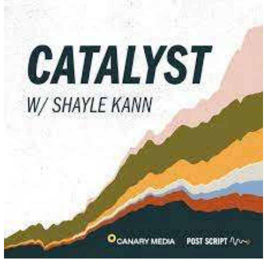
Renewable Energy Podcasts

Wood Mackenzie


Stephen Lacey


Shayle Kann



Irish / French

Energyinsiders))
a RenewEconomy podcast

Australians

English

Question # **1**

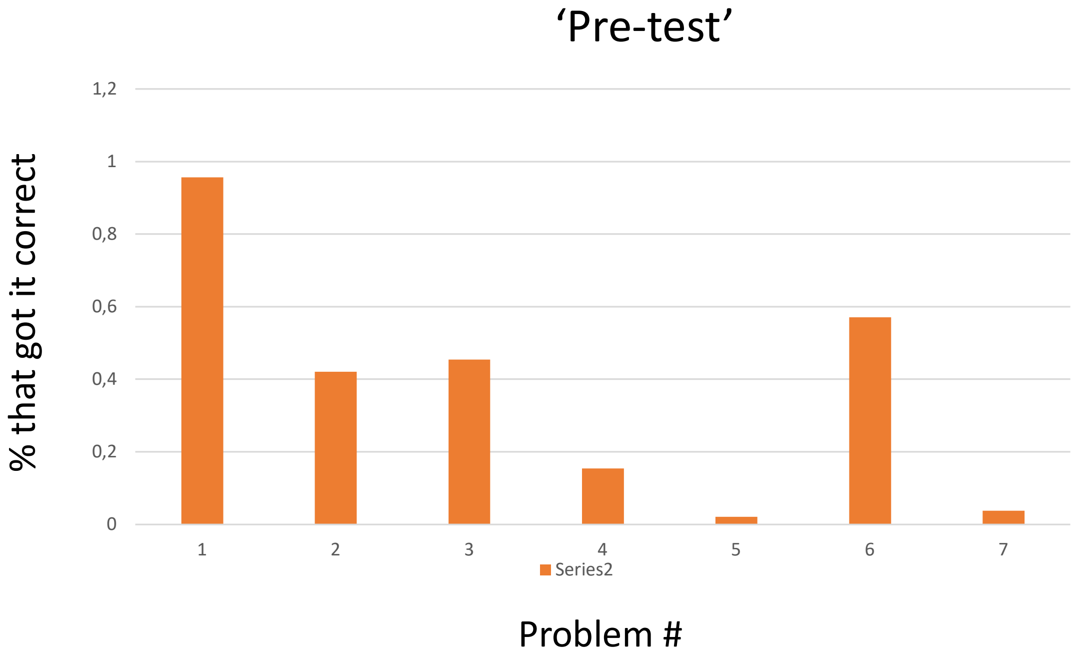
Difficulties
Physical feasibility
Science behind-2
The underlying physics behind engineering designs
Compare fundamental science between different approaches
Viability of sustainable projects
Detailed equations behind sustainable energy
Development of solutions

Question # **2**

Storage-5
New startups
Conversion-2
Nuclear-5
Batteries-1
Wind Power - 7
Electrochemistry-2
H2 Storage
Electrolysis-2
CO2 capture-4
Power2X-
Photosynthesis
Solar-9

Question #3

Lecture	Reading	Exercises
8,13	6,74	8,70
1,26	1,70	1,33



Photovoltaics

Lecture - Learning Objectives

At the end of this lecture you should:

- Understand the detailed balance for solar cells, and why maximum efficiency for a single photoabsorber is 33%
- Be able to analyze the basic principles of photovoltage and factors that can effect it
- Understand how p-n junctions work and their relation to solar cells.

How much energy can we get ?

- Comparison of renewable energy sources:
  - Geothermal: 0.3-2 TW
  - Hydro Power: 3-4 TW
  - Biomass: 2-6 TW
  - Wind Power: 25-70 TW
  - Solar Power: 123,000 TW

- Solar will always provide us with enough energy to power the planet.

- *The real question is can we do it cheap enough to be economically viable.*

Extremely Wrong

Secretary Chris Wright @SecretaryWright · 5h

Even if you wrapped the entire planet in a solar panel, you would only be producing 20% of global energy.

One of the biggest mistakes politicians can make is equating the ELECTRICITY with ENERGY!

Readers added context

Earth gets ~1.5M TWh/day of solar energy—over 3,000× global energy use (~165K TWh/year). Covering just 1% of land with panels could—theoretically–power the planet. Electricity is energy, and electrification replaces fossil use in transport, heat, and industry.

8:28 PM · Sep 2, 2025

Ambitious PV system goals

Ambition: Cost effective grid power from PV

Requirements:

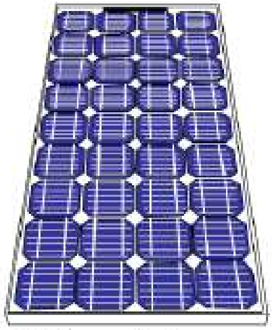
		2012	July 2024
Utility system costs:	C_s~1 $/W	Currently ~ 3.5 $/W	1.00 $/W
Reliability:	~ 30 yrs		
Efficiency:	$\eta \geq 25\%$ (!)		
Materials: Earth abundant, preferably non-toxic, recyclable			
Module cost:	~ 0.5 $/W	Currently ~ 1.7 $/W	0.085 $/W
Cell cost:	~ 0.25 $/W	Currently ~ 1 $/W	0.032 $/W

$\boxed{\text{Electricity cost: } \propto C_s/\eta}$

+ affordable energy storage

Data from PVinsights.com & SEIA.org


PV cell


PV module

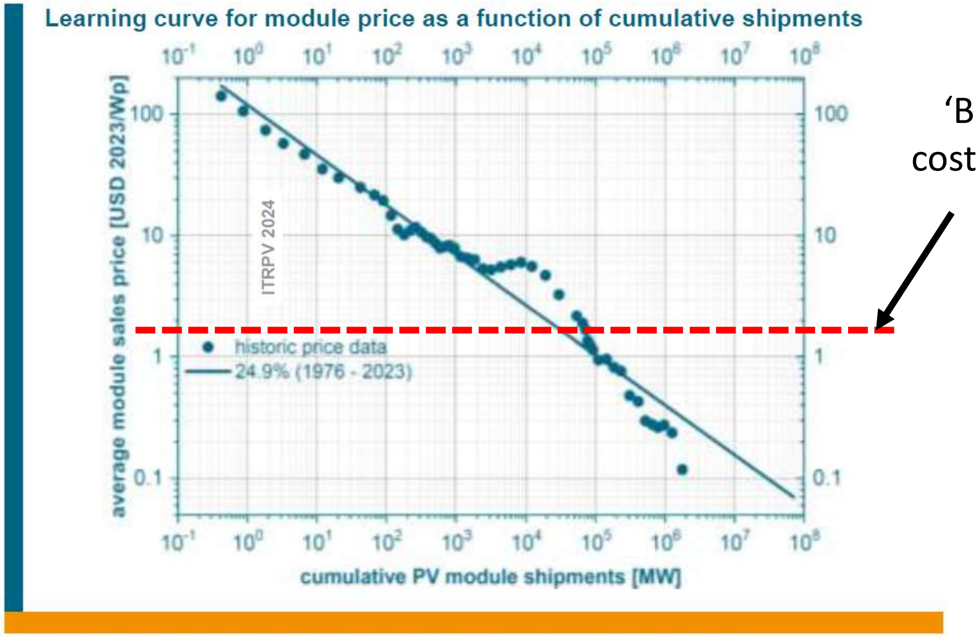

PV system (Nellis Air Base, US)

Solar Cell Costs

- Record solar price: 2020: 10.4 $/MWh (Saudia Arabia)
  2022: -4.5 $/MWh (Portugal)- Deal also includes storage.

- Avg. residential electricity cost in EU: 250 $/MWh

- The top ~10 biggest companies for Si solar cells all are from China.



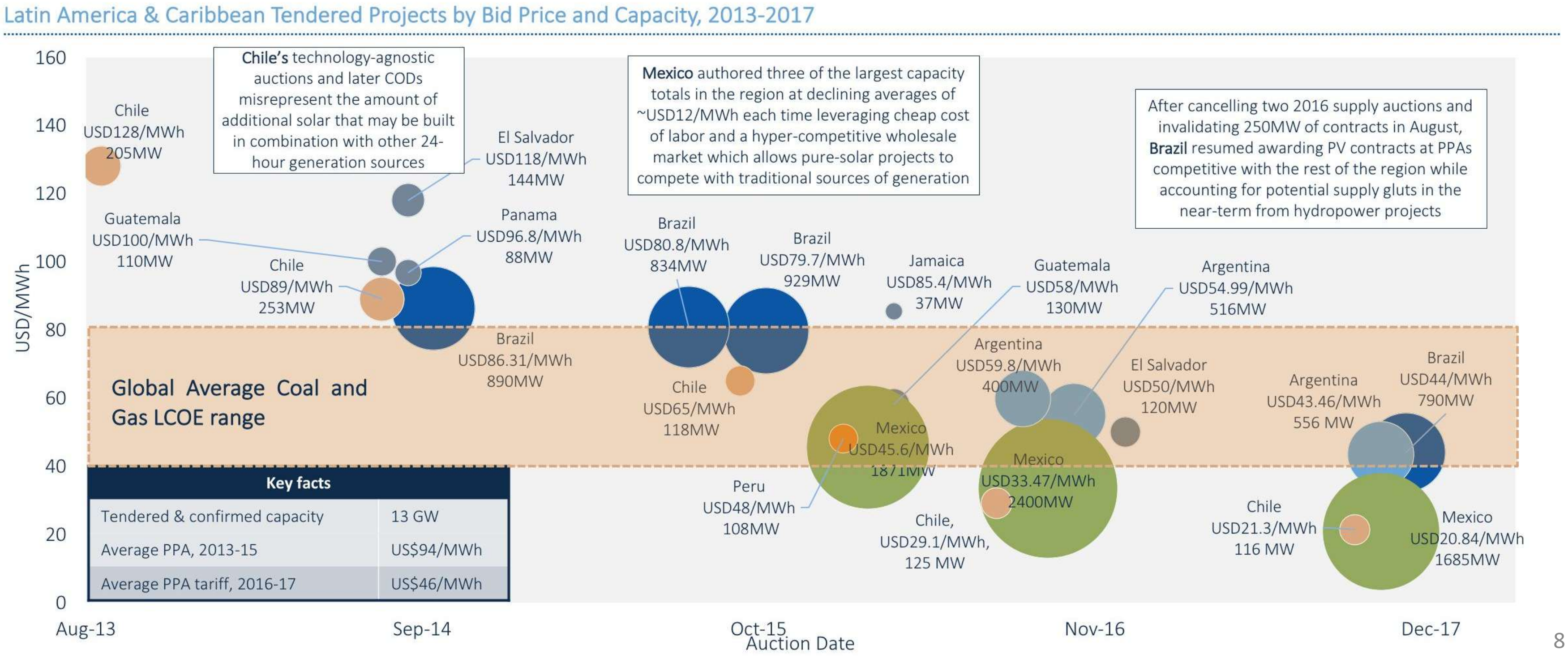
Point where 'Balance-of-plant' costs are greater than module costs

Fig. 1: Learning curve for module spot market price as a function of cumulative PV module shipments.

Reference: ITRPV Report 15th Edition

Reverse Auction

- Countries say they want a given amount of renewable electricity (with conditions) and then the lowest bid gets the job.
- This has been an absolute success. Prices have dropped incredibly due to this.



Latin America & Caribbean Tendered Projects by Bid Price and Capacity, 2013-2017

Chile's technology-agnostic auctions and later CODs misrepresent the amount of additional solar that may be built in combination with other 24-hour generation sources

Mexico authored three of the largest capacity totals in the region at declining averages of ~USD12/MWh each time leveraging cheap cost of labor and a hyper-competitive wholesale market which allows pure-solar projects to compete with traditional sources of generation

After cancelling two 2016 supply auctions and invalidating 250MW of contracts in August, **Brazil** resumed awarding PV contracts at PPAs competitive with the rest of the region while accounting for potential supply gluts in the near-term from hydropower projects

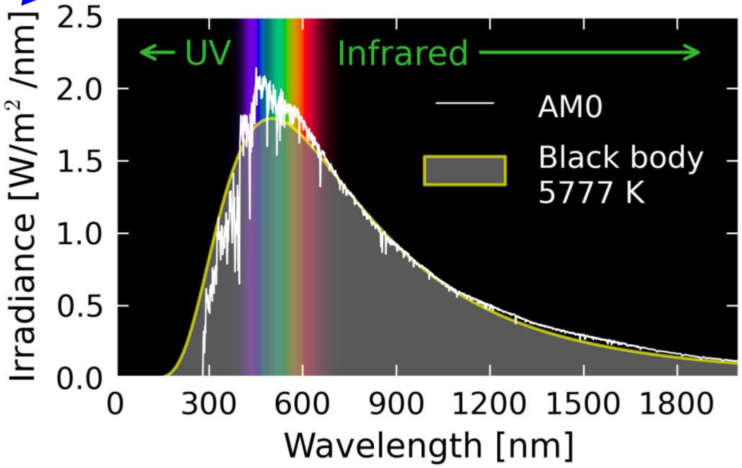
Key facts	
Tendered & confirmed capacity	13 GW
Average PPA, 2013-15	US$94/MWh
Average PPA tariff, 2016-17	US$46/MWh

Source: GTM Research *Global Solar Demand Monitor Q4 2017*

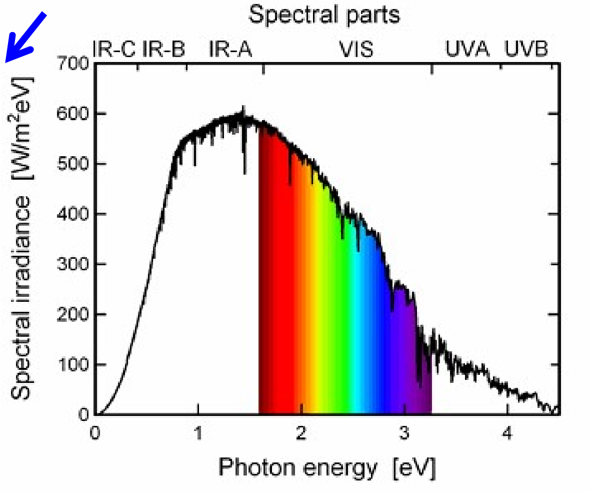
Incoming light– quick review

- While typically the plots are irradiance vs. wavelength, irradiance vs. photon energy can also be useful.
- We can convert these graphs using the following equation:

$$E(eV) = \frac{1240}{\lambda(\mathrm{nm})}$$



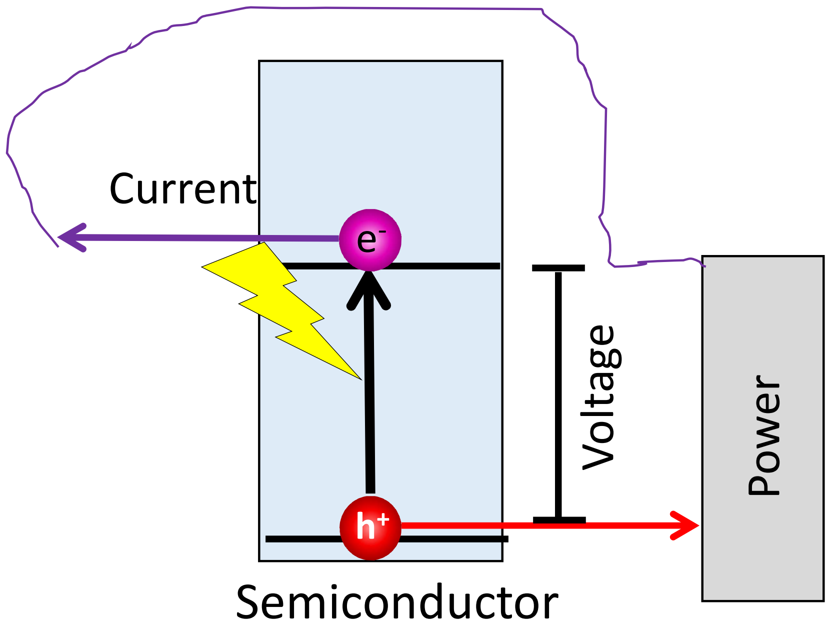
Per nm of wavelength



Per eV of photon energy

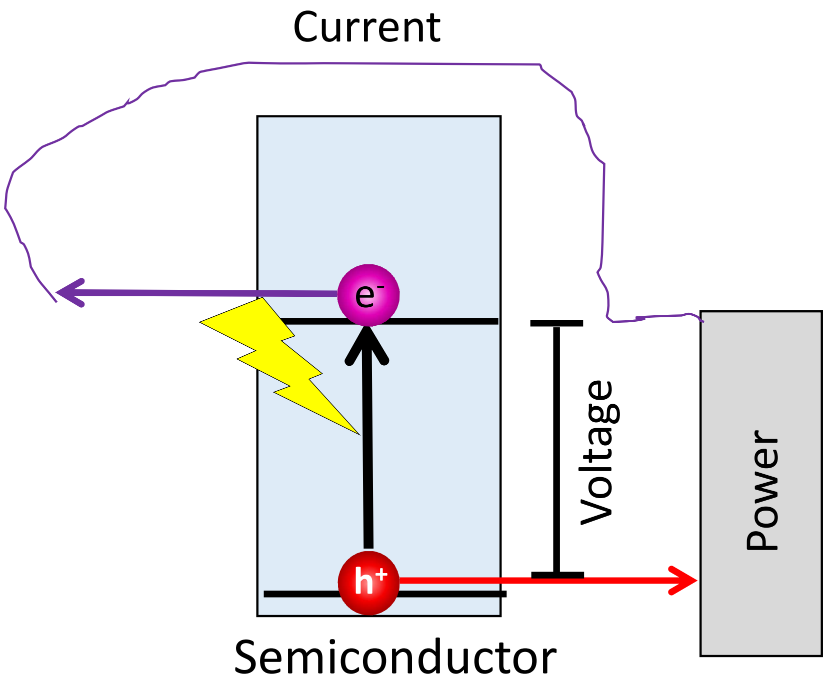
Solar cells – quick review

- From a first order theory we should be able to get power according to the voltage and current

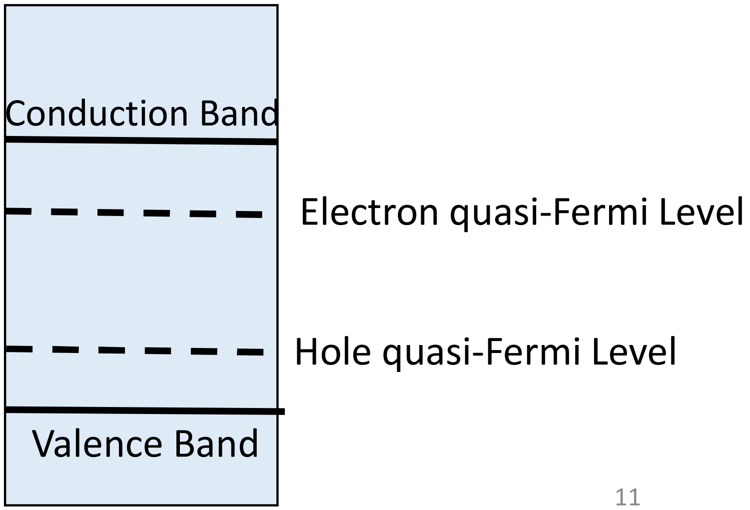


Solar cells – more detailed description

- From a first order theory we should be able to get power according to the voltage and current



- From a more in-depth approach it is actually the splitting of our Fermi level that gives us photovoltage.



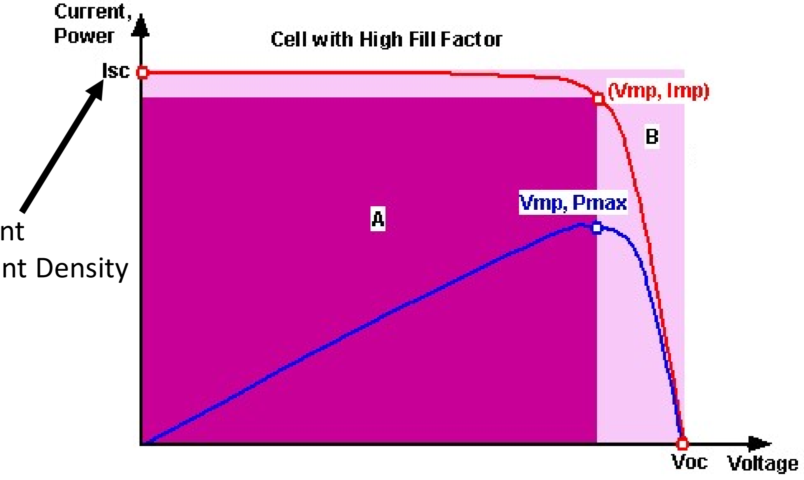
Relating voltage to current

- We want power (or power density) from our solar cell and this is simply:

$$P = V \times j$$

where *V* is voltage and *j* is current density.

- Increasing our current decreases our voltage, leading to a j-V curve as shown below



I = Current
J = Current Density

$$FF = \frac{J_{mp}V_{mp}}{J_{SC}V_{OC}}$$

$$Power_{Max} = FF \times J_{SC}V_{OC}$$

V_{OC} = Open circuit voltage
V_{mp} = Max power voltage
J_{sc} = Short circuit current
J_{mp} = Max power current

Variables

h = *Planck's constant =* 4.1×10^{-15} eV* s

c = *speed of light =* 3.0×10^{8} *m/s*

k_B = *Boltzmann's constant* = 1.38×10^{-23} m^2 kg s^{-2} K^{-1}

$q = e$ = *elementary charge =* 1.6×10^{-19} *C*

B = *Intensity- in* W/m^2

λ *=wavelength- in nm (can also be in m)*

E = *Energy- in eV (can also be in J)*

I = *Current (mA)*

J = *Current density* (mA/cm^2)

J_0 = *Dark saturation current density* (mA/cm^2)

J_{sc} = *Short-circuit current density* (mA/cm^2)

μ = *efficiency (in %)*

$\Delta\mu$ = *Chemical potential*

F_s = *Solid angle of emission from the Sun to Earth =* 6×10^{-5}

F_e = *Solid angle emission of Earth*

F_a = *Solid angle of emission from solar cell (normally Pi, but can vary)*

Ideal Diode Equation

- Lets integrate the entire J_{net} equation over all energies:

$$J_{net} = q\int_{E_G}^{\infty} (1 - R(E)) \times (b_{sun}(E) + b_{amb}(E) - b_{emit}(E, \Delta\mu))$$

$$J_{net} = J_{sc} - J_0\left[exp\left(\frac{qV}{kT}\right) - 1\right]$$

where J_o is defined as:

Important point of J_o

This is a function of temperature

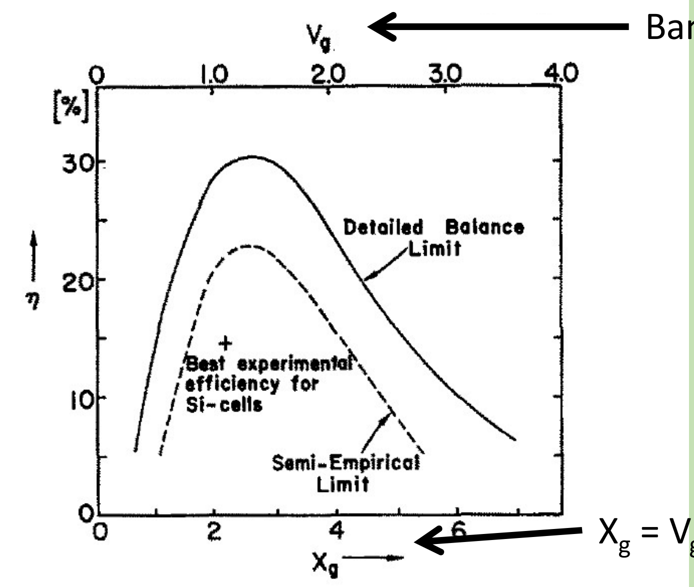
$$J_0 = \frac{1}{\eta} q F_a \frac{4kT}{h^3c^2} \times \left({E_g}^2 + 2kTE_g + (kT)^2\right) \times \exp\left(\frac{-E_g}{kT}\right)$$

Emission angle (π if you have a perfect back reflector)

Collection efficiency (includes reflection)

Maximum efficiency- Shockley-Queisser

- If we actually integrate the current over all energies/wavelengths and assume 100% absorption and 0% reflection, we get the Shockley-Quiesser limit.



Band Gap Energy

$X_g = V_g/kT$

FIG. 1. Comparison of the "semiempirical limit" of efficiency of solar cells with the "detailed balance limit," derived in this paper. + represents the "best experiment efficiency to date" for silicon cells. (See footnote 6.)

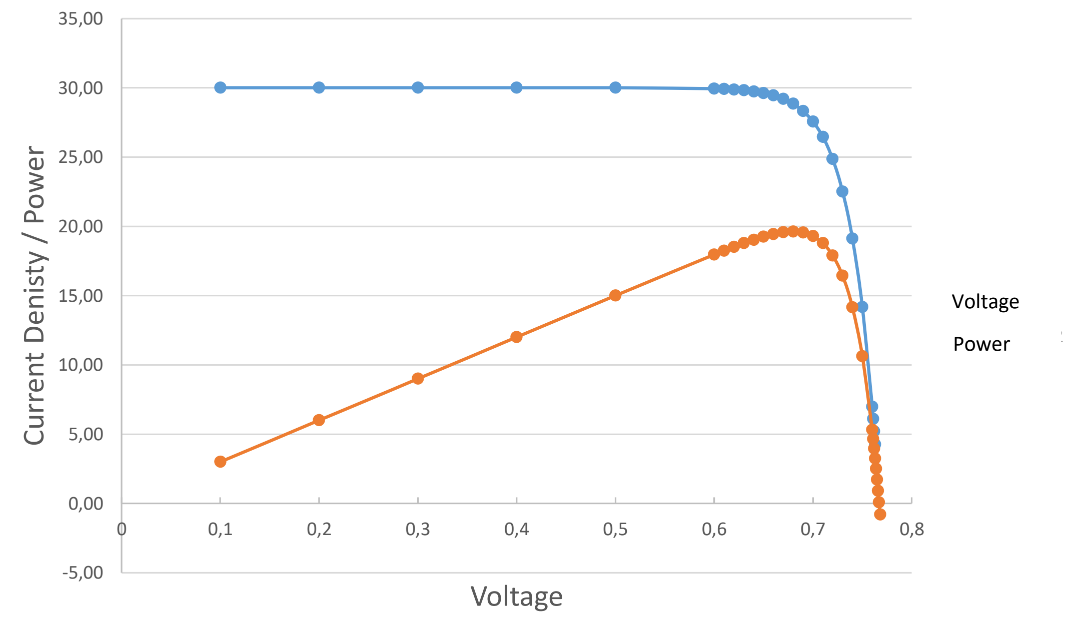
[Shockley and Queisser, J. Appl. Phys. 1961]

- The maximum efficiency for a single band-gap photoabsorber under normal sunlight is **33%**

Applying diode equation

- If I have a solar cell with a dark saturation current (J_0) of 1 x 10^{-11} mA/cm^2 and a short circuit current (J_{Sc}) of 30 mA/cm^2, what is my maximum power at a temperature of 25 °C ? or more simply, what is the power density at 0.5V?

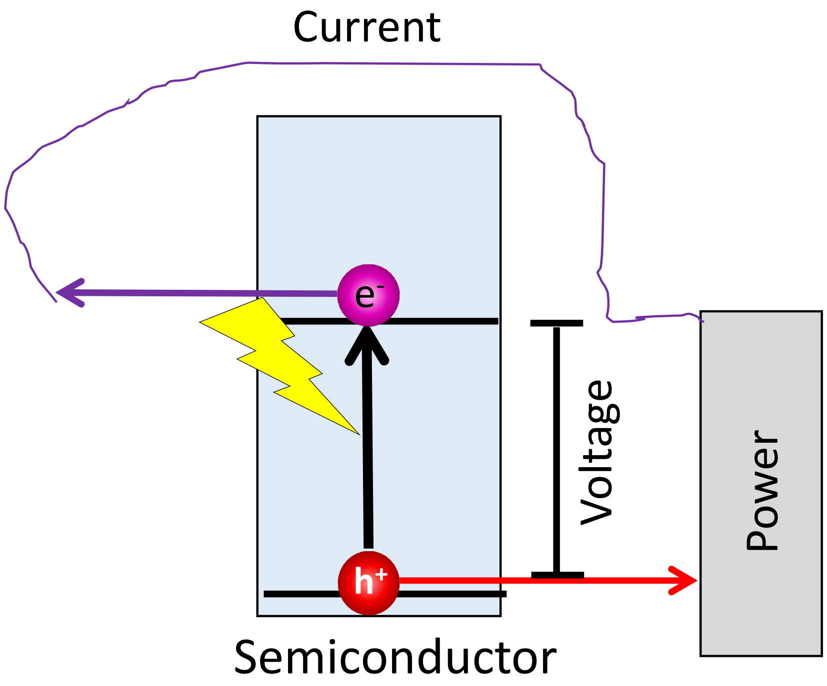
Note kT/q at 25C is 25.7 mV



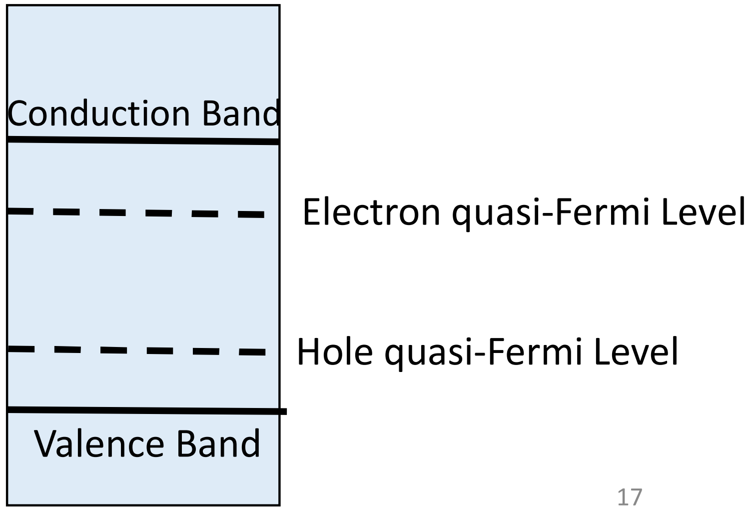
Answer = at 0.68V power is 19.6 mW/cm^2

Solar cells – more detailed description

- From a first order theory we should be able to get power according to the voltage and current

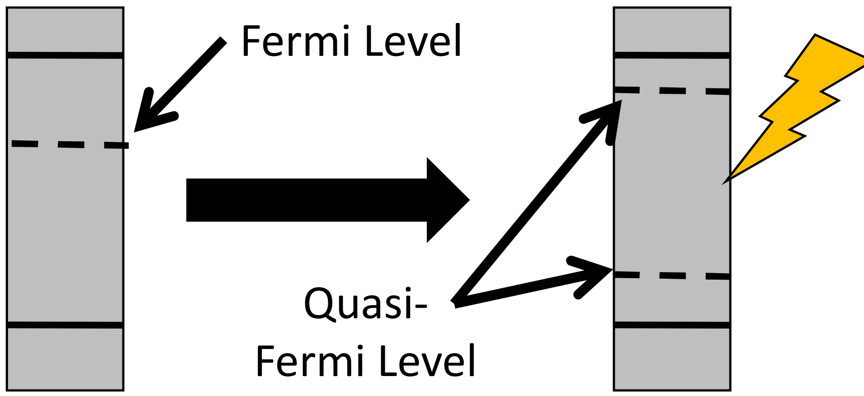


- From a more in-depth approach it is actually the splitting of our Fermi level that gives us photovoltage.



Physics of a Photovoltage

- During irradiation we add electron-hole pairs (add *n* and *p*)
- This provides a splitting of the Fermi level



Conduction Band: $E_{f,e-} = E_c + k_b T Ln\left(\frac{n}{N_c}\right)$

Valence Band: $E_{f,h+} = E_v - k_b T Ln\left(\frac{p}{N_v}\right)$

Photovoltage: $qV_{Phot} = E_{f,e-} - E_{f,h+}$

$$N_c = 2\left(\frac{m_c^* k_B T}{2\pi\hbar^2}\right)^{3/2}$$

m_c- effective mass of electrons

$$N_v = 2\left(\frac{m_v^* k_B T}{2\pi\hbar^2}\right)^{3/2}$$

m_v- effective mass of holes

Analysis of Photovoltage

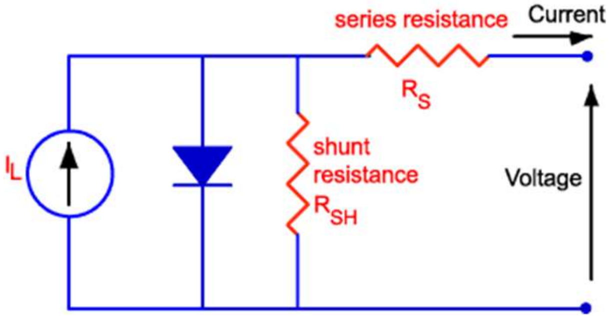
- The photovoltage is sometimes denoted at a difference in chemical potential ($\Delta\mu$)
- By rearranging the photovoltage equation we get the following

$$qV_{Photo} = \Delta\mu = E_g + k_b \overbrace{TLn\left(\frac{pn}{N_v N_c}\right)}^{\text{This is a negative term since Ln <1 is negative}}$$

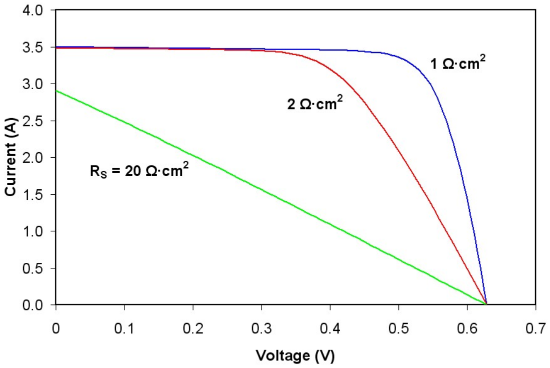
- N_v and N_c relate to band gap (intrinsic property) and effective mass (material specific).

Practical Losses -Shunt & Series Losses

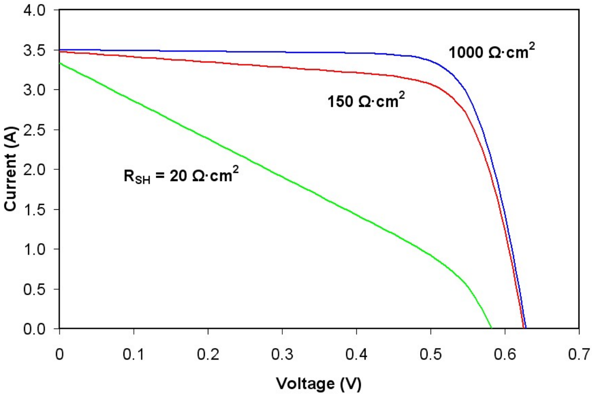
- The circuit for a shunt and series loss solar cell looks as followed:



Effects of Series Losses i.e. ohmic losses



Effects of Shunt Losses-i.e. short circuit



Diode Equation + Practical Losses

$$J_{net} = J_{sc} - J_0\left[exp\left(\frac{qV}{kT}\right) - 1\right]$$

- Series Resistance (R_S) are losses due to any ohmic resistance in the system. We want low series resistance
    - This can be external (resistance in wire to solar cell) or internal (resistance within the semiconductor)

- Shunt Resistance (R_{SH}) are losses due to internal short circuiting of the cell. Thus we want high shunt resistance

- Including shunt and series into our diode equation we get:

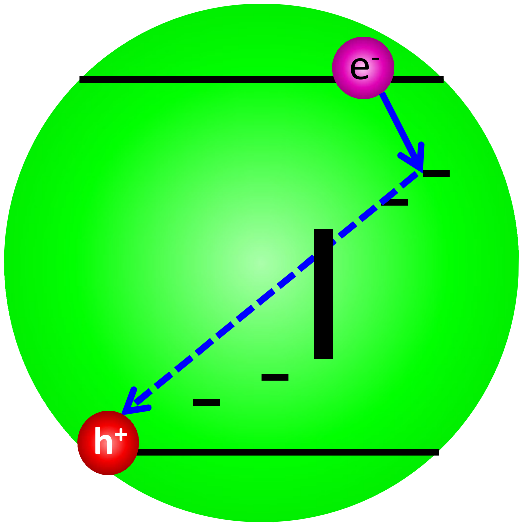
$$J_{net} = J_{sc} - J_0\left[exp\left(\frac{q(V + J_{net}R_s)}{kT}\right) - 1\right] + \frac{q(V + J_{net}R_s)}{R_{SH}}$$

Non-radiative Recombination - Qualitative

- If we have defect sites in our solar cell, electrons and holes will recombine at these sites giving off heat.

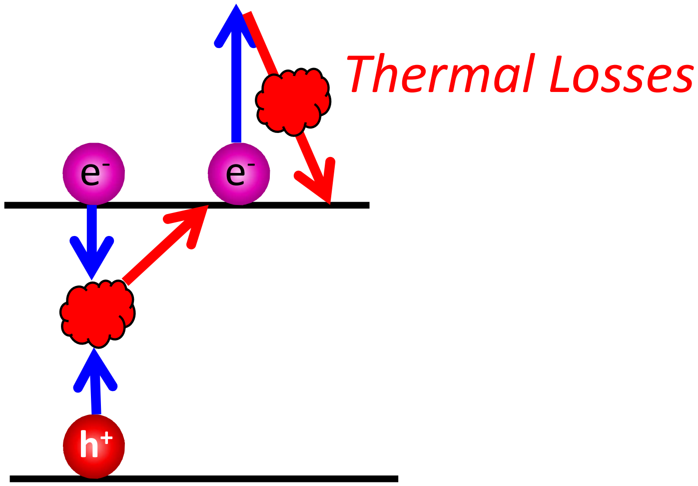
- More precisely, the electron-hole recombination will emit photons, but just at too small of wavelengths to be readsorbed by the semiconductor.

- This is also known as Shockley-Reed-Hall (SRH) recombination.



Auger Recombination (also non-radiative)

- If an electron and hole recombine, they can transfer their energy to a 2nd electron in the conduction band
- This 2nd electron goes up and energy, and then comes back down.



- When the 2nd electron comes back down, its energy is lost as non-radiative recombination.
- For this to take place, their needs to be a lot of electrons in the conduction band.

Recombination Losses in General

- *Shockley-Hall-Reed recombination (SRH)-* is always a bad thing thus this must be avoided.
  - High purity materials and good engineering can almost completely eliminate these losses

- *Radiative recombination (RR)-* This is black-body emissions that occur when deriving the Schockly-Queisser Equation
  - Note these radiated photons can get readsobred by the solar cell.

- *Auger recombination (AR)-* This is a minor loss
  - AR only occurs if there are lots of electron-hole pairs.

An analysis of efficiency

- Let’s look at our diode equation and see where the losses are from a fundamental standpoint.

$$J_{net} = J_{sc} - J_0 \left[exp\left(\frac{qV}{mkT} \right) - 1 \right]$$

m = non-ideality factor (defects, etc.)

m= 1 for ideal case

$$V = \frac{mkT}{q} ln\left(\frac{j_{SC} - j_{net}}{j_0} + 1 \right) \Longrightarrow V_{OC} = \frac{mkT}{q} ln\left(\frac{j_{SC}}{j_0} + 1 \right)$$

Does increasing the temperature increase the open circuit voltage?

Finding all the efficiency losses

- By isolating V_{OC}, we can expand the J_o term, simplify and more easily analyze our losses.

$$V_{OC} = \frac{kT}{q} ln\left(\frac{j_{SC}}{j_0} + 1\right)$$

$$V_{OC,Max} \approx \frac{E_G}{q}\left(1 - \frac{T}{T_S}\right) + \frac{kT}{q} Ln\left(\frac{T_S}{T}\right) - \frac{kT}{q}\overbrace{\left(ln\left(\frac{\Omega_{Device}}{\Omega_{Sun} * \tau}\right) + ln\left(4{n_r}^2\right) + ln\left(\frac{R_{rad} + R_{non}}{R_{rad}}\right)\right)}^{\text{Entropy Terms}}$$

Angle of emission
vs. absorption

Reflection losses

Effectively combination
of ‘m’ and ‘η’

- The above equation lets us analyze where are our losses coming from

Finding all the efficiency losses

- Putting all the loss and gain terms together and simplifying yields:

$$V_{OC,Max} = \overbrace{\frac{E_G}{q}\left(1-\frac{T}{T_S}\right)+\frac{kT}{q}Ln\left(\frac{T_S}{T}\right)}^{\text{Blackbody radiation losses}} - \frac{kT}{q}\overbrace{\left(ln\left(\frac{\Omega_{Device}}{\Omega_{Sun}*\tau}\right)+ln\left(4n_r{}^{2}\right)+ln\left(\frac{R_{rad}+R_{non}}{R_{rad}}\right)\right)}^{\text{Entropy Terms}}$$

- Determine how much loss each term contributes.
- Determine the maximum efficiency for the following materials:
  - Si (E_g= 1.1 eV, average n_r = 3.4)
  - GaAs (E_g = 1.4 eV, average n_r = 3.3)
  - $PbCH_3NH_3I_3$ Perovskite (E_g= 1.5 eV, average n_r = 2.5)

-Assume Ω_{Device} = π, no non-radiative recombination, and a no light concentration (i.e τ =1) .

Ω_{Sun} = 6 x 10^{-5}

Finding all the efficiency losses

- Putting all the loss and gain terms together and simplifying yields:

$$V_{OC,Max} = \frac{E_G}{q}\left(1-\frac{T}{T_S}\right) + \frac{kT}{q} Ln\left(\frac{T_S}{T}\right) - \frac{kT}{q}\overbrace{\left(ln\left(\frac{\Omega_{Device}}{\Omega_{Sun} * \tau}\right) + ln\left(4{n_r}^{2}\right) + ln\left(\frac{R_{rad} + R_{non}}{R_{rad}}\right)\right)}^{\text{Entropy Terms}}$$

- If all terms are highly optimized the $V_{OC,\ Max}$ is typically about 300 mV less than the band gap (i.e. E_G)

- In theory the entropy terms can be engineered to almost zero, but this may create an impractical design from a manufacturing or economic perspective.

Best Experimental $V_{OC,\ max}$		
Material	E_G	$V_{OC,\ max}$
Si	1.1	0.740
GaAs	1.4	1.12
$PbCH_3NH_3I_3$ (Perovskite)	1.55	~1.2

Removing non-radiative recombination

- Understanding all the terms.

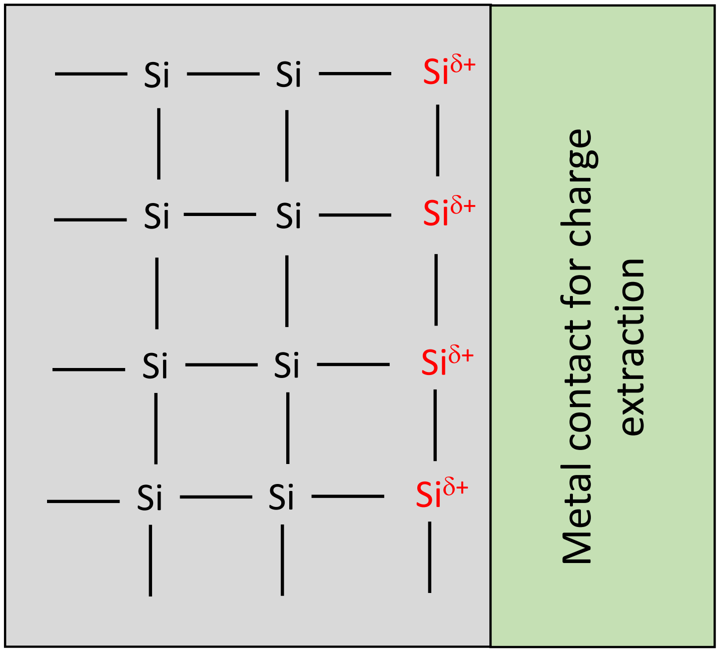
$$V_{OC,Max} = \frac{E_G}{e}\left(1-\frac{T}{T_S}\right) + \frac{kT}{e}Ln\left(\frac{T_S}{T}\right) - \frac{kT}{e}\left(Ln\left(\frac{\Omega_{Device}}{\Omega_{Sun} * \tau}\right) + Ln\left(4{n_r}^{2}\right) + Ln\left(\frac{R_{rad} + R_{non}}{R_{rad}}\right)\right)$$

How can we effectively limit this term?

- Have a more pure, and well ordered semiconductor (don’t have junk in your silicon)

Other non-radiative recombination sites

- Surface defects are the other major area for non-radiative recombination.
- These results from incomplete bonds between surfaces.



Si Wafer

- This is probably the biggest fixable loss in solar cells.
- The best way to mitigate these is to create an insulating layer at the surface.
- There is a lot of technology in trying to resolve this issue.

Finding all the efficiency losses

$$V_{OC,Max} = \frac{E_G}{q}\left(1-\frac{T}{T_S}\right) + \frac{kT}{q} ln\left(\frac{T_S}{T}\right) - \frac{kT}{q}\left(\overbrace{ln\left(\frac{\Omega_{Device}}{\Omega_{Sun} * \tau}\right) + ln\left(4n_r{}^{2}\right) + ln\left(\frac{R_{rad} + R_{non}}{R_{rad}}\right)}^{\text{Entropy Terms}}\right)$$

- Is there any tricks to mitigate the first two entropy loss terms.

- Obviously we can’t beat the 1st law of thermodynamics, but we can manipulate entropy to our advantage.

Trying to 'Beat the system'

- Understanding all the terms.

$$V_{OC,Max} = \frac{E_G}{e}\left(1-\frac{T}{T_S}\right) + \frac{kT}{e}Ln\left(\frac{T_S}{T}\right) - \frac{kT}{e}\left(Ln\left(\frac{\Omega_{Device}}{\Omega_{Sun} * \tau}\right) + Ln\left(4{n_r}^{2}\right) + Ln\left(\frac{R_{rad} + R_{non}}{R_{rad}}\right)\right)$$

How can we effectively limit this term?

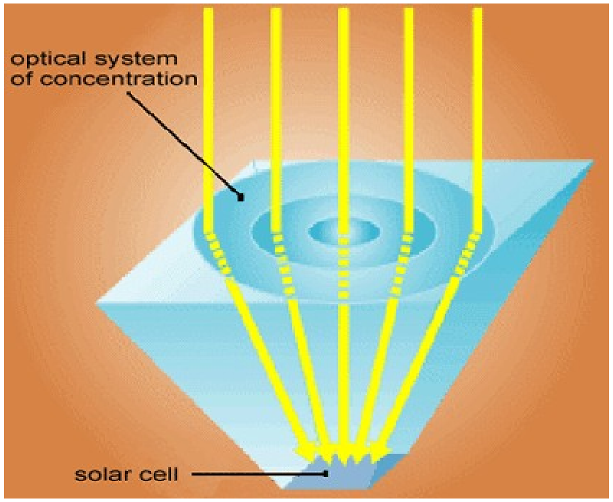
Concentrator cells

- Concentrator cells simply are mirrors that concentrate the light onto a solar cell.
- Concentrators are nice for 2 reasons:
  - Increase efficiency slightly.
  - You lower the solar cell cost.

$$V_{OC} = \frac{mkT}{q} ln\left(\frac{j_{sc}}{j_0} + 1\right)$$

$$V_{increase} = \frac{mk}{q} Ln\left(\frac{i_{con.}}{i_{uncon}}\right)$$

Assume m= 1 for ideal case



Concentrator cells

- If the solar cell cost is high (i.e. use rare or expensive materials, this approach is very beneficial.)
- These cells work good in direct sunlight, not indirect or diffuse sunlight, thus they need to track the sunlight
- Increase in temperature can be a major issue *(Why?)* and cooling systems are needed on these devices.
- Thus the economic viability of these cells is very geography dependent.
- Concentrators range from 10x concentration up to 1,000x.

Trying to 'Beat the system'

- Understanding all the terms.

$$V_{OC,Max} = \frac{E_G}{q}\left(1 - \frac{T}{T_S}\right) + \frac{kT}{q} Ln\left(\frac{T_S}{T}\right) - \frac{kT}{q}\left(Ln\left(\frac{\Omega_{Device}}{\Omega_{Sun} * \tau}\right) + Ln\left(4{n_r}^{2}\right) + Ln\left(\frac{R_{rad}^{net} + R_{non}}{R_{rad}^{net}}\right)\right)$$

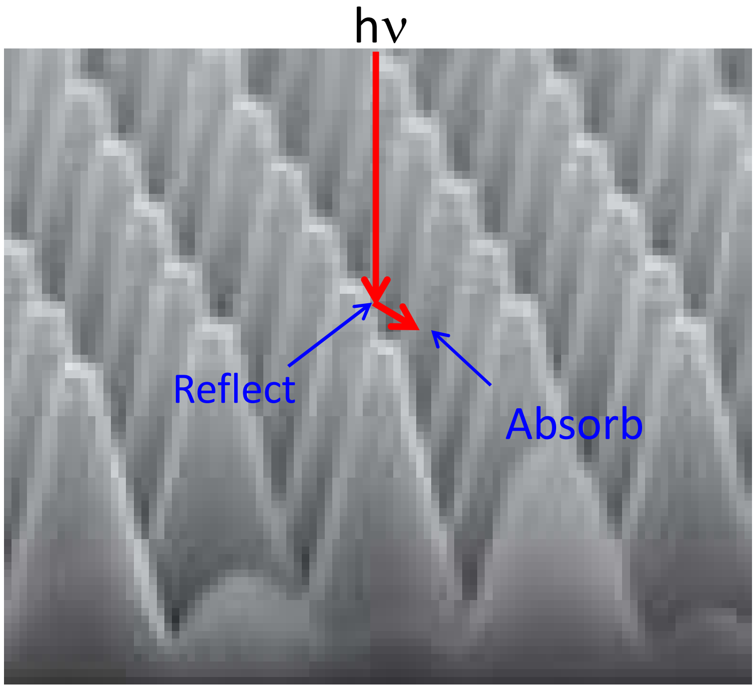
How can we effectively limit this term?

Mitigating Light Reflection

Air Substrate

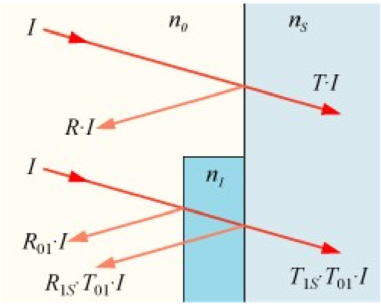
$$r = \frac{(\underset{\uparrow \text{Air}}{n_o} - \underset{\uparrow \text{Substrate}}{n_s})^2}{(n_o + n_s)^2}$$

- <u>Strategies to reduce r</u>
  - Nanotexturing the surface.
  - This allows the light to have multiple chances to get absorbed.
  - Basically $r_{eff} = r^n \leftarrow$ n= # of reflections



  - If the probability of reflection is 20%, and the light bounces off the semiconductor 3 times, the effective reflectivity is 0.8%.

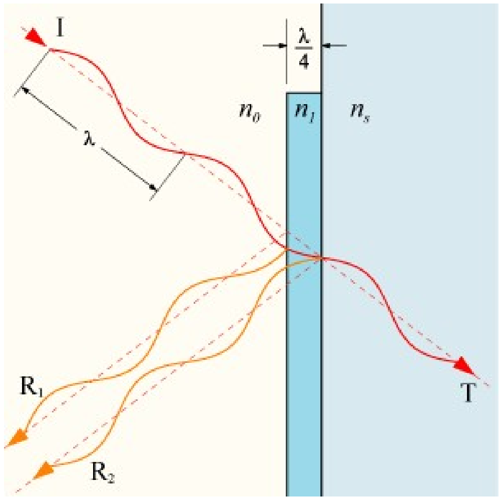
Mitigating light reflection



- Antireflective coating- Approach #1
  - By having a coating with an intermediate n_r, it is possible to decrease reflection losses.
  - The optimum index of refraction should be:

$$n_1 = \sqrt{n_0 n_s}$$

Remember: $r = \frac{(n_o - n_s)^2}{(n_o + n_s)^2}$



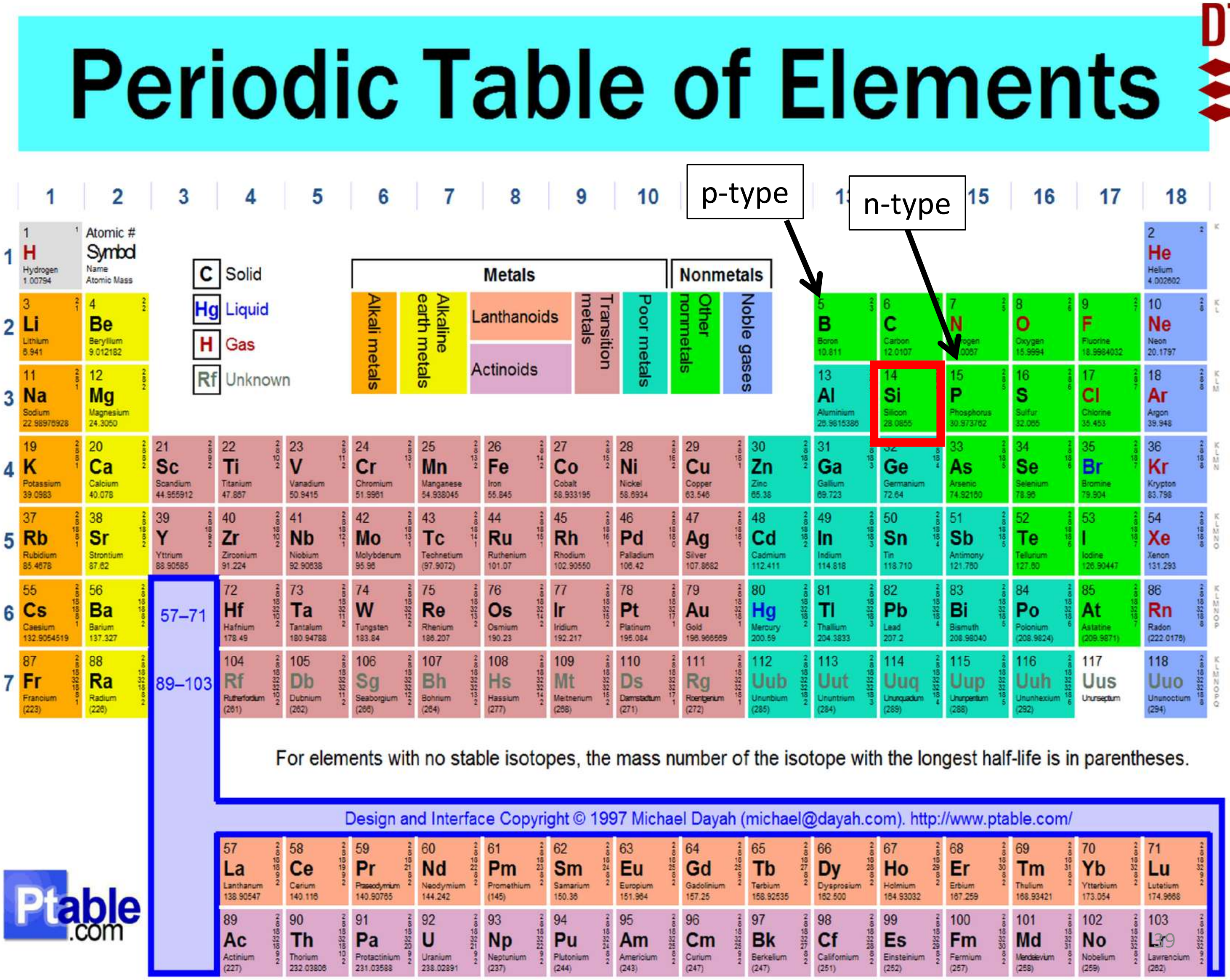
- Antireflective coating- Approach #2
  - If the anti-reflective layer is ¼ the wavelength of incoming light, the reflected light will destructively interfere.
  - This is a limited approach since solar irradiation is not a single wavelength, but a range of wavelengths.

p-n Junctions

(may be done in Week 3)

Doping a Semiconductor

i.e.
Changing the Fermi level



Periodic Table of Elements

p-type

n-type

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H Hydrogen	Atomic # Symbol Name Atomic Mass																2 He Helium
2	3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
3	11 Na Sodium	12 Mg Magnesium											13 Al Aluminium	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
4	19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
5	37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
6	55 Cs Caesium	56 Ba Barium	57–71	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
7	87 Fr Francium	88 Ra Radium	89–103	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111 Rg Roentgenium	112 Uub Ununbium	113 Uut Ununtrium	114 Uuq Ununquadium	115 Uup Ununpentium	116 Uuh Ununhexium	117 Uus Ununseptium	118 Uuo Ununoctium

57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium
89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium	103 Lr Lawrencium

C Solid
Hg Liquid
H Gas
Rf Unknown

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

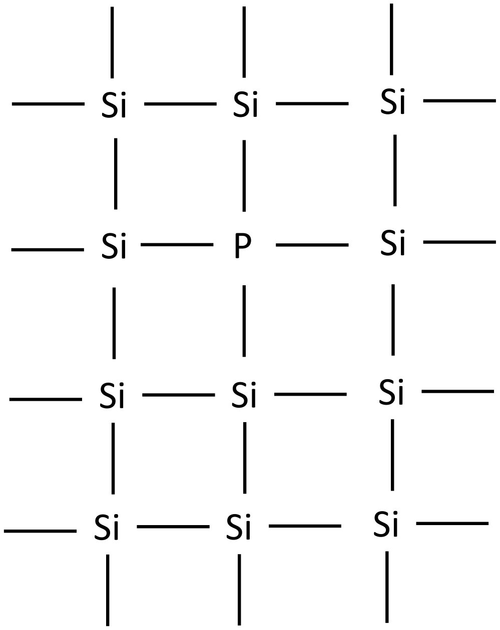
Nonmetals: Other nonmetals, Noble gases

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

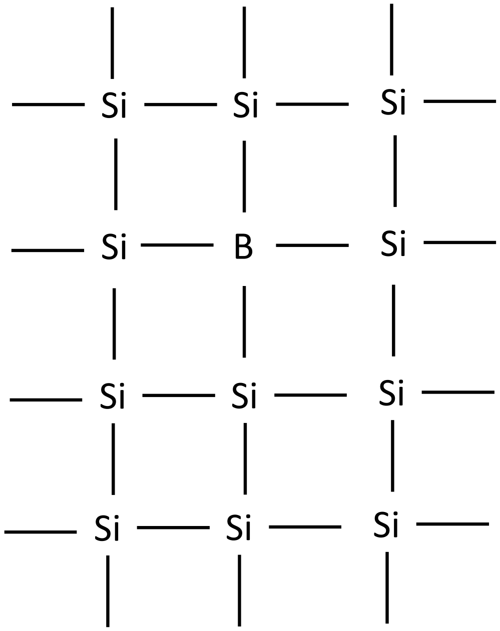
Ptable.com

How to get an n-type or p-type material

- Here are the most common ways to make Si n-type or p-type.



n-type



p-type

- Here are the most common ways to make Si n-type or p-type.

Separating the charge

- Creating a p-n junction allows us to create a built in electrochemical bias.
- At the interface charge transfers between n-side and p-side due to diffusion until it builds enough potential to make current = 0.

$$J_n(r) = q(D_n \nabla \mathrm{n} + \mu_n n \mathrm{F})$$

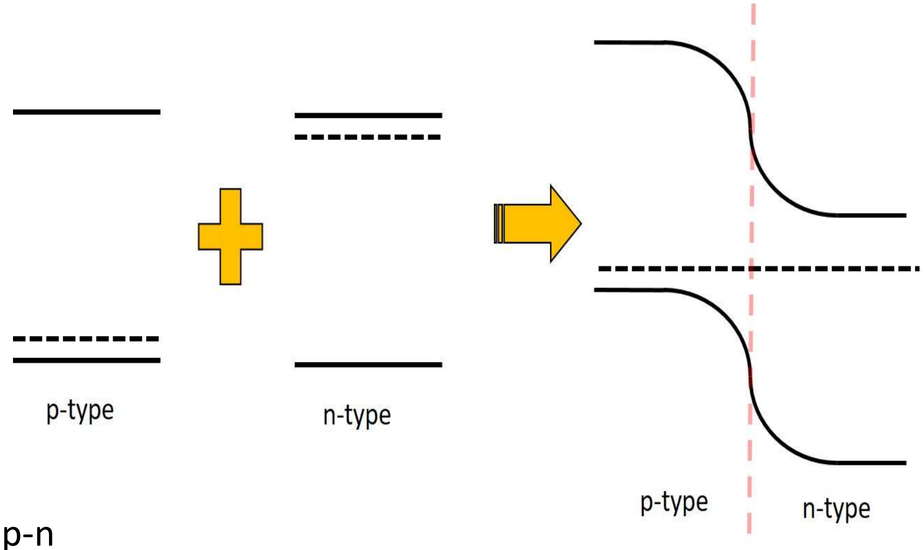
⬇

$$0 = q(D_n \nabla \mathrm{n} + \mu_n n \mathrm{F})$$

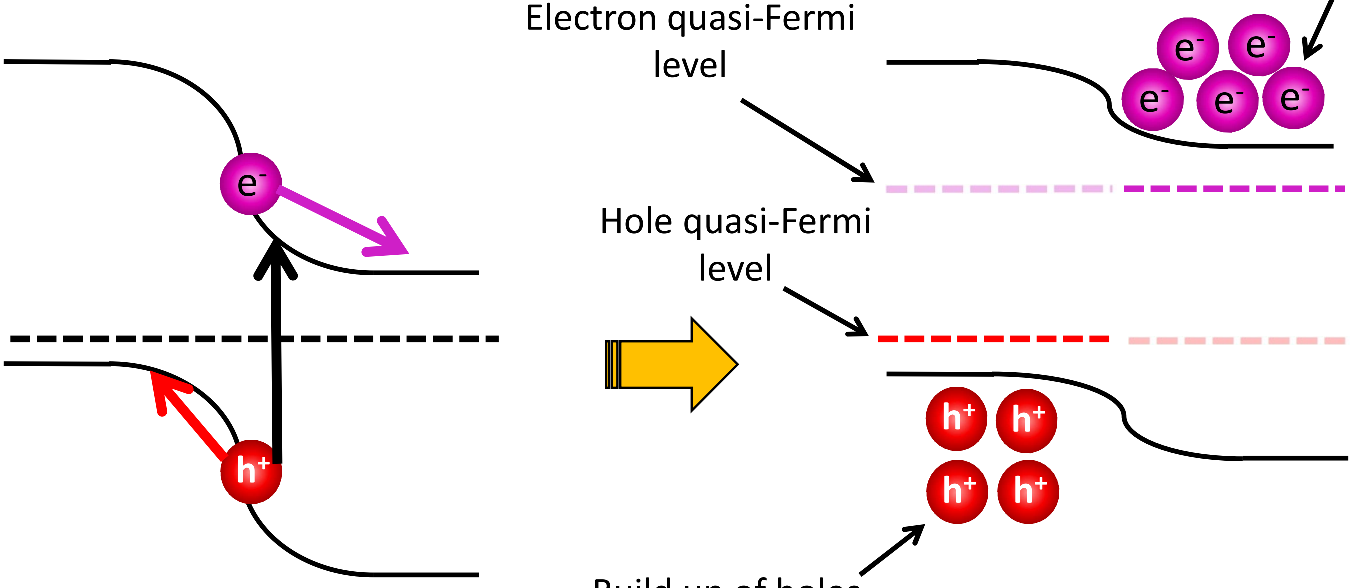
⬇

$$F_{n-si} = \frac{-q D_n \nabla \mathrm{n}}{\mu_n n}$$

Gradient at p-n junction



Separating the charge



Build up of electrons
pushes conduction
band up.

Electron quasi-Fermi
level

Hole quasi-Fermi
level

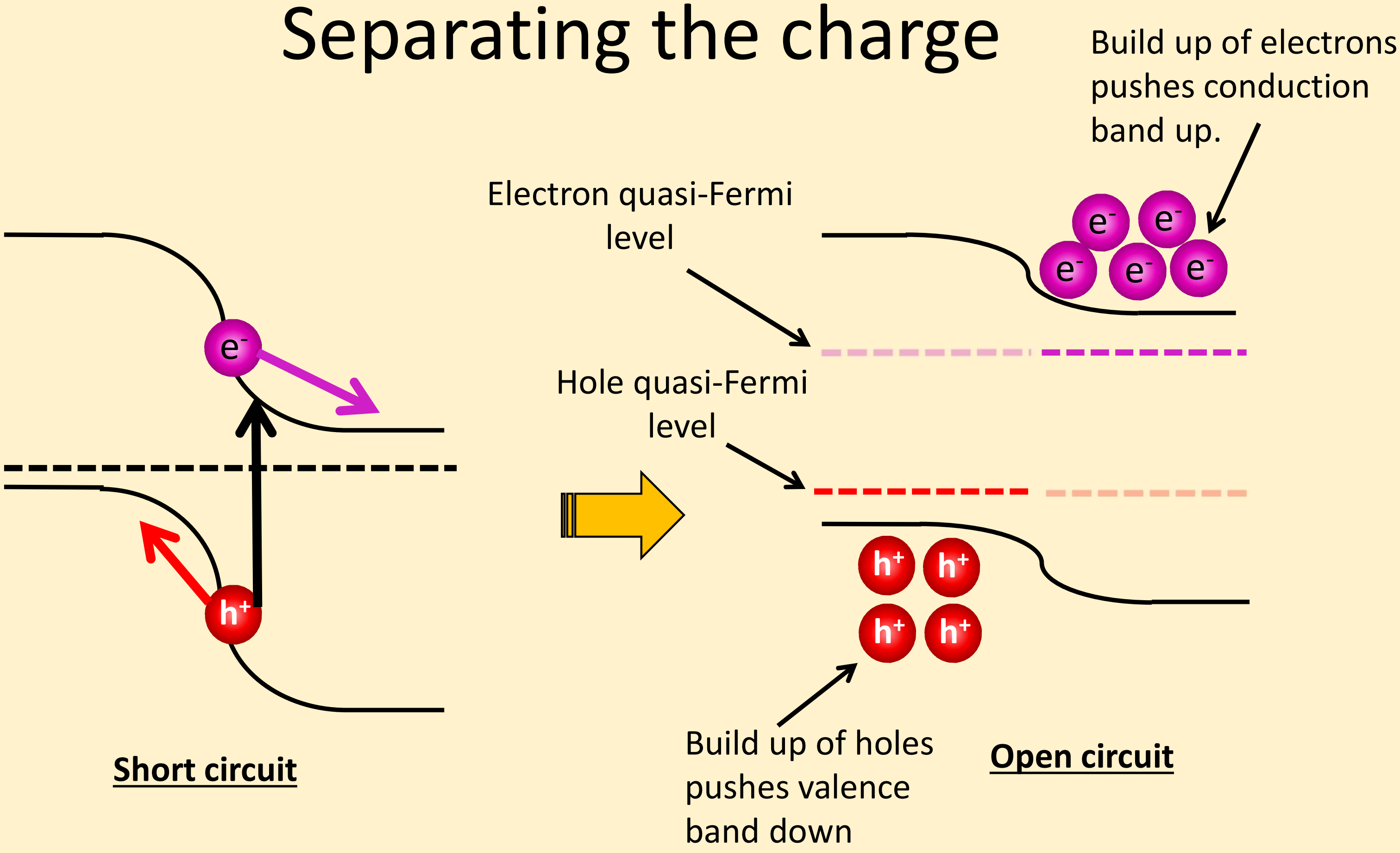
Build up of holes
pushes valence
band down

Short circuit

Open circuit

- Just because an electron is in the conduction band, doesn’t mean that this is the chemical potential of the electron.
- The chemical potential of the electron is that of the quasi Fermi-Level

Separating the charge



Build up of electrons pushes conduction band up.

Electron quasi-Fermi level

Hole quasi-Fermi level

Build up of holes pushes valence band down

Short circuit

Open circuit

- Will the band-bending thickness be equally between the p and n side.

Doping Profiles

- The doping is inversely proportional to the doping density.

$$V_{p-typ} = V_{Bias} \times \frac{N_D}{N_D + N_A}$$

$$V_{n-type} = V_{Bias} \times \frac{N_A}{N_D + N_A}$$

N_A = Acceptor (p-type) density
N_D = Donor (n-type) density

- V_{bias} is the potential difference in Fermi levels between the n-type and p-type semiconductor.
- For more detailed description of these equations see Malizia, et al, JMC-A, 2014.

Doping Profiles

- Basically the high dopant density material has a stronger pull than the lower doped material.
- By using Poisson's equation to distribute the charge, we can determine the depletion width.

Depletion width (band bending thickness)

$$x_p = \left(\frac{N_D}{N_A}\frac{2\varepsilon\varepsilon_0 V_{bias}}{q(N_D + N_A)}\right)^{1/2}$$

$$x_n = \left(\frac{N_A}{N_D}\frac{2\varepsilon\varepsilon_0 V_{bias}}{q(N_D + N_A)}\right)^{1/2}$$

ε = permittivity of semiconductor
ε_0 = permittivity in vacuum
V_{bias} = Total band-bending voltage (difference in p-n Fermi levels)
q= elementary charge

Concept Check

In a p-n junction solar cell, a p-type side has a dopant density of 10^{16} and an n-type side has a dopant density of 10^{20}. This means:

a) The p-type has a larger voltage drop across it and a longer depletion layer.

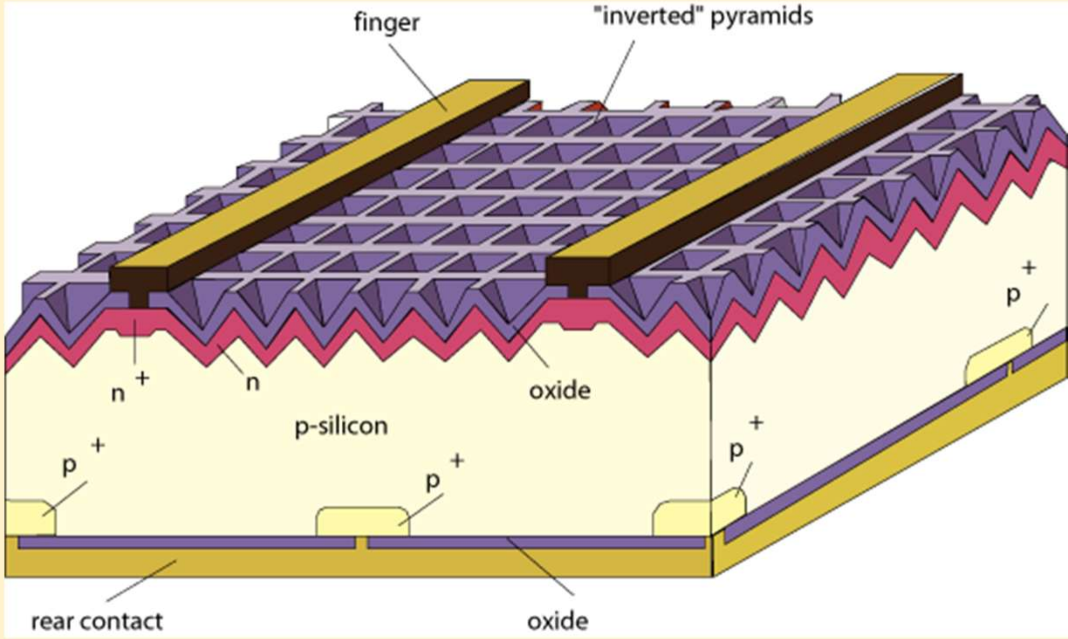
b) The p-type has a larger voltage drop across it and a shorter depletion layer.

c) The n-type has a larger voltage drop across it and a longer depletion layer.

d) The p-type has a larger voltage drop across it and a shorter depletion layer.

State of the art - 2013

- Creating small point contacts allows for minimal surface recombination.
- Doping both sides prevents charge carriers from going to the wrong contact.
- Creating small point contacts allows for minimal surface recombination.
- This approach gave a record efficiency of 24.7%.

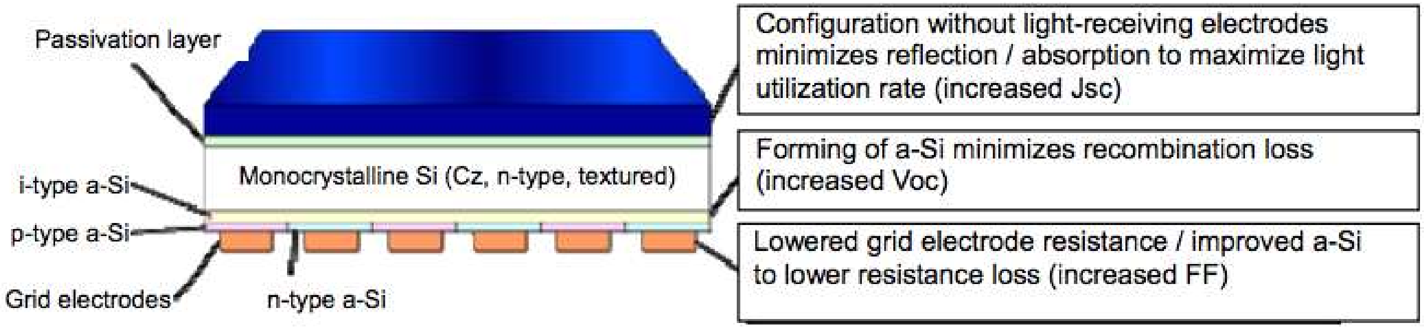


- What is the biggest failure of this device?

PVeducation.org

State of the art - Current

- Panasonic decided to put both the electron and hole contact on the same side.
- This eliminated light shading by the electrical contact fingers and allowed complete surface passivation on one side.
- Amorphous Si was used as back contacts because they minimize recombination losses.
- This device reached a record 26.7% efficiency.
- It is still surprising that having both the p and n junction near each other gives such good efficiency.



Configuration without light-receiving electrodes minimizes reflection / absorption to maximize light utilization rate (increased Jsc)

Forming of a-Si minimizes recombination loss (increased Voc)

Lowered grid electrode resistance / improved a-Si to lower resistance loss (increased FF)

Image from Natural Group

Lecture - Learning Objectives

At the end of this lecture you should:

- Understand the detailed balance for solar cells, and why maximum efficiency for a single photoabsorber is 33%
- Be able to analyze the basic principles of photovoltage and factors that can effect it
- Understand how p-n junctions work and their relation to solar cells.

Exercises

- Currently the best crystalline Se solar cells have an open circuit voltage of 1.2 V at 10 times solar concentration. What is their thermodynamic maximum voltage they can achieve? Is it worth investing more research money into this material?

- If I use TiN as an antireflection layer on Silicon, how much will I reduce the reflection by (at a wavelength of 590 nm)?

- At 8 AM my silicon solar cell has a short circuit current of 100 A and an open circuit voltage of 0.6 V and a fill factor of 80%. What is its maximum power? Now At 12 PM there is 4 times more light (but the same temperature, and same fill factor). In theory, how much will my solar cell produce at this time?