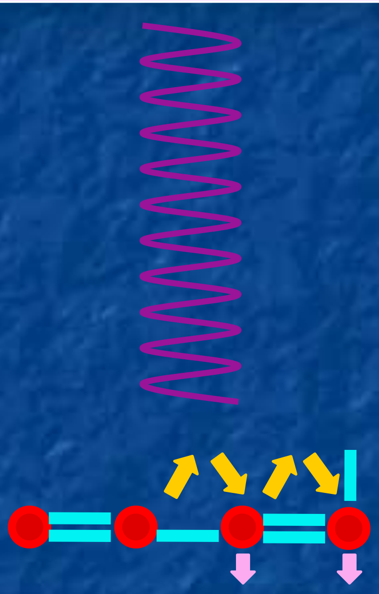
But **MOST** of it passes right through thin layers of material

Visible

Liberates electrons from bonds

IF the material has an electron liberation energy ≤ light energy

UV



Liberates electrons from bonds but gives them so much **excess energy** that they ricochet all around

Excess energy is lost as struck atoms start to vibrate (=heat)

*Solar-powered electron pumps = **Photovoltaics** (a.k.a. "solar cells")*

What happens when light strikes a material? From above:

Case 1) Photon energy < Material's bond energy:

Photon can't shake anything loose, most just proceed on through

Meaning that the material is ~ transparent to these too low energy photons

Case 2) Photon Energy ~ Material's bond energy

Photon IS now absorbed and its energy used to kick an electron out of a bond

Case 3) Photon Energy > Material's bond energy

Photon is absorbed: Part of its energy kicks an electron out of a bond

Rest of its energy also goes to that electron in the form of **kinetic energy:**

Photon kicks electron out of the bond, then kicks it in the butt!

So when a material is exposed to light having its bond energy:

That light is (at least eventually) going to be absorbed by a bond in the material:

Before: Atom cores (positive nuclei + inner electrons) + bonding electrons

In 1D:

After: One negative electron is liberated, leaving behind a positive region:

But electron is DRAWN BACK to positive region, falling back into bond

(or a FEW might wander out the left or right end)

This gives only a "photoconductor" and NOT a solar cell!

(Wake up all of you so-called science journalists!)

Most of the liberated electrons just wander around until pulled back into bonds

Or ones that DO exit are equally likely to exit right or left

Nothing is pumping (pushing) electrons to flow in one direction!

Application? ADD external battery/power supply and use as a light detector:

No light: All electrons in bonds, no current through sample (despite battery)

Light: Freed electrons

Battery can now suck them out one end and push back into other

But where does the light's energy go? Ultimately, into the atoms

Freed electrons later fell back into atoms' clutches,

giving those atoms a kick => Atomic vibrations (a.k.a. **heat**)

To produce power we've ALSO got to drive (PUMP) electrons somewhere!

The Classic Technique:

START with fully-bonded electrically neutral material, most commonly **silicon**

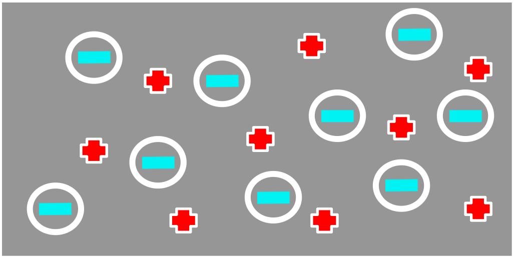
It sets the bonding rules with its crystal structure: Rule with Si = **four bonds**

ADD atom of almost the same size but with one less bonding electron (e.g., **boron**)

Fits into crystal, steals electron from elsewhere, making it an **Acceptor** ion (thief?) ⊖

Bond where electron was stolen **from** now becomes a positive **Hole** ✚

Add **neutral** Acceptor atoms to Si => Negative ions + Liberated holes:



← Silicon atoms = Grey (fixed neutral atoms)

← Acceptor ions also FIXED in position

← Holes = MOBILE Why?

ANSWER: Hole grabs electron from neighbor, leaving hole in a NEW place . . .

And holes don't fill with electrons from outside because that would add net charge

We can also add things that will shed electrons

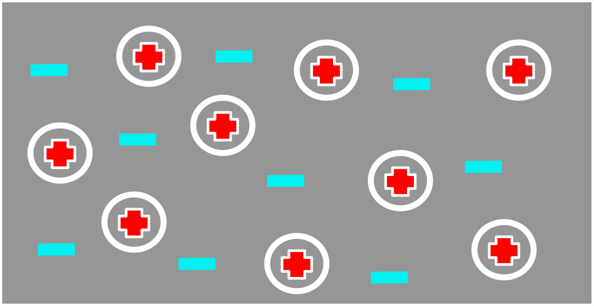
Donor = Similar to Si in size, but with one additional bonding electron (e.g., P, As)

Fits into crystal but final electron has nothing to pair with and bond. Thus:

It easily loses that electron (ionizes), becoming a positive **Donor** ion: ⊕

With that last, now liberated, **electron** free to wander: −

Add **neutral** Donor impurity atoms to Si => Positive ions + Liberated electrons:



Here only liberated electrons are MOBILE

And, as in other material, net charge is still zero!

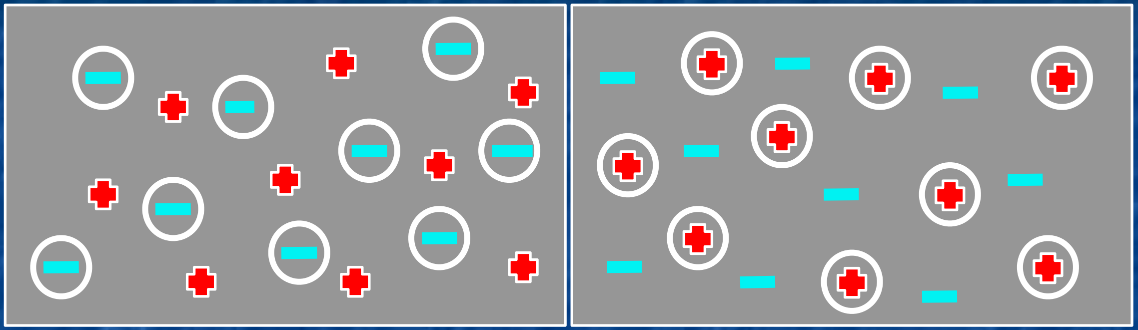
So James Clerk Maxwell is still happy

And if mobile electrons return home, heat will eventually kick them back out!

NOTE: Acceptor and Donor impurities are called "DOPANTS"

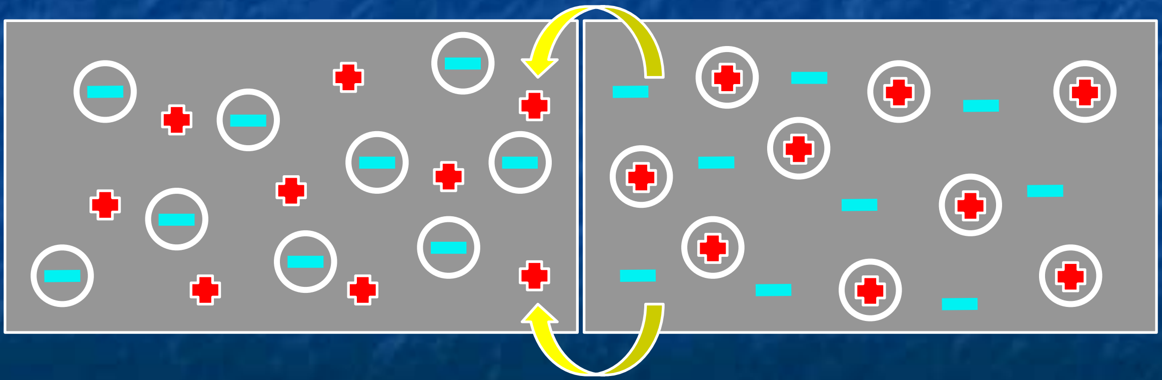
The payoff comes when you put two such "doped" regions side by side:

Acceptor ions + Mobile Holes: Donor ions + Mobile Electrons:



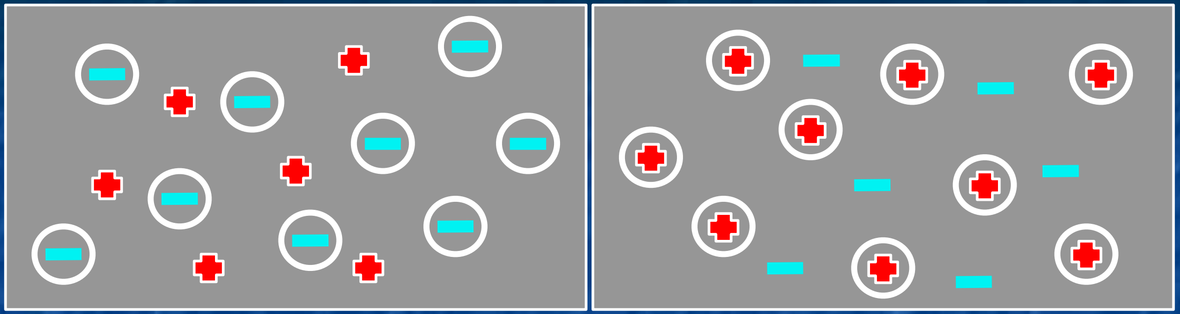
At the intersection ("**junction**") mobile electrons rush across to FILL mobile holes!!

(Because holes ARE just bonds that have lost one of the normal paired electrons)



Mobile electrons filling the mobile holes (in the bonds) = "**Recombination**"

Central junction thus becomes **depleted** of ALL mobile charges (liberated electrons or holes):

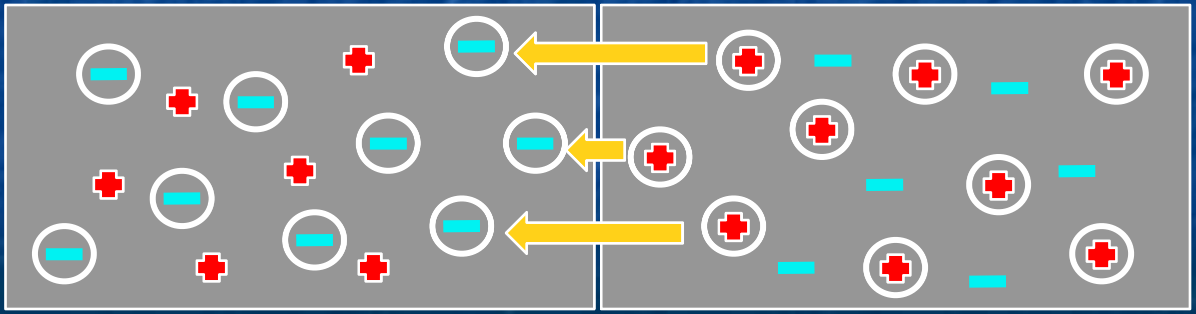


But this leaves uncompensated FIXED acceptor ions (-) / donor ions (+) at the junction

Which produces a growing **Electric field** at that junction

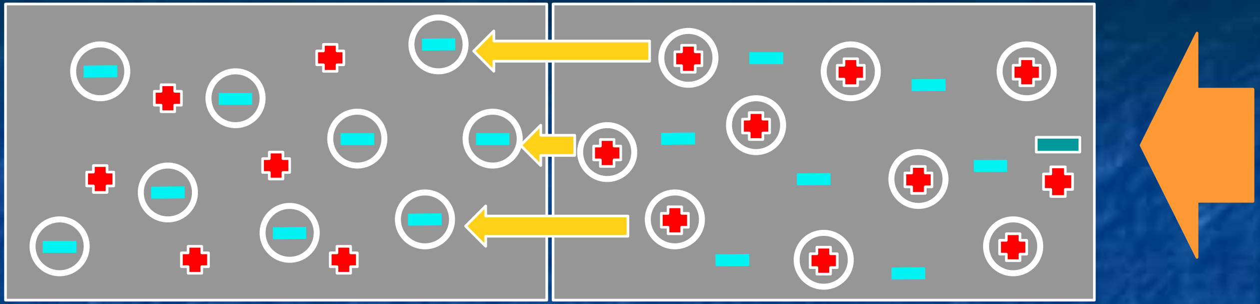
Migration / recombination continues UNTIL field is strong enough to block further migration

Because **Electric field** pushes positive charges left and negative charges right



Electric field thus locks **remaining** mobile holes and electrons on their respective sides

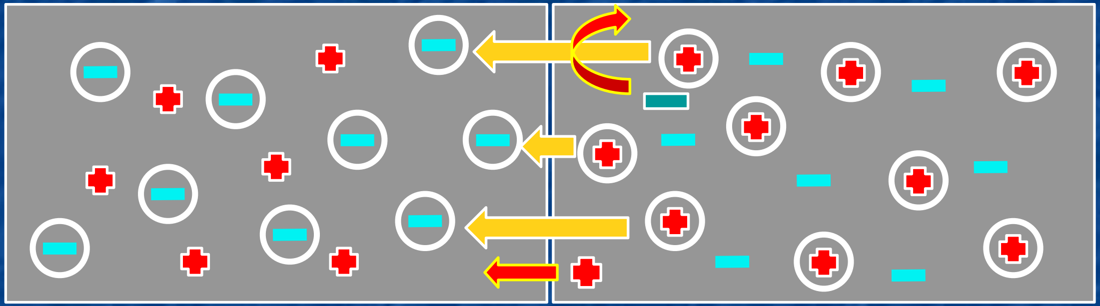
NOW add light to knock electrons out of background silicon:



Light photon knocks an electron out of a bond, creating a wandering electron + hole

(traveling together ="exciton")

New electron and hole can both wander, but if they reach the "junction:"



"Built-in" electric field **traps new electron on right**, but **propels hole to left**

If instead created on left, hole's trapped there, but electron's swept to right

= A CHARGE PUMP

(BTW this is also a **DIODE**: You can only force current through it in **ONE** direction)

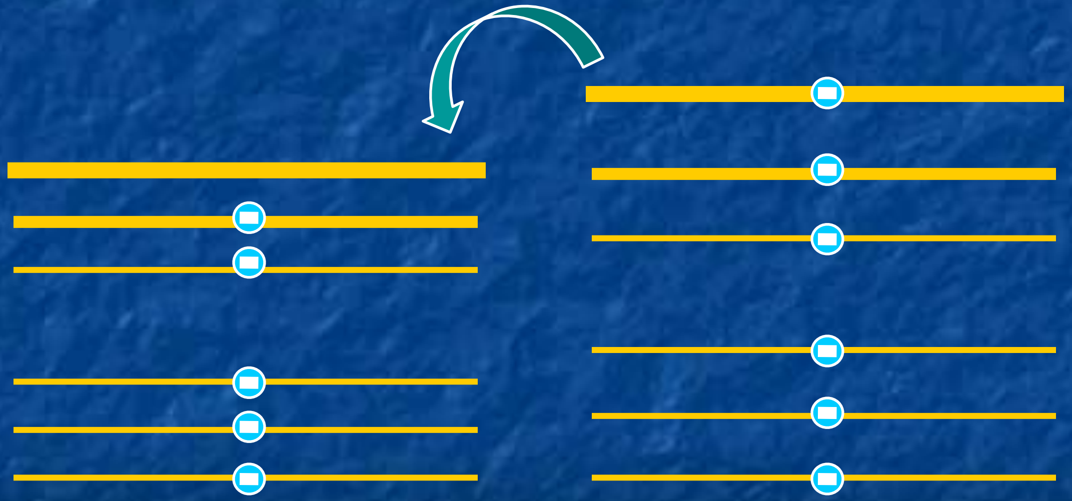
Two ways of creating that boundary charge-separating electric field:

ABOVE: ONE MATERIAL but divided into TWO DIFFERENTLY BEHAVING REGIONS

Two regions **made** different by adding acceptor OR donor impurity atoms

ALTERNATIVE: Just put two DIFFERENT MATERIALS side by side

Electrons at higher energies on one side may try to cross over to other side

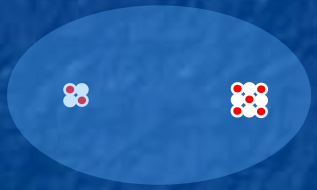


NET RESULT (again) = Build up of electric field at boundary

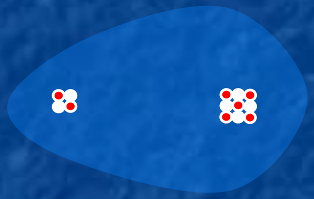
It's analogous to diatomic bonding in molecules:

Atoms of two different materials:

Possibility 1) **Covalent Bond** = Equal sharing of electrons in bond:



Possibility 2) **Polar Covalent Bond** = Unequal sharing of electrons in bond:



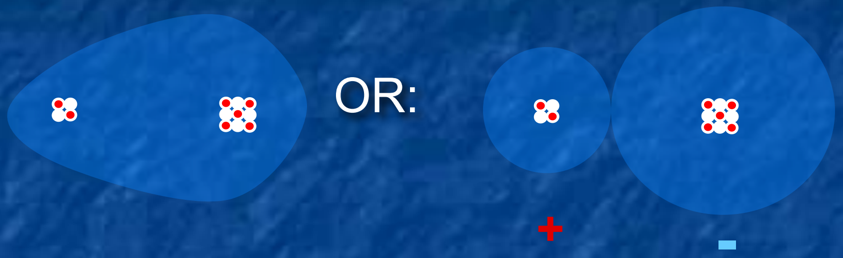
Slight Electric Field

Possibility 3) **Ionic Bond** = Transfer of electron from one atom to other:

Big Electric Field!

Solar cell materials MUST allow some electron movement, then:

At junction of **two different materials**, interfacial bonding **can** be polar or ionic:



Both => Interfacial Electric field

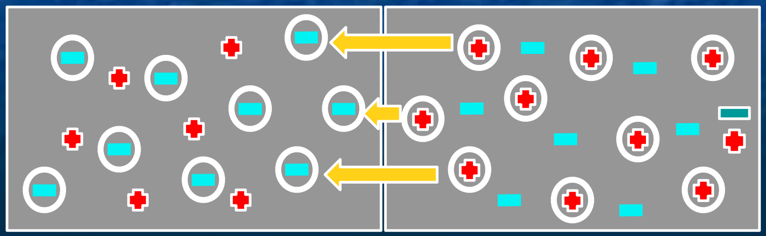
UNLESS the electron energy levels of the two materials are too similar

Then electron in one material may not find a lower energy state in the other

And the interfacial bonding will remain covalent (and E field =>0)

If layers are of **same material** there's no reason for electrons to shift (and E =>0)

But we can then, instead, add **different impurities** to layers (as in Si cells):



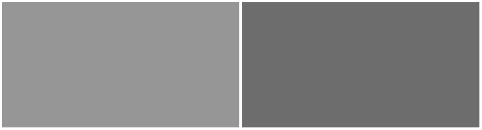
Impurities => Interfacial Electric field

But remember, charge only shifts NEAR the interface:

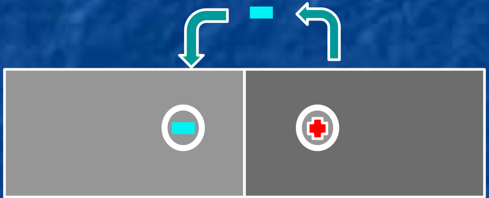
Materials are composed of **atoms which are intrinsically charge neutral**

So natural state of any single layer is ALSO neutral:

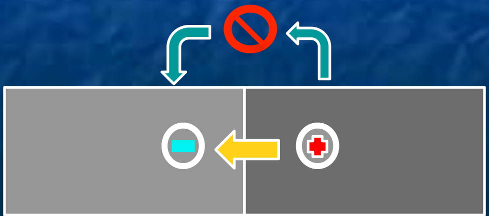
And junction between two materials also "starts out" neutral



But if energy levels in materials are different enough, charge can cross interface:



However, charge shift builds electric field eventually blocking further charge transfer



So charge **DEEPER** in layers will not get chance to cross!

Leading to common rules for almost all photovoltaics (solar cells):

- You must have at least one set of paired materials:
  - Be it two distinctly different materials OR
  - One basic material (e.g., silicon) modified into two differently acting layers
- In that pair, one layer/material must cling onto electrons more tightly
  - So that electrons will flow into it from the second material
  - Until shift of charge across boundary builds the INTERFACIAL ELECTRIC FIELD
    - to a level that stops further shifting of charge
- That interfacial electric field will then provide the critical push
  - When light IS added, it liberates more electrons from bonds
    - But the ELECTRIC FIELD then pushes freed electrons all in one direction

But how much POWER will such a solar cell PRODUCE?

Power = Current x Voltage

Current comes from the number of electrons liberated by light / second

- A function of how strongly **that** material absorbs photons of **that** color

- AND of **how much** material is doing the absorbing (due to its layer thickness)

Voltage comes from charge driving/separating junction ELECTRIC FIELD

Which was created by process of bond filling/liberating. Leading to fact that:

Photo-electrons/holes are driven out of cell by ~ 60-70% of the liberation energy =>

Solar cell voltage ~ (0.65) (liberation energy) / (electron charge = "e")

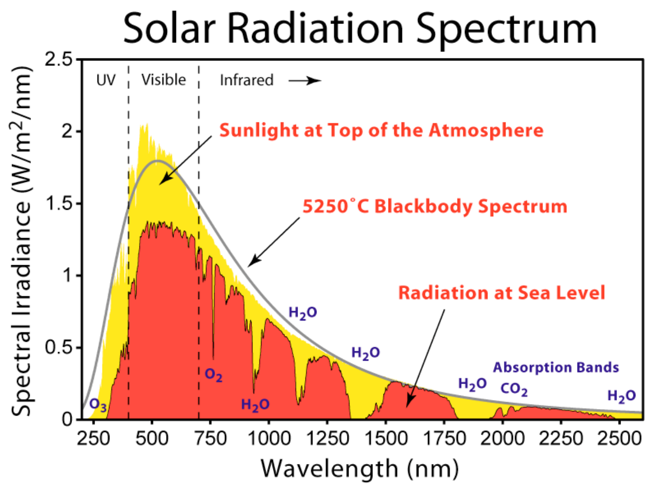
For Si solar cell, "V_{oc}" ~ (0.65) (Si electron liberation energy = 1.1 eV) / e ~ 0.7 Volt

Larger liberation-energies => More VOLTAGE but Less CURRENT:

Why?

The somewhat complicated answer starts with the solar spectrum:

← Energy



Wavelength →

If this strikes a solar cell made of a material having **Small liberation energy** =>

MOST colors liberate electrons, but they're driven out of cell by small voltages

If this strikes a solar cell made of a material having **Large liberation energy** =>

Only HIGH ENERGY light liberates electrons

But fewer electrons that ARE liberated will be driven by higher voltages!

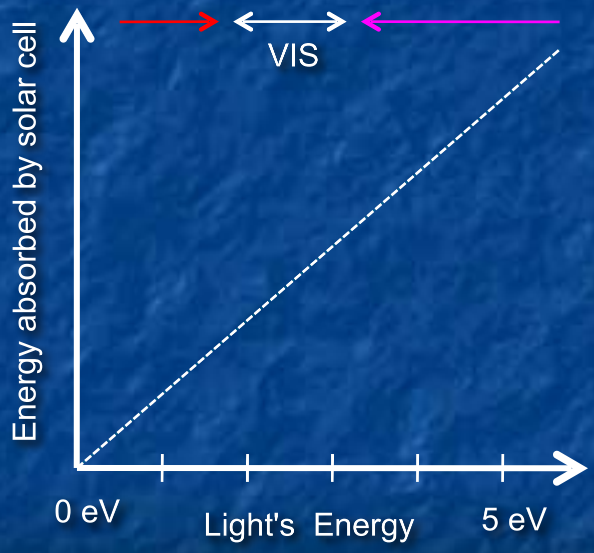
So now try to find optimum combination (based on choice of optimum material):

Figuring out energy absorbed by cells made of different materials:

On the horizontal axis, plot the energy of variously colored solar photons

On the vertical axis, plot the energy such a photon can deliver to the material

Ideal result is a simple straight line: Photon Energy = Energy Deliverable

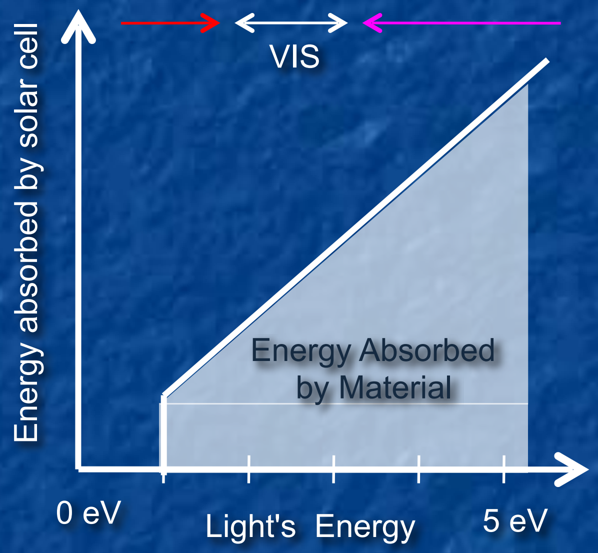


Now take into account our solar cell's chosen material

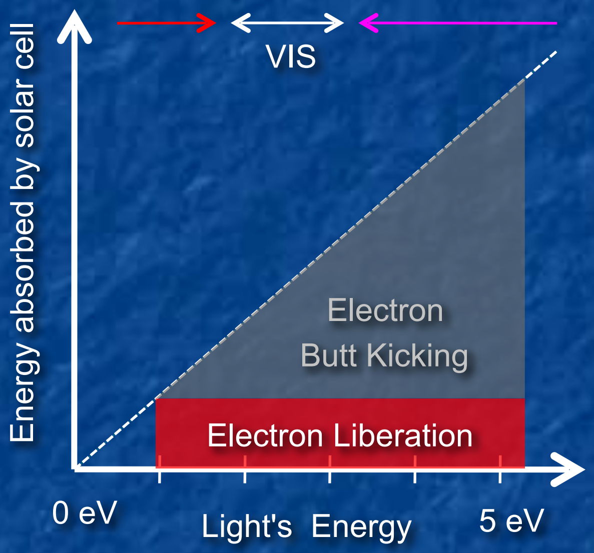
Say our solar cell's material has a low "electron-liberation energy" (= **bandgap**)

Below that energy, light is NOT strongly absorbed (mostly passing through)

But key thing is HOW energy that IS absorbed is USED by the material:



Material's **Bandgap**

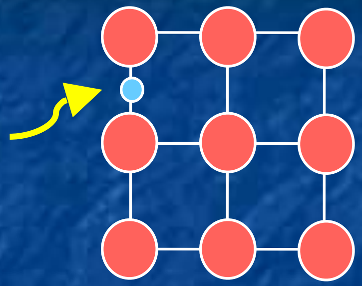


1st part of photon's energy is used to **liberate an electron**

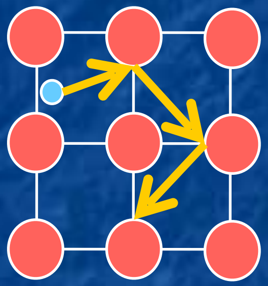
But remainder of energy only accelerates that electron = **Butt Kicking**

Butt-kicked electron WASTES that extra energy:

1) Excessively energetic photon is absorbed by bonding electron:

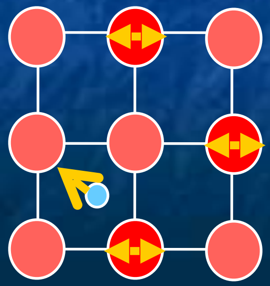


2) Electron is freed and, with extra energy, crashes madly through the crystal:



3) Struck atoms absorb energy:

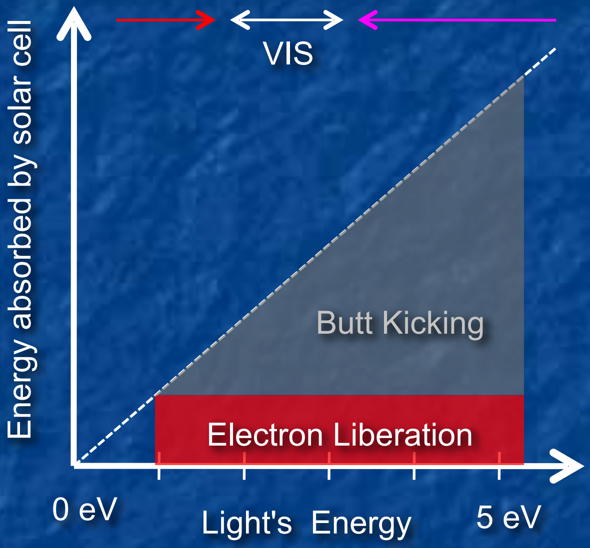
=> Atomic vibrations (= Heat) + Slowed down electron



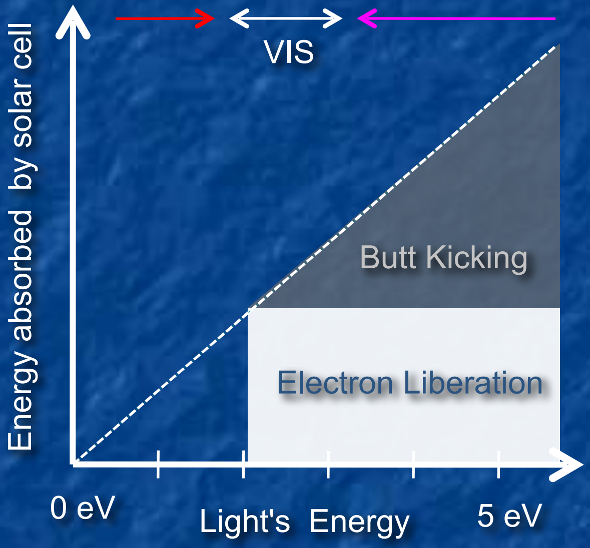
Heat energy is not converted to electrical power!

*Energy absorbed by cells made of **different** solar cell materials:*

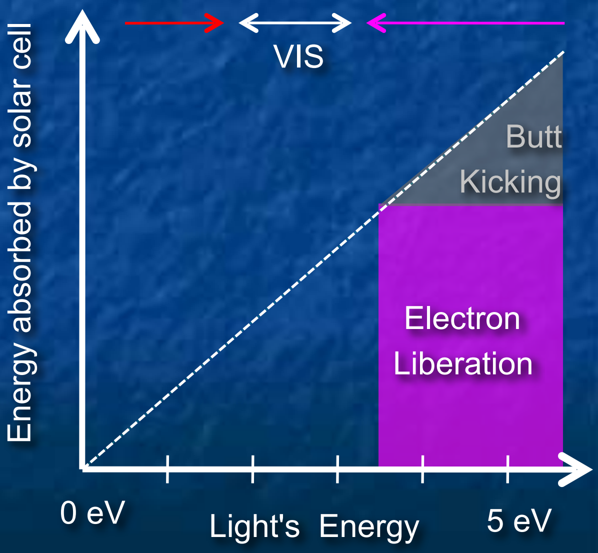
Cell with small "bandgap"



Cell with medium "bandgap"



Cell with large "bandgap"



Gray Triangles => Energy lost to heating of the cell

Rectangles (only) => Electrical energy out of the cell

*Using that to plot the maximum possible **efficiency** of a solar cell:*

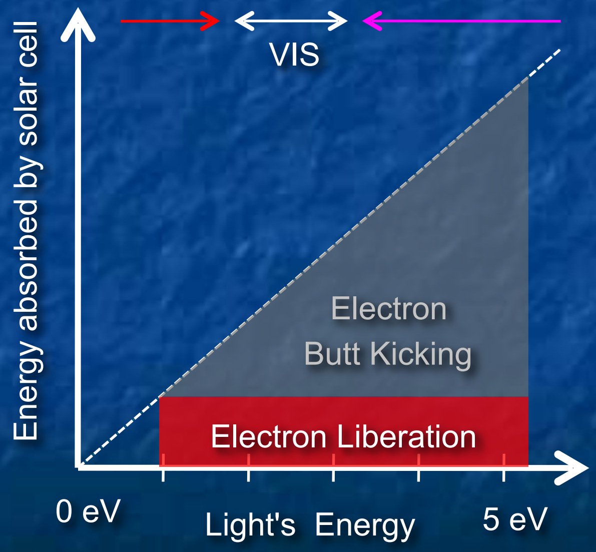
SOLAR CELL EFFICIENCY = (Electrical Energy Out) / (Total Energy Absorbed)

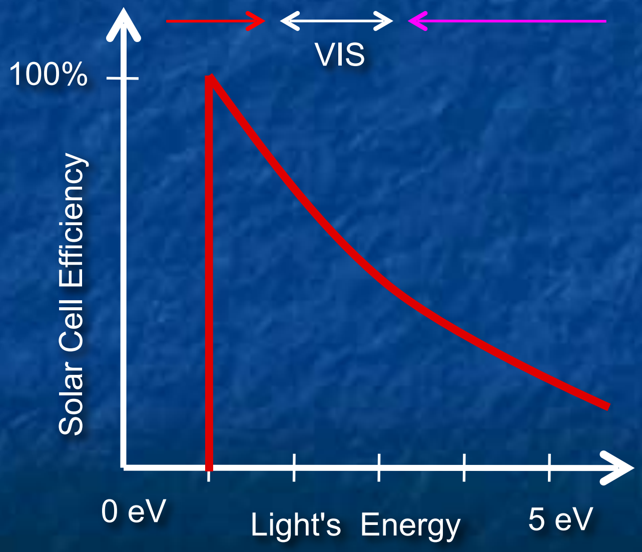
= (Area of lower rectangle) / (Area of rectangle + Butt-Kicking triangle):

For our solar cell using small bandgap material:

Energy Absorbed vs. Light's Energy:

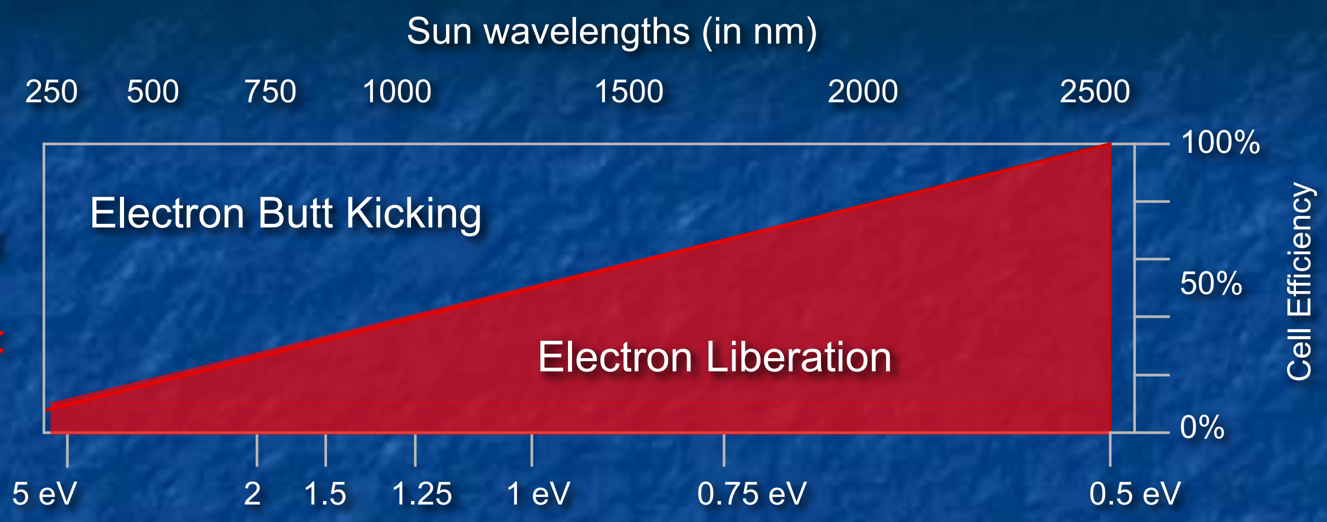
Cell Efficiency vs. Light's Energy:



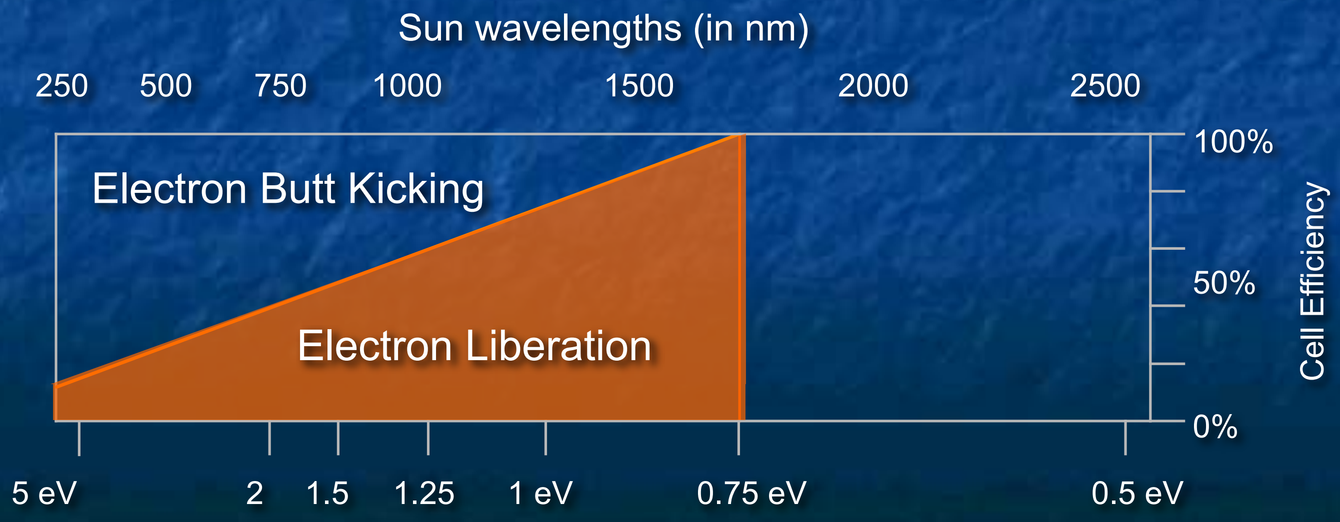


*Instead plotting cell efficiency vs. light **wavelength** (~ flipping right-left)*

For solar cell using material with 0.5 eV electron liberation energy (bandgap):



For solar cell using material with 0.75 eV electron liberation energy (bandgap):



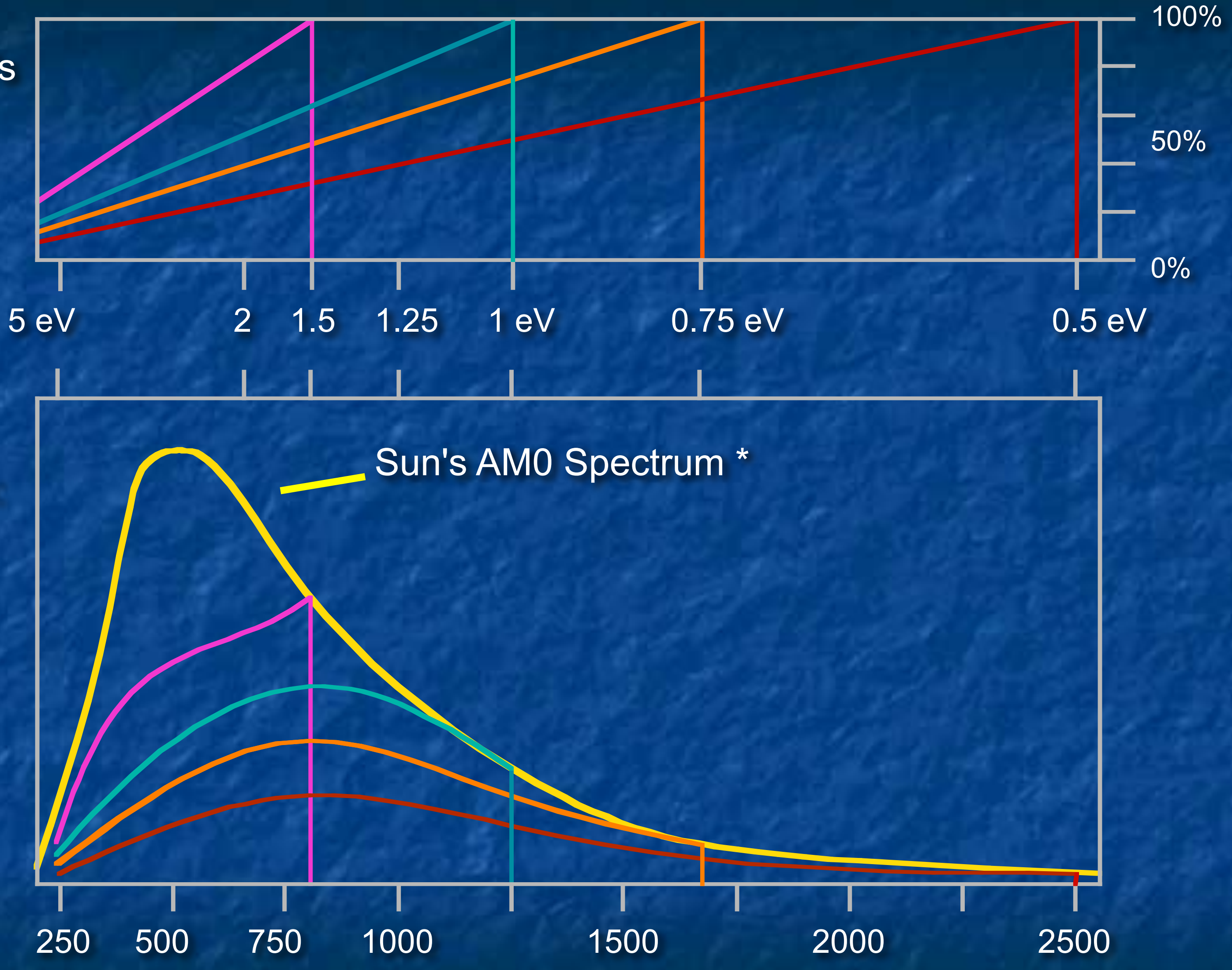
FINALLY: Comparing solar cells with a LOT of different bandgaps:

PERCENTAGE of light's energy captured as electricity by different bandgap solar cells:

Sun's Energy Spectrum:

Energy captured by different bandgap cells:

= Top lines x AM0



Wavelength in nm (or above, equivalent energy in eV)

* I really should've used complex AM1.5 spectrum

Larger the area under a bottom curve => More solar energy captured

BIGGEST area comes between 1 eV and 1.5 eV curves

Material with a 1.3 eV bandgap could capture & convert ~ 35% of Sun's energy

It's called the **Shockley-Queisser Limit** after William Shockley & Hans Queisser

This 35% efficiency limit is NOT because of poor engineering!

It is instead because:

We ONLY CAPTURE that part of light energy liberating electron from bond,

REST of light energy is wasted giving liberated electron kick in the butt

All because a photon insists on giving ALL of its energy to a single electron

(even photons with enough energy to liberate multiple electrons!)

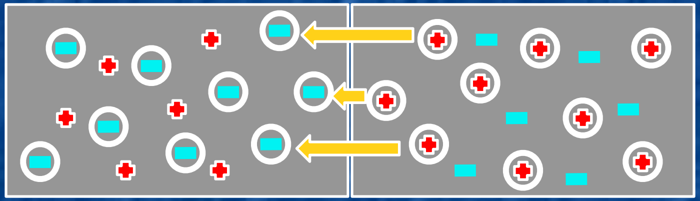
But in addition to having a 1.3 eV bandgap, the ideal material must also:

Be made of atoms that try to hold their own valence electrons within bonds

While allowing foreign **acceptor** atoms to steal electrons

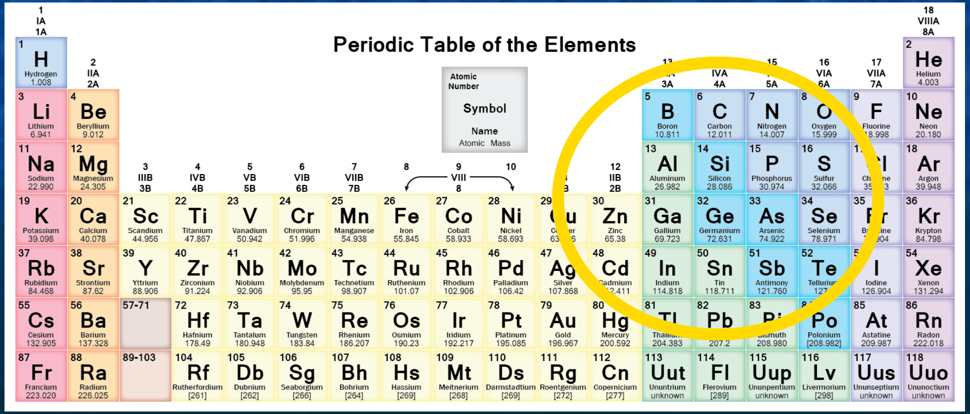
and foreign **donor** atoms to liberate their electrons

Which sets up the necessary electron-pumping configuration (explained earlier):



Materials meeting those added requirements are called **SEMICONDUCTORS**

They're built of atoms from this region of the periodic table:



Periodic table from:
http://byjus.com/chemistry/periodic-properties/

*At the center of that region is **silicon***

Which is already the king of semiconductors based on its use in integrated circuits

But it **also** has a 1.1 eV bandgap near the Shockley-Queisser efficiency sweet spot!

However: Solar-cell-quality silicon is strangely expensive

Which stems from the peculiar way photons interact with it

In many semiconductors, energetic photons simply liberate electrons

But in silicon **photons must get an assist from vibrating atoms**

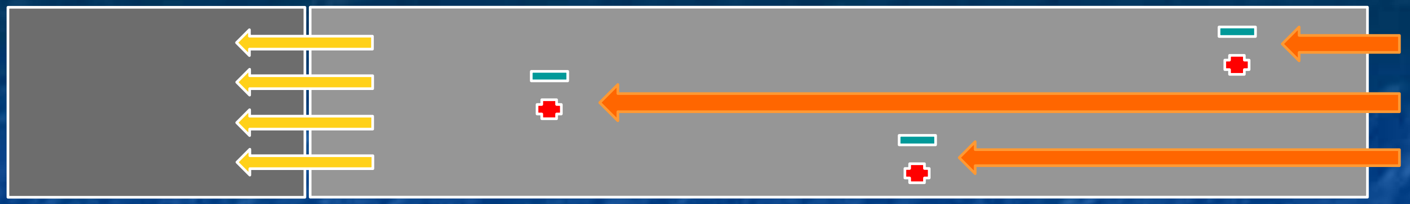
(Making silicon what is called an **indirect** bandgap semiconductor)

That makes it harder for silicon to absorb light, particularly low energy light

Which means that silicon solar cells must be unusually thick

(Hundreds of thousands of atoms thick = Tens of microns)

Making the cross-section of a silicon solar cell more like this:



Different photons are absorbed **throughout** the thick right layer

But for a photon absorbed early, there is a big problem:

The electron & hole it liberates have a **long way to wander**

before reaching the electric field at the boundary between the cell's layers

REMEMBER: That field is what makes this a solar cell (vs. a mere photoconductor)

Because that field sorts things out, sending + to the left and — to the right

= The absolutely essential **solar cell pumping action**

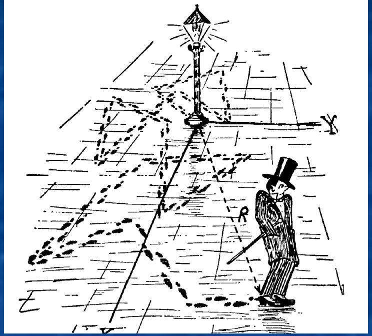
*Before reaching the electric field, the electron & hole **ARE** just wandering*

Liberated & created, they have no reason to move in ANY particular direction

This random wandering motion is called **diffusion**

Which is famously explained by the **drunkard's walk**

= Analogy of a drunk randomly bouncing off light posts:



But we've got **two types of wandering drunks: electrons and holes**

And these unique types of drunks can "annihilate" one another

That is, the electron can just fill the hole (in the bond) => zip!

To create a net flow (=> electricity) our drunks MUST reach boundary **cliff**

Over which the "electron drunks" will fall (and the "hole drunks" ascend)

Or the way I was first taught it: Electrons ~ Ball bearings (which fall DOWN)

Holes ~ bubbles (which FLOAT up)

Figure: http://www.sos.siena.edu/~jcummings/teaching/astronomy/lectures/reveal.js-master/ch10.html#/

But there is an additional complication: "traps"

Light-liberated electron & hole must not recombine before reaching the electric field

Normally, they cooperate by either **not** wandering into one another

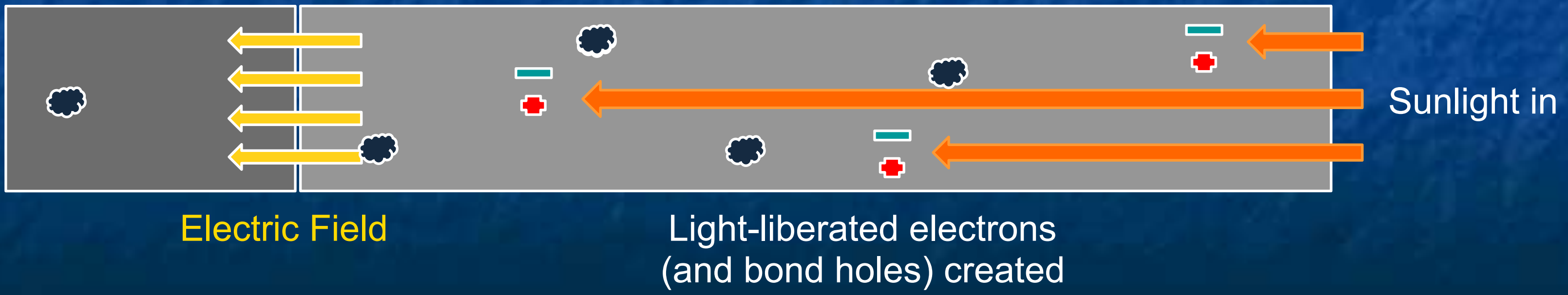
OR by "orbiting" each other when then **do** meet (orbiting pair = an "exciton")

But if there are crystal faults (misbonded atoms) or certain impurities:

Wandering electrons or holes tend to get "trapped" at these flaws

and if both end up at the same trap, they quickly recombine => zip!

Using black blobs to represent such traps, our solar cell can end up more like this



Crystalline silicon succumbs to one type of trap but not the other

Silicon's bonds are extraordinarily strong

- It is the 3rd hardest material (after only diamond and silicon carbide)

That bond strength makes it possible to grow near perfect crystals:

- Si solar cell crystals can have as few as one Si atom in 10^{15} mis-bonded
  - Which pretty much eliminates crystal flaws as traps

But in Silicon, **metal impurities make exceptionally effective traps**

- Silicon for solar cells must thus pass through extra (expensive) purification steps

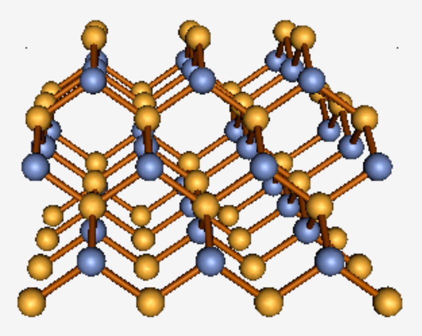
NET RESULT: Crystalline Si solar cells define today's "gold standard"

- Commercial cell efficiencies are in the 20-25% range
  - Research versions push 30%
    - But (like gold) this comes with a steep price tag

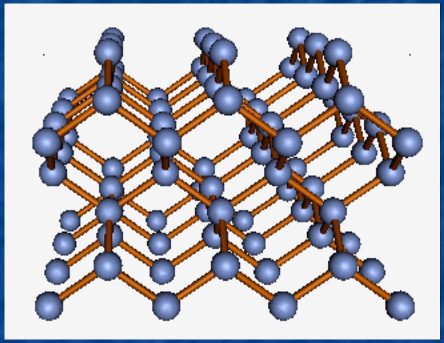
Gallium Arsenide offers competition for that gold standard:

It has a very similar crystal structure with weaker, but still strong, bonds:

GaAs's "zincblende" type crystal:



Si's "diamond" type crystal:



GaAs's 1.5 eV bandgap is slightly closer to the Shockley-Queisser optimum

And, unlike silicon, its bandgap is **direct** allowing for use of thinner layers

Which, together, boost its cells to almost the full S-Q 35% efficiency limit

However, containing arsenic, it raises concerns about toxicity

And its crystals are even more expensive to grow

Qualifying it more as an (impractical?) **diamond standard**

Figures from my Virtual Lab website: https://www.wecanfigurethisout.org/VL/Semiconductor_crystals.htm

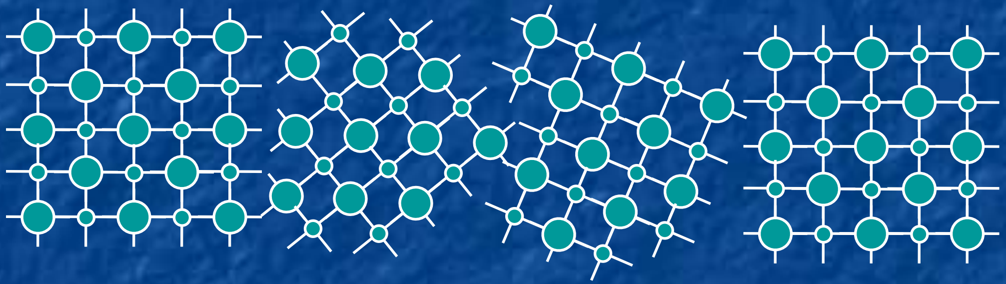
So what about more affordable silver or even bronze standards?

Today's **silver standard** is probably **polycrystal silicon**

Here crystal growth conditions are markedly relaxed yielding,

instead of a single crystal, a tightly packed collection of "crystallites"

Which can be represented as:



But wandering electrons & holes **can** now get trapped at crystallite edges

Where there are plenty of mis-bonded atoms

Which might acquire a charge attractive to those wanderers

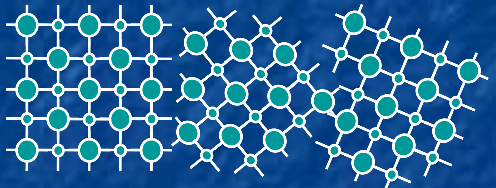
Result? Polycrystal Si cells have efficiencies about 4/5th that of single crystal Si

But if cost is correspondingly reduced, they can still make sense!

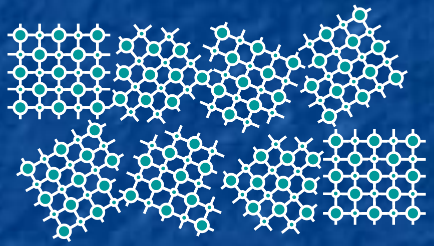
And "amorphous Si cells" yield a candidate for the bronze standard:

By amorphous, we mean a cell in which there is almost no crystalline order:

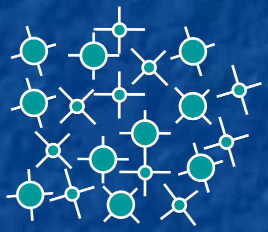
Multi-crystalline



Poly/microcrystalline:



Amorphous:



You'd think, with virtually every atom either mis-bonded or unbonded,

that a super-abundance of "traps" would make amorphous solar cells hopeless

Amorphous cells of pure silicon DID turn out to be hopeless!

But then people (including a friend) tried adding **hydrogen**

which bonded with enough of those unhappy Si atoms

that trapping of electron & holes was radically decreased

=> Efficiency ~ ½ of single crystal Si cells, but at a much lower price

Trying to put these (and other) alternatives into perspective:

The **U.S. National Renewable Energy Lab (NREL)** publishes an annual plot of

the latest,

greatest,

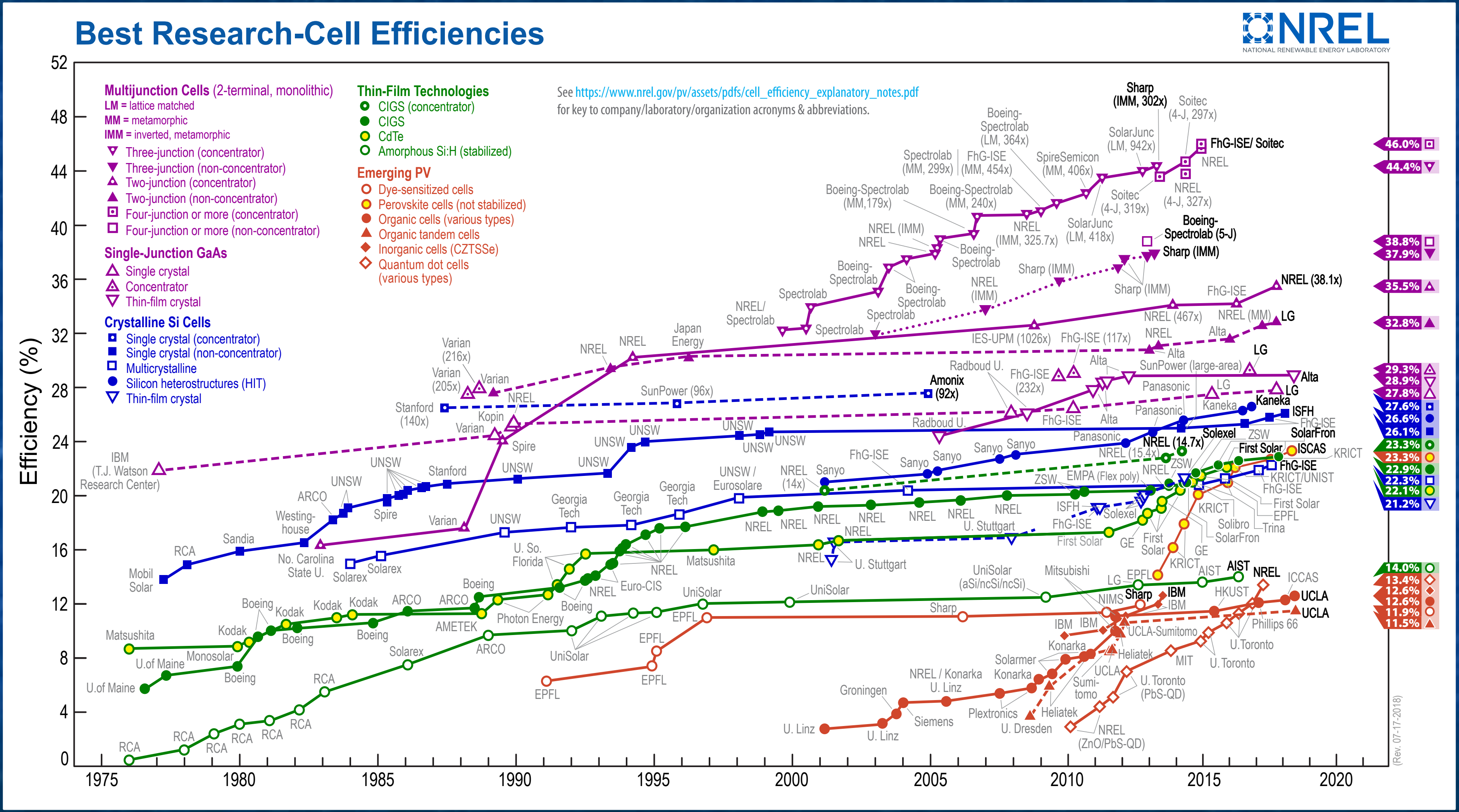
possibly one of a kind,

maybe never even reproduced,

(and/or horrendously expensive),

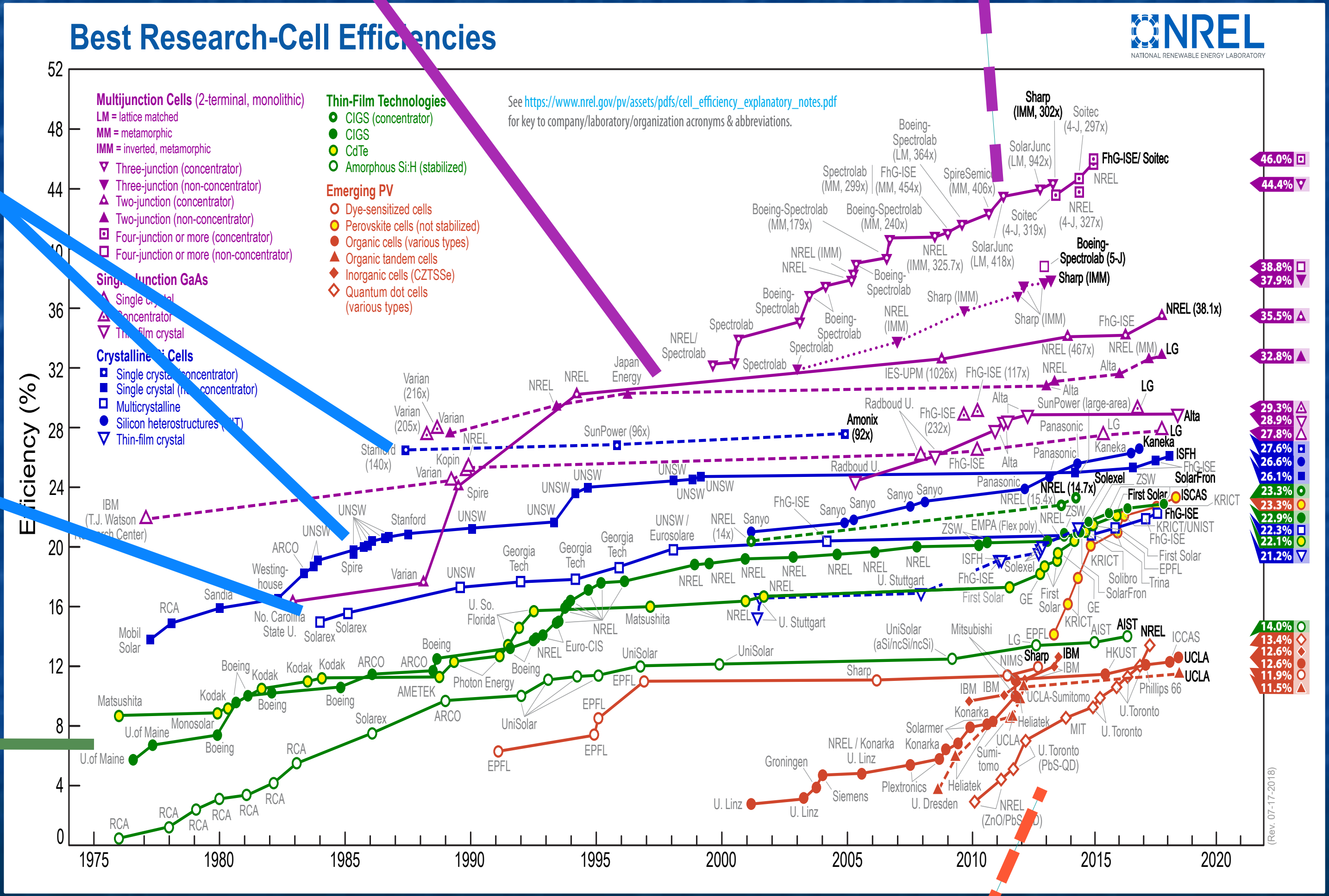
research solar cell efficiency records:

NREL: Best RESEARCH solar cells (1976 – 2018):



https://www.nrel.gov/pv/assets/pdfs/pv-efficiencies-07-17-2018.pdf

With some added guidance as to cell types:



Single crystal GaAs

Emerging multi-junction cells

Single crystal Si

Polycrystal Si

Mature thin films

Emerging thin film and/or quantum dot cells

"Hero" (best in lab / single shot) efficiencies, top to bottom:

Multi-junction solar cells: Highest at 46%

Beating but not shattering the Shockley-Quiesser Limit

Crystalline GaAs solar cells (more exotic/$ crystal than Si): 35.5%

Crystalline silicon solar cells: Highest at 27.6%

Thin-film cells (e.g. polycrystalline/amorphous Si and CdTe): Highest at 23.3%

Perovskite cells: Highest at 23.3%

Dye-sensitized, organic . . . cells: Highest at 12.6%

Quantum Dot solar cells: Highest at 13.4%

What about all those very rapidly climbing "emerging" cells?

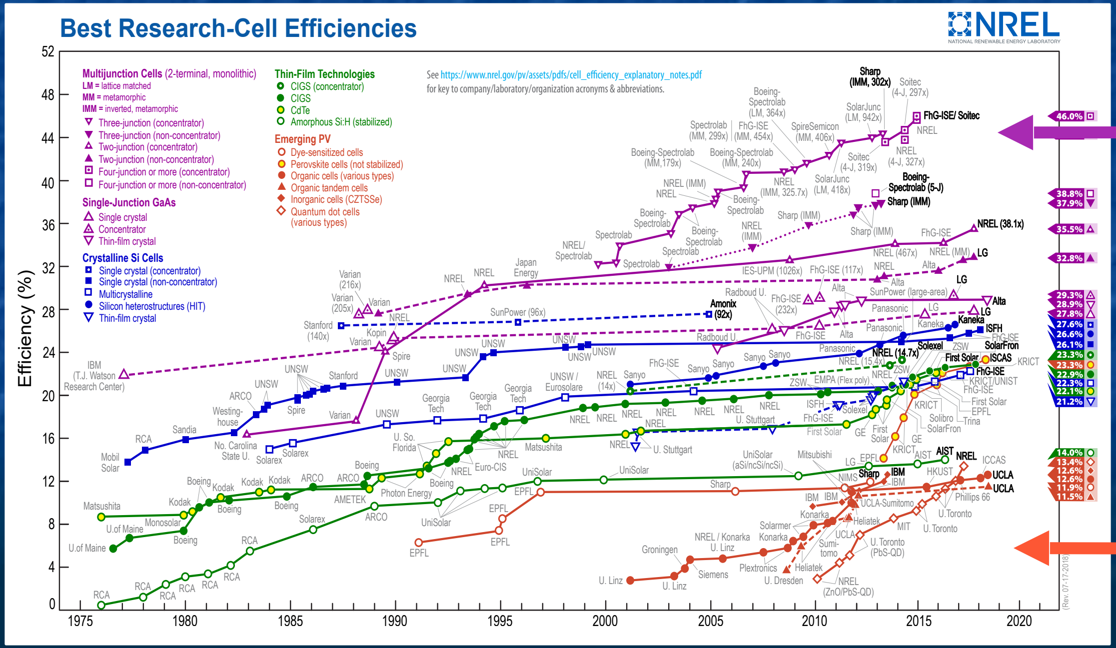
Well, they ARE still emerging which means that they:

Are still largely unproven

Employ radically different materials

And/or radically different device principles

Making them the subject of the note set **Tomorrow's PV Solar Cells** (pptx / pdf / key)

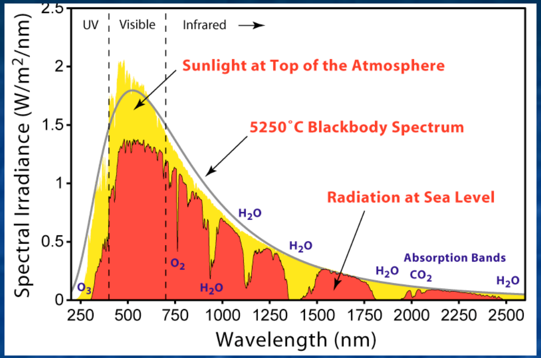


Emerging multi-junction cells

Emerging thin-film & quantum dot cells

*To finish this note set, here are some issues with **today's** PV solar cells:*

First, going back to our earlier discussion of sunlight:



The MAXIMUM solar power EVER reaching the earth's surface

is called **AM1.5** (air mass 1.5) and equals ~ **1000 Watts / square meter**

But to capture that maximum intensity:

1) **The PV solar cells must directly face the sun**

2) **The sun must be DIRECTLY overhead**

So light takes the shortest path through the light-obstructing atmosphere

3) **There must be no haze, fog, or clouds to absorb or redirect sunlight**

*At best, such **peak** conditions occur for an hour or so, a few days a year!*

Thus: **AVERAGE SOLAR POWER << PEAK SOLAR POWER**

OK, then you read marketing literature or news articles declaring that:

"This new solar plant will produce Y kilowatts of power"

OR

"It will be able to power Z thousand homes"

But **which** power are they talking about?

AVERAGE power would most fairly represent the plant's likely impact

But marketing literature is much more likely to cite PEAK power

Which naive journalists then parrot in news headlines & articles

Leaving **YOU** to figure out how PEAK power relates to AVERAGE power!

My Solar Rule: Multiply by ½ x Another ½ x Maybe Another ½

Multiply by the first factor of ½ because:

Averaged over a year, the sun is up only 50% of the time

Multiply by the second factor of ½ because:

Solar intensity peaks near noon, falling to ~ zero at sunrise & sunset

Sun's motion means that power to a surface falls sinusoidally away from noon

Absorption via the longer atmospheric path makes that falloff even sharper!

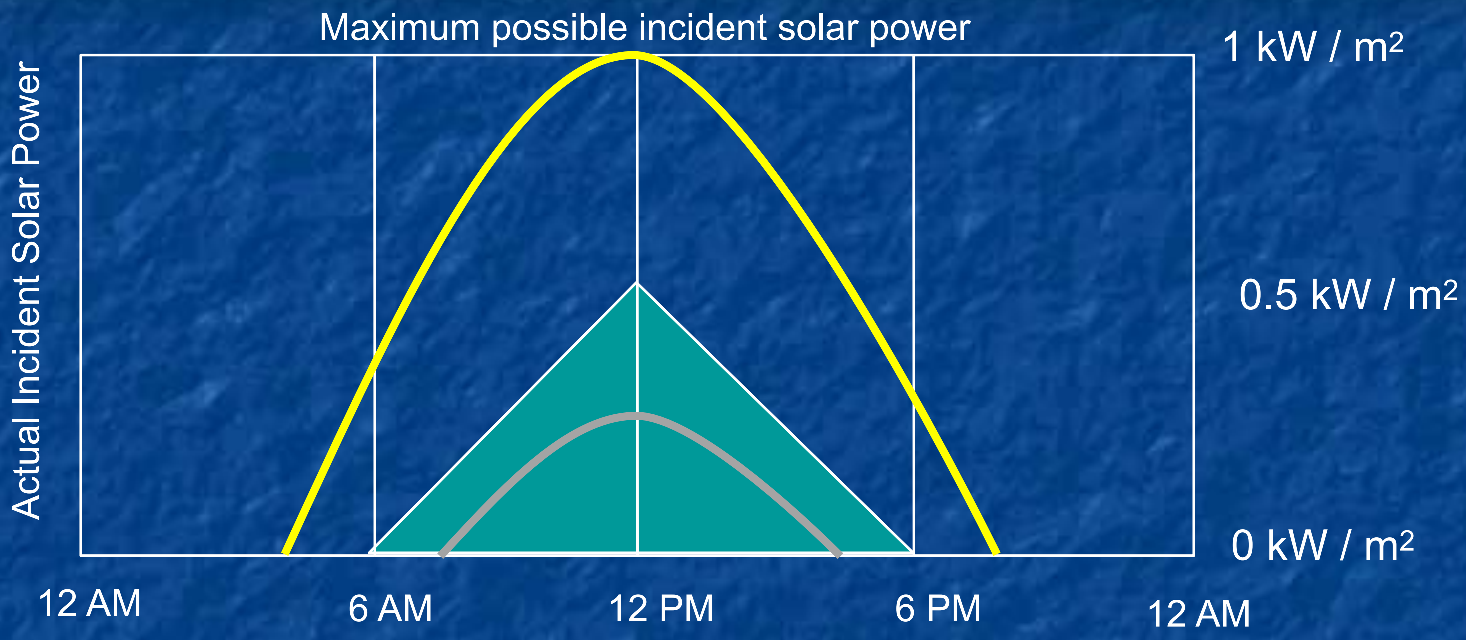
Then maybe multiply by a third factor of ½ because:

Clouds, haze or smog stop the sunlight from reaching the solar cell

Pictorial explanation drawn from my **Introductory Note Set** (pptx / pdf / key):

Daily solar energy delivered to a solar cell:

Yellow = Clear summer day **Gray** = Non-summer and/or cloudy day



Green = Eyeball approximation of **typical** (possibly cloudy) day's solar power

Area of triangle = Power x Time = **ENERGY** per day per square meter

= (½)(base)(height) = (½)(½ day)(½ kW/m^2) = ½ x ½ x ½ x (1 kW-day/m^2)

= **1/8 x (Energy if sun were ALWAYS directly overhead in a clear sky)**

Leading to discussion of CAPACITY and CAPACITY FACTOR:

We use "capacity" to describe what some person or thing is capable of

That is, the **best performance** we can expect of them or it

In this sense, a solar cell's power capacity would equal its BEST possible output

Which **would** be its output at noon on those special few sunny days

= PEAK POWER which is so much larger than solar's AVERAGE POWER

To deal with this, power plants are also described by a CAPACITY FACTOR

CAPACITY FACTOR = **TIME AVERAGED POWER OUT / POWER CAPACITY**

Which, from above, I expect to be 1/4 for nearly cloud-free locations

Or possibly as little as 1/8 for more typically cloudy locations

So how important **ARE** cloudy days?

The U.S. Energy Information Administration evaluates CAPACITY FACTORS

And reports these, for every type of power plant, every year

- As detailed in my note set **Power Plant Economics** (pptx / pdf / key)

The EIA consistently reports SOLAR PV CAPACITY FACTOR as being about 25%

- = ½ x ½ and not ½ x ½ x ½, suggesting that clouds are NOT important

However, the EIA sensibly bases its estimates on **current** U.S. power plants

- And the vast majority of U.S. solar plants are **now** in southwestern deserts

So while the EIA validates the first two parts of my "½ x ½ x maybe ½" rule,

- It does not verify the final ½ and thus does not answer questions such as:

What if solar PV plants are built in less remote / more typical locations?

How much lower will their power output be?

The U.S. National Renewable Energy Lab (NREL) provides an answer:

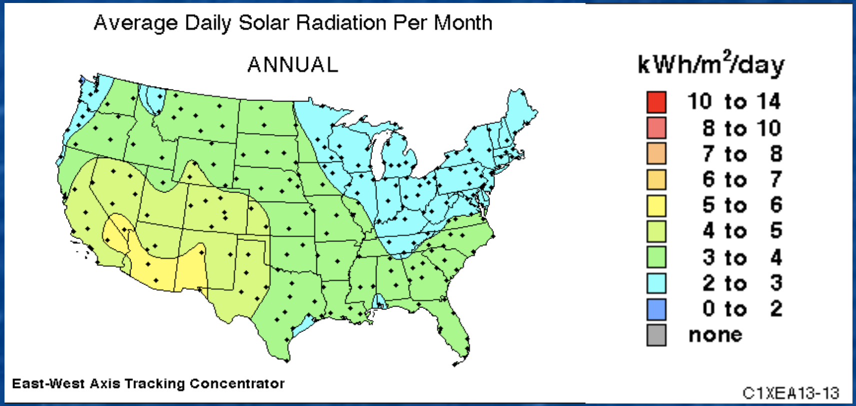
Their website maps yearly averaged and seasonal data, taking into account if:

PV cell arrays are fixed in one position

Or if they daily swing East to West tracking the sun's arc

AND/OR if they adjust their North-South tilt with changing season

Selecting for yearly averaged data, with only East to West daily tracking:



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

Power in currently used "best" southwest locations: 5-6 kW-h/m^2/day

vs. 3-4 in west/south locations vs. 2-3 in midwest / northeast locations

In non-SW locations weather DOES knock power down by another ~½!

LIKELY TIME-AVERAGED SOLAR CELL POWER OUTPUT:

To calculate SOLAR POWER INPUT ("insolation") you first either:

1) START with maximum possible solar insolation ~ 1000 Watts / square meter

THEN apply my "½ x ½ x maybe ½" rule

2) OR use solar insolation mapping websites such as NREL's

Yielding ~ 2000-6000 W-h/m^2/day ~ **80–250 Watts / square meter**

BUT TO THEN GET A SOLAR PANEL'S POWER OUTPUT:

You must multiply by component solar cells' energy **conversion efficiency**

Which, from earlier discussion, is now typically ~ 15-20%, yielding:

Averaged solar panel power output => **12-50 Watts / square meter**

Meaning that
ONE of these:

Could only power a
small ONE of these:

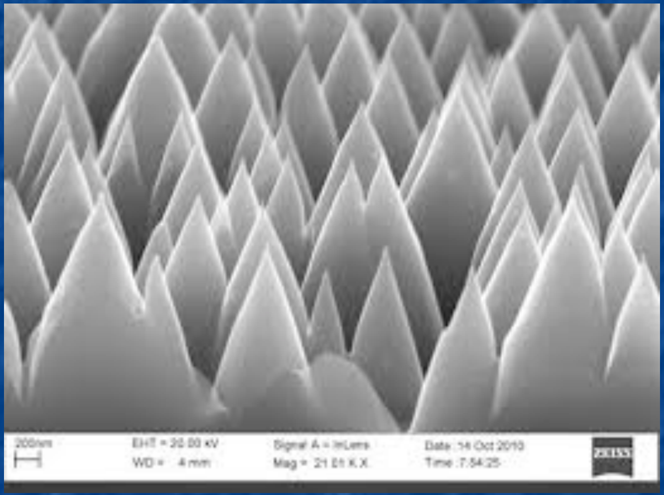
How optimized capture of sunlight leads to solar cell's apparent color:

In addition to carefully tuning the absorption of sunlight **within** a solar cell

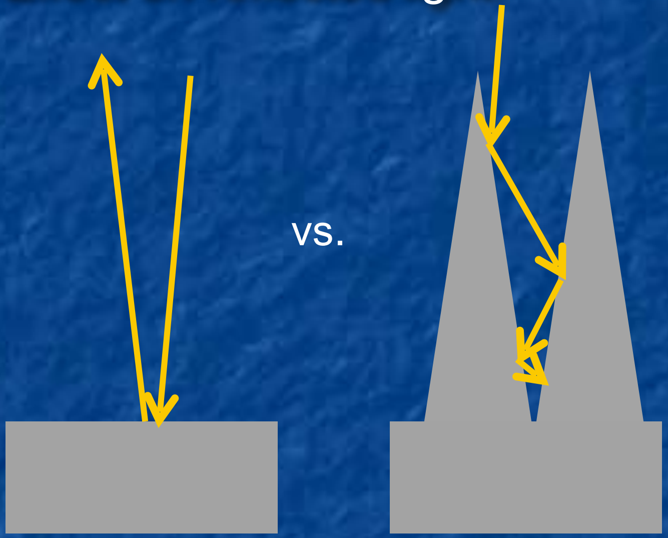
You must also minimize reflection of sunlight **right off its front surface**

Laboratory cells can almost eliminate such reflection via "surface micro-texturing"

SEM image of micro-textured Si:



Effect on reflected light:



Reflected light is effectively trapped, forcing it to **eventually** penetrate into PV cell

Near total elimination of ANY color reflection makes this into "Black Silicon"

SEM Image: https://www.nanowerk.com/spotlight/spotid=19590.php

But commercial PV cells aren't black, most are in fact blue:

www.upsbatterycenter.com/blog/a-new-and-more-efficient-solar-cell/

DESPITE being made of silicon

which has a silver-gray color:

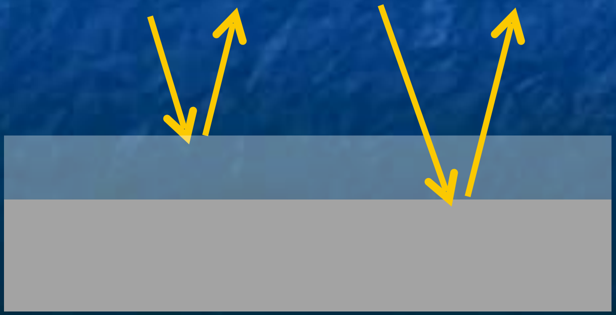
www.quora.com/Why-are-silicon-wafers-round

Why? Because commercial cells suppress reflection using a different method

Which is considerably less expensive but also significantly less effective

A thin flat clear glass layer is added to the surface of flat PV cells

Light then reflects from **both** the top of the glass, and the top of the PV cell



However, light is a wave, with both crests and troughs

If the **crests** of one reflected wave overlay the **troughs** of the other,

They can cancel each other = **Destructive interference** => No reflection

When will this occur? Consider a glass layer ¼ of the light's wavelength (λ) thick

If the incoming light ray strikes almost vertically,

the penetrating ray travels an **extra** λ/2 before returning to the surface,

where it meets up with the ray reflecting **directly** from that surface

But a half wavelength takes you from a wave's crest to a wave's trough

So that ray's **troughs** will overlay the other ray's **crests** => Cancellation!

Such "quarter wave plates" are the stock way of suppressing reflections

But what if you have light of multiple colors (as you do with sunlight)?

The wavelength of red light is almost twice that of blue: $\lambda_{red} \sim 2\,\lambda_{blue}$

Say, trying to suppress reflection of red, you choose glass thickness of $\lambda_{red} / 4$

The penetrating red ray then travels extra distance $\lambda_{red} / 2$ => Cancellation

The penetrating blue ray follows the same path, so it also travels an extra $\lambda_{red} / 2$

But $\lambda_{red} / 2 \sim \lambda_{blue}$ so the penetrating blue travels **one** of its wavelengths

That penetrating blue ray thus ends up **strengthening** the surface-reflected blue

Crests overlay crests, troughs overlay troughs => **Reinforced blue reflection**

Commercial Si PV cells, trying to capture as much energy as possible from sunlight,

employing analyses similar to my earlier Shockley-Quiesser optimization,

increase capture of red at the expense of reflecting blue

*Closing with two common criticisms of today's **silicon** PV cells:*

"Solar PV cells require more energy to make than they will ever produce!"

Yes, much of silicon's strength comes from its . . . well, strength

It does have extremely strong bonds, as reflected in its 1415°C melting point

And much of its processing does occur near or above that melting point

So it IS appropriate to question the amount of energy consumed in its manufacture

But that ends up being a valid concern for **many** energy technologies

Which is why I've written a whole stand-alone note set about **EROI** (pptx / pdf / key):

Energy **R**eturn **O**n **I**nvestment = (Lifetime Energy Out) / (Lifetime Energy In)

Which, for energy production technologies, sure as heck better be >> 1 !

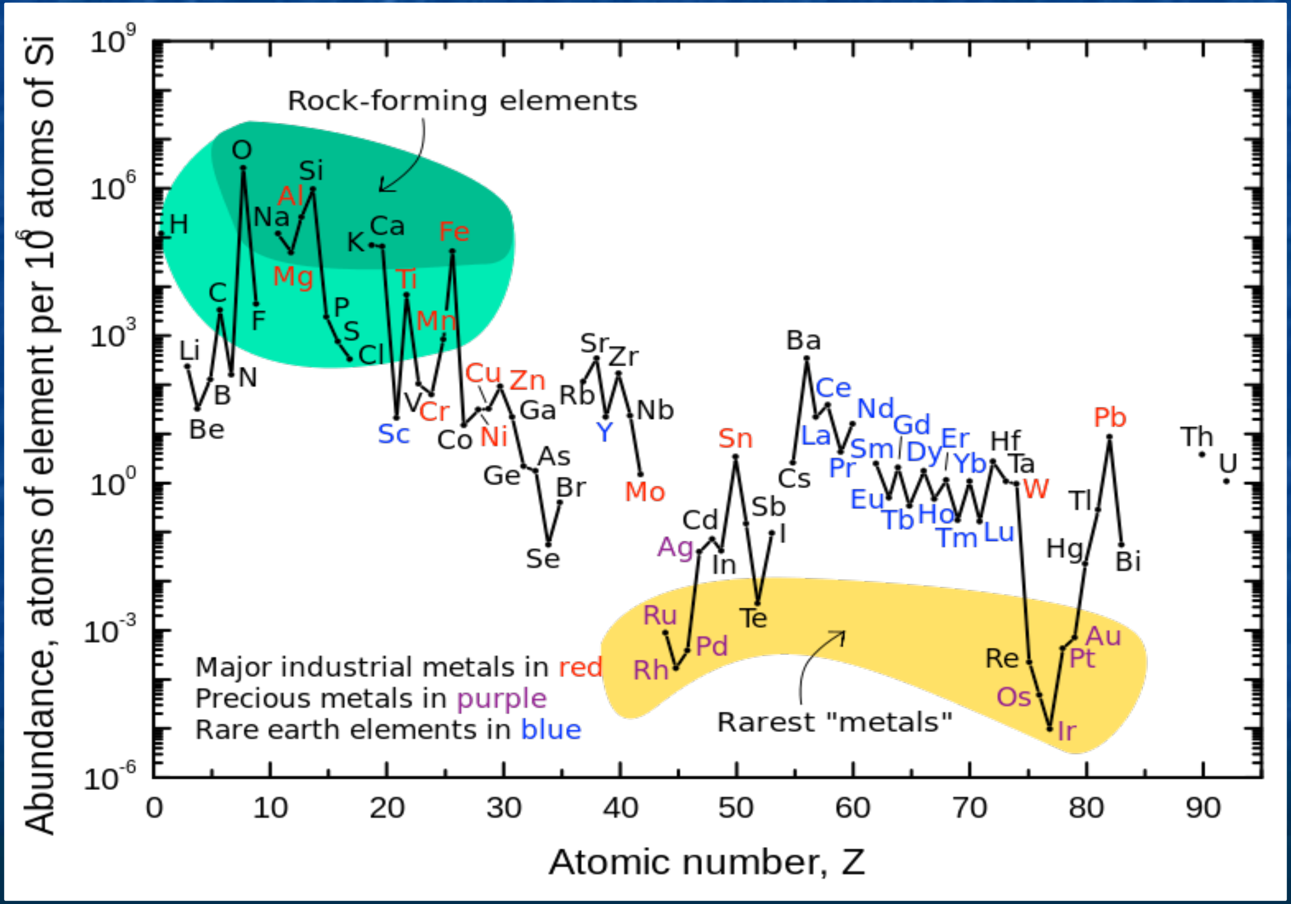
You can preview that EROI note set now, but its short answer on Solar PV is:

Solar PV EROI's **ARE** >> 1: About 10 for crystal Si => 35 for some thin films

*A second common criticism of today's **silicon** PV cells:*

"Si is a rare and exotic material that requires exceptionally toxic fluoride chemicals to extract and purify"

Well, here are elemental abundances in the earth's crust (look at the top left):

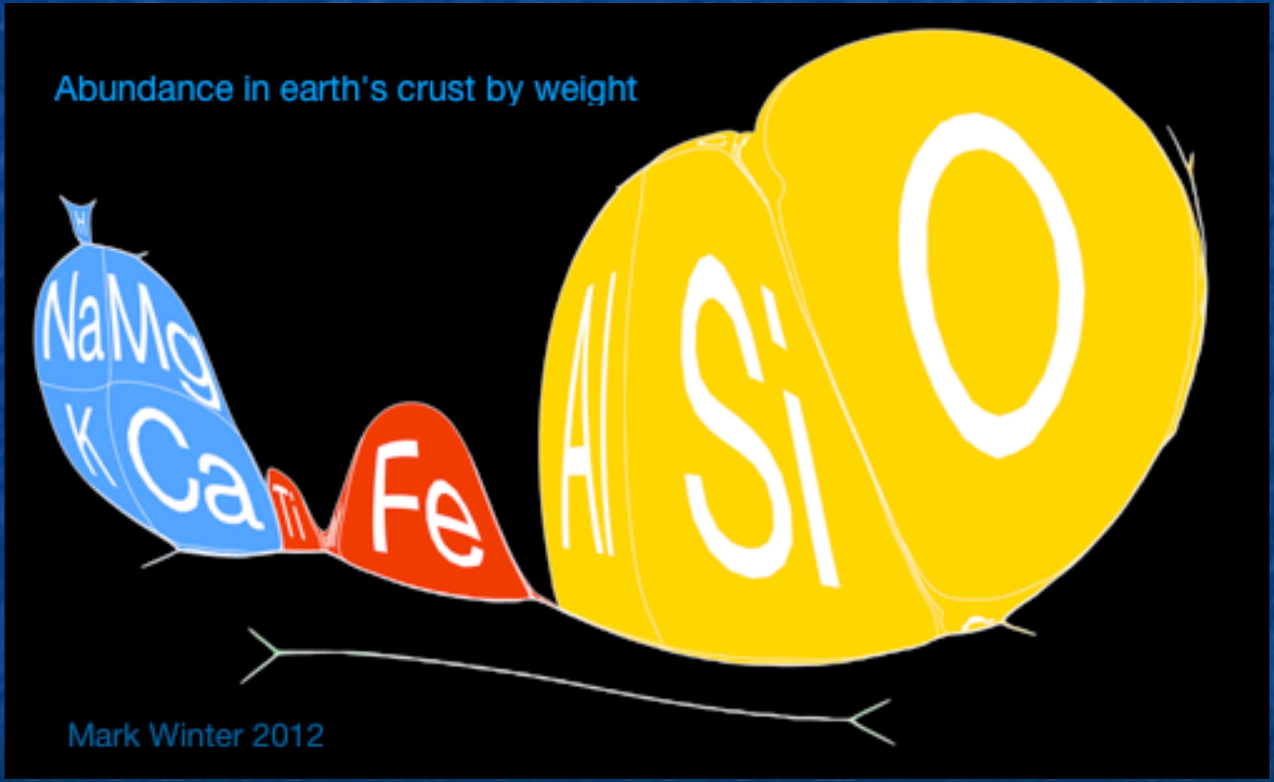


Source: http://www.webelements.com/

Which showed that Si is the 2nd MOST COMMON element in the earth's crust

As emphasized in this almost comically reworked version of **The Periodic Table**

in which cell size has been made proportional to an element's crustal abundance:



Narrow lines at the bottom = **All of the other elements** – drawn in proportion

Source: http://www.webelements.com/

*And it's not hard to **find** silicon in the earth's crust:*

Along with the #1 most common element, oxygen, it makes up **beach sand**

In the form of SiO_2 (a.k.a. "quartz" or "silica")

And beach sand is indeed the source of a PV cell's silicon:

http://boraboraphotos.com/beautiful-white-sand-beach-in-bora-bora/

But yes, if its separation required fluorine, that would be a concern

Because, among the halogens, fluorine is an extremist:

Oxidizing strength: $F_2 > Cl_2 > Br_2 > I_2$ Reducing strength: $I^- > Br^- > Cl^- > F^-$

So fluorine compounds **DO** often have extreme (and very toxic) chemical properties

Including a tendency for even dilute residues to attack nerve cells

But it turns out that **chlorine (not fluorine)** is used in Si refining!

Silica sand (SiO_2) is first heated with carbon at 2000°C

Which burns off the O as CO_2 [1]

But the resulting purity is not then high enough for electronics (much less for PV)

So it is then heated to 300°C in the presence of **HCl** gas

Which produces liquid trichlorosilane ($SiHCl_3$)

Then, in the "Siemens Process,[1,2] trichlorosilane is passed (at 1100°C)

over pure "seed" crystals of Si where trichlorosilane decomposes,

depositing hyper pure Si (and releasing chlorine gas)

So does Si refining does involve not very nice chemicals and byproducts? **Yes!**

But they are not atypical of chemicals used in **most** raw material extraction

1) http://www.techradar.com/us/news/computing-components/processors/how-sand-is-transformed-into-silicon-chips-599785
2) https://en.wikipedia.org/wiki/Silicon

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This set of notes was authored by John C. Bean who also created all figures not explicitly credited above.