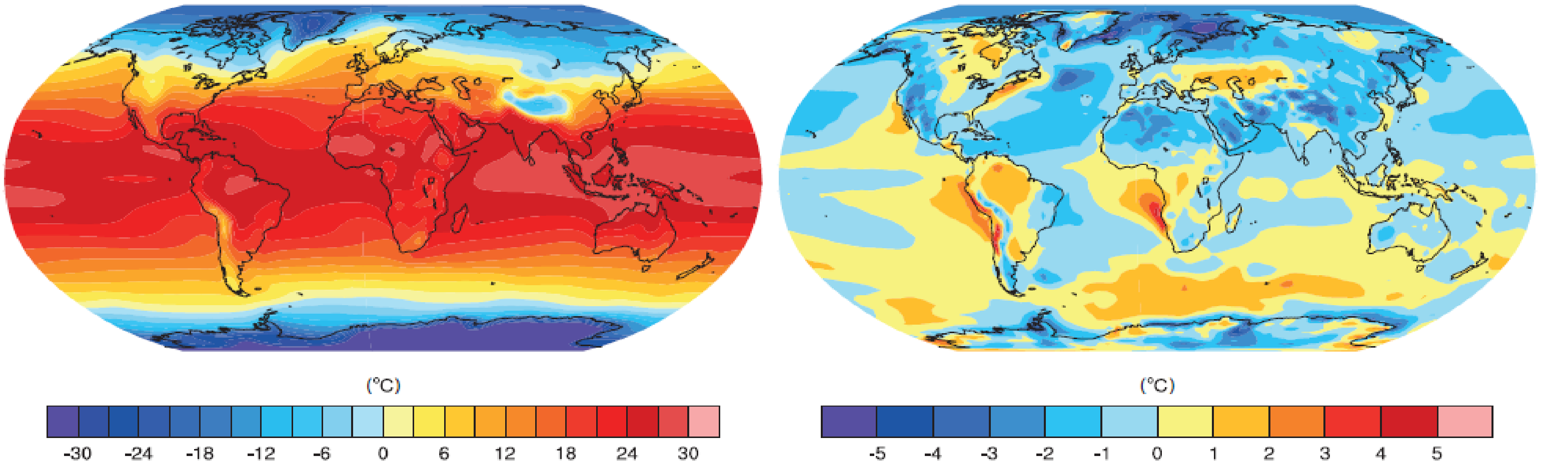
Results- Temperature



(a) Multi Model Mean Surface Temperature

(b) Multi Model Mean Bias

(c) Multi Model Mean of Absolute Error

(d) Mean Reanalysis Inconsistency

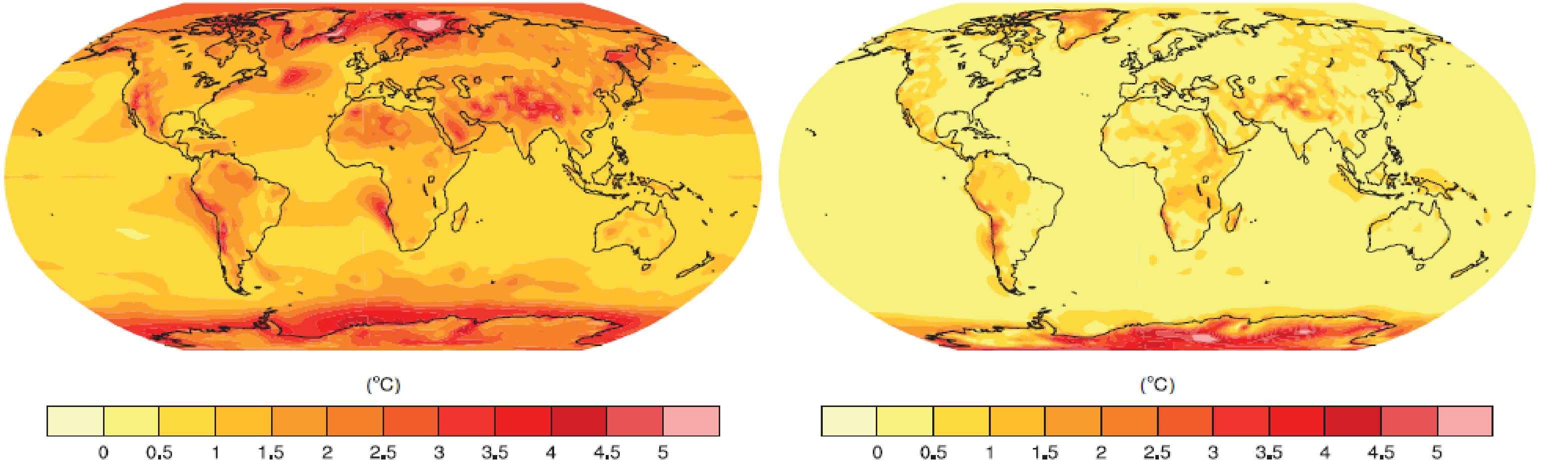
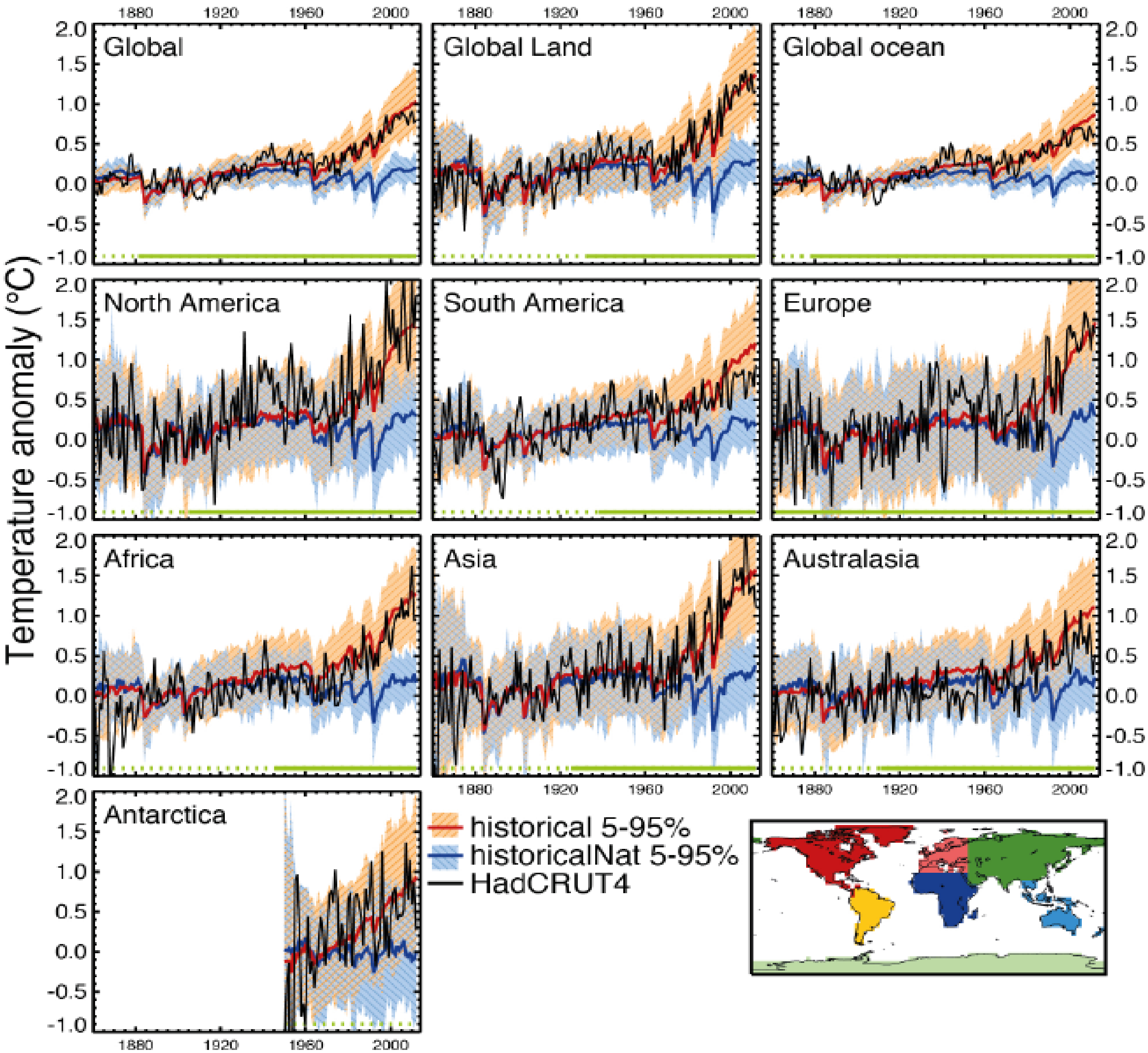


Figure 9.2 | Annual-mean surface (2 m) air temperature (°C) for the period 1980–2005. (a) Multi-model (ensemble) mean constructed with one realization of all available models used in the CMIP5 historical experiment. (b) Multi-model-mean bias as the difference between the CMIP5 multi-model mean and the climatology from ECMWF reanalysis of the global atmosphere and surface conditions (ERA)-Interim (Dee et al., 2011); see Table 9.3. (c) Mean absolute model error with respect to the climatology from ERA-Interim. (d) Mean inconsistency between ERA-Interim, ERA 40-year reanalysis (ERA40) and Japanese 25-year ReAnalysis (JRA-25) products as the mean of the absolute pairwise differences between those fields for their common period (1979–2001).

Taken from IPCC report (AR5, Chapter 9)

Global
Global Land
Global ocean
North America
South America
Europe
Africa
Asia
Australasia
Antarctica
Temperature anomaly (°C)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
1880
1920
1960
2000
historical 5-95%
historicalNat 5-95%
HadCRUT4

Photovoltaics

Lecture - Learning Objectives

At the end of this lecture you should be able to:

- Understand light absorption and how it applies to solar cells.
- Explain why we can not get 100% efficiency from our solar cells and denote where the losses are coming from.
- Understand what parameters makes a material a good solar cell.
- Understand where practical losses are coming from in 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.*

Ambitious PV system goals

Ambition: Cost effective grid power from PV

Requirements:

Utility system costs: C_s ~1 \$/W   Currently ~ 3.5 \$/W

Reliability: ~ 30 yrs

Efficiency: $\eta \geq 25\%$ (!)

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

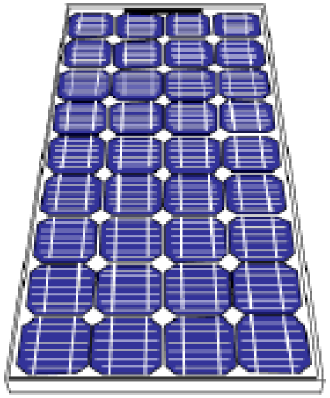
Materials: Earth abundant, preferably non-toxic, recyclable

Module cost: ~ 0.5 \$/W   Currently ~ 1.7 \$/W

Cell cost: ~ 0.25 \$/W   Currently ~ 1 \$/W

+ affordable energy storage

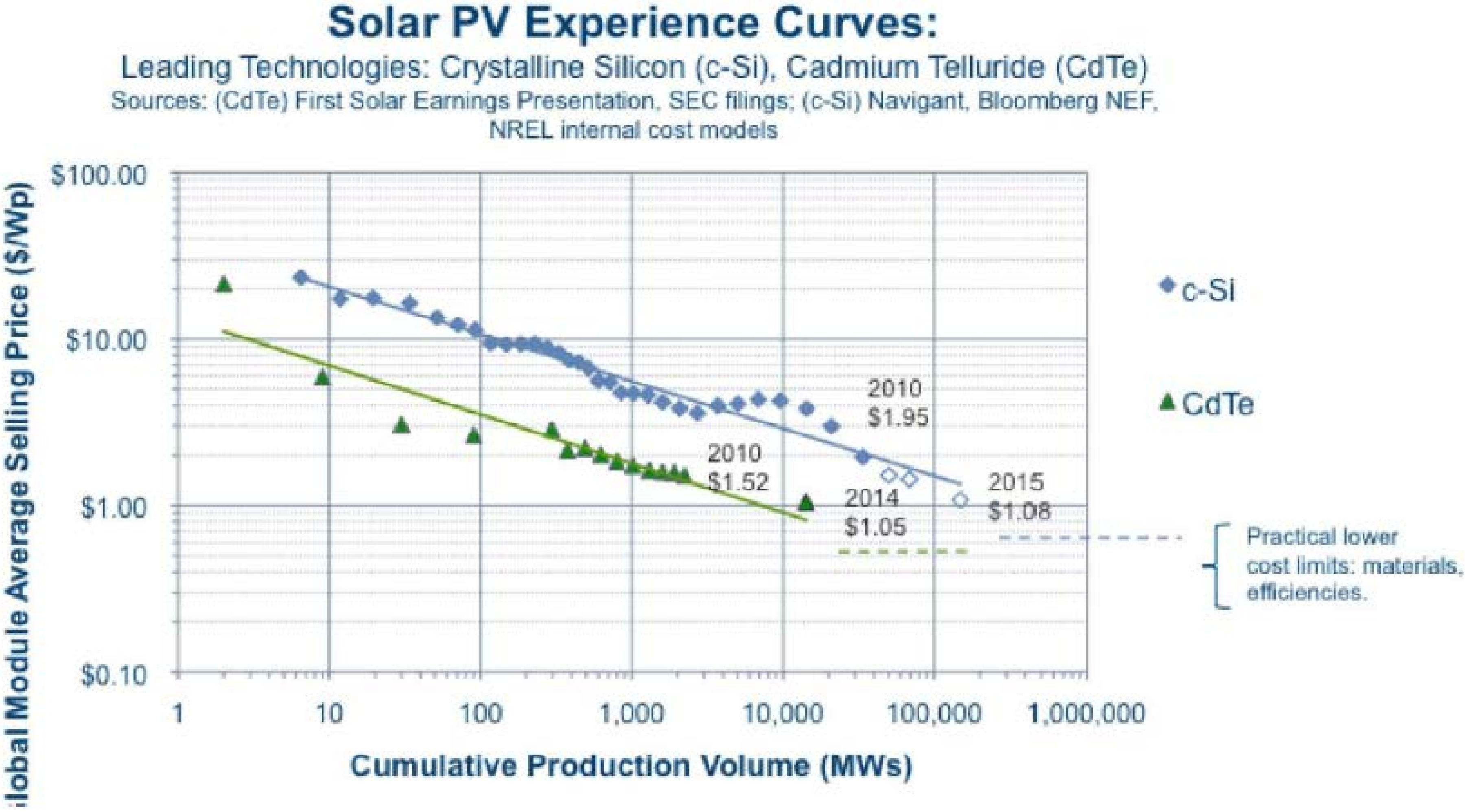
PV cell



PV module

PV system (Nellis Air Base, US)

PV learning curve



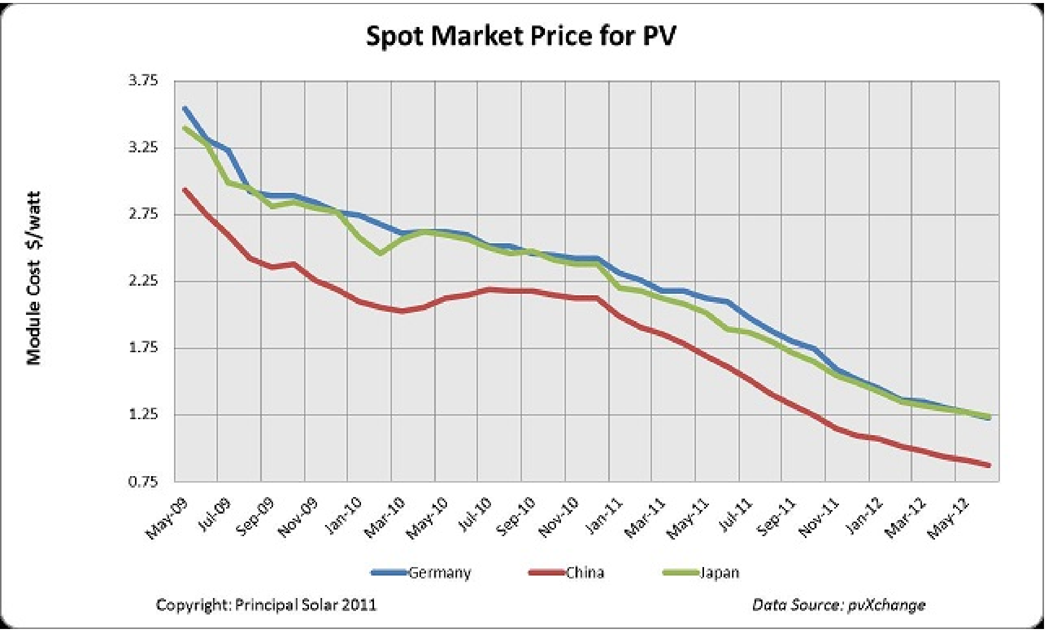
Solar PV Experience Curves:

Leading Technologies: Crystalline Silicon (c-Si), Cadmium Telluride (CdTe)

Sources: (CdTe) First Solar Earnings Presentation, SEC filings; (c-Si) Navigant, Bloomberg NEF, NREL internal cost models

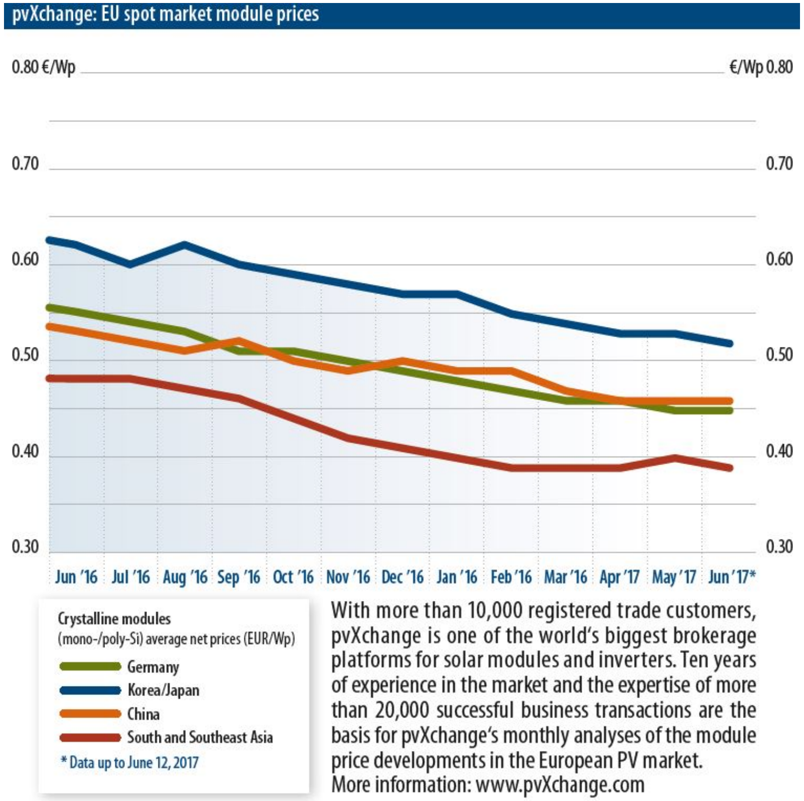
Solar Cell Costs

- They have dropped ridiculously in the last 8 years.
- The top ~10 biggest companies for Si solar cells all are from China.
- National grids are getting solar cells pricing at 0.03 $/kWh



Copyright: Principal Solar 2011

Data Source: pvXchange



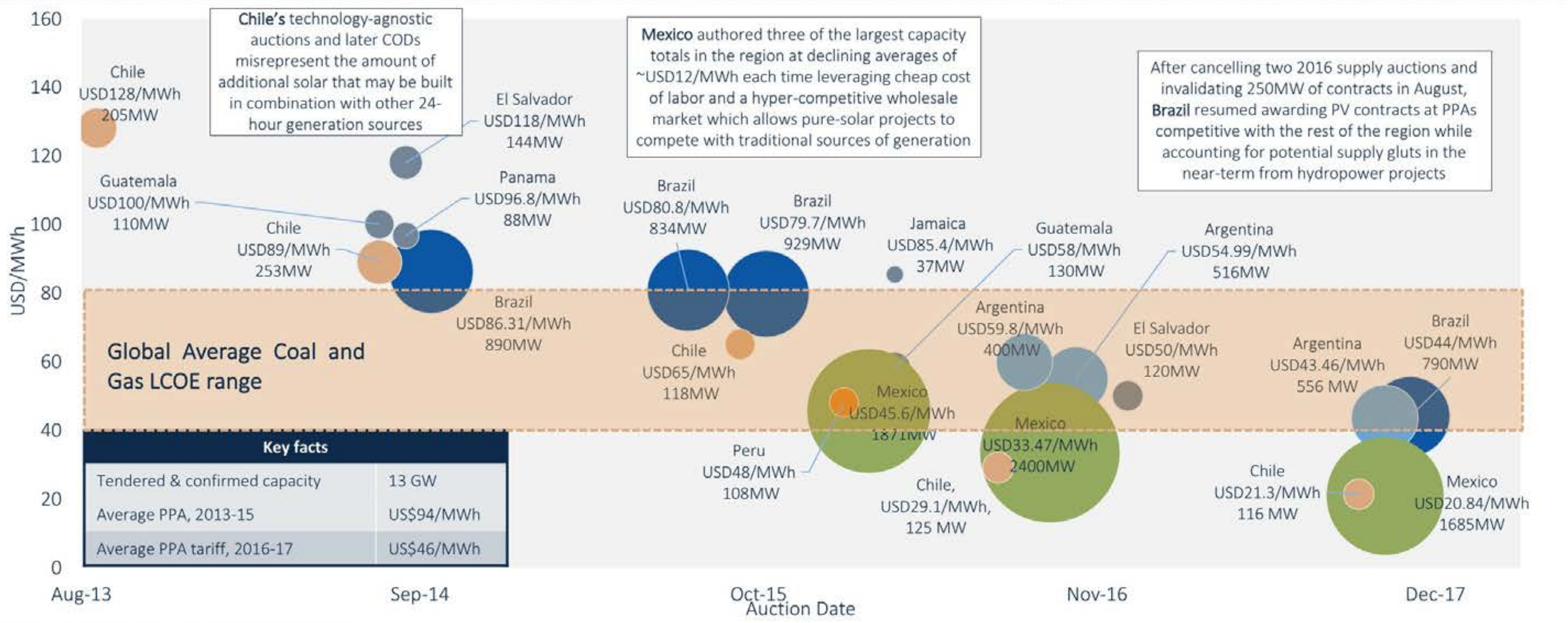
* Data up to June 12, 2017

With more than 10,000 registered trade customers, pvXchange is one of the world's biggest brokerage platforms for solar modules and inverters. Ten years of experience in the market and the expertise of more than 20,000 successful business transactions are the basis for pvXchange's monthly analyses of the module price developments in the European PV market.
More information: www.pvXchange.com

Reverse Auctions

- 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

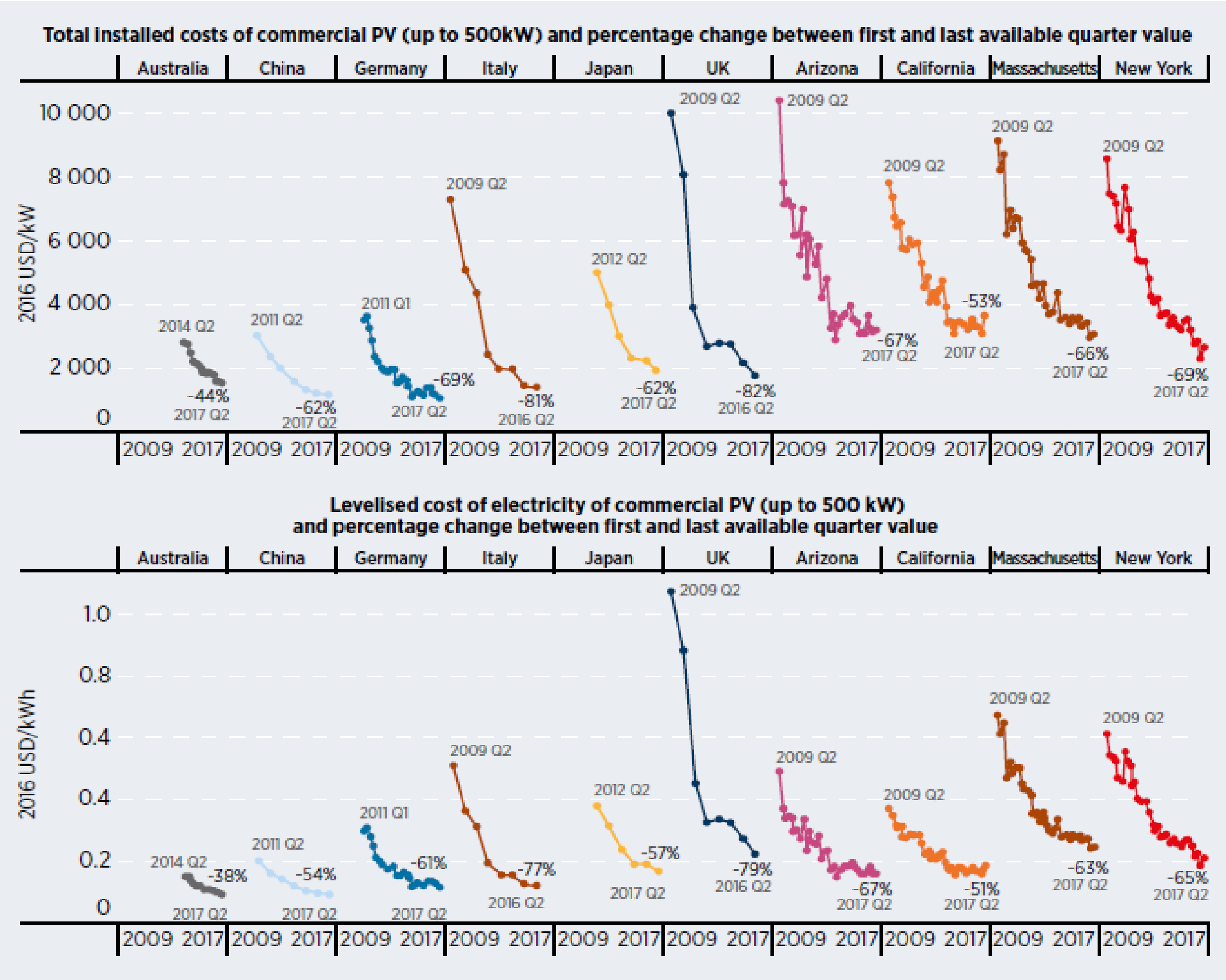
After cancelling two 2016 supply auctions and invalidating 250MW of contracts in August, **Brazil** resumed awarding PV contracts at PPAs competitive with the rest of the region while accounting for potential supply gluts in the near-term from hydropower projects

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*

Reverse Auctions

- Solar prices are dropping prices across all countries



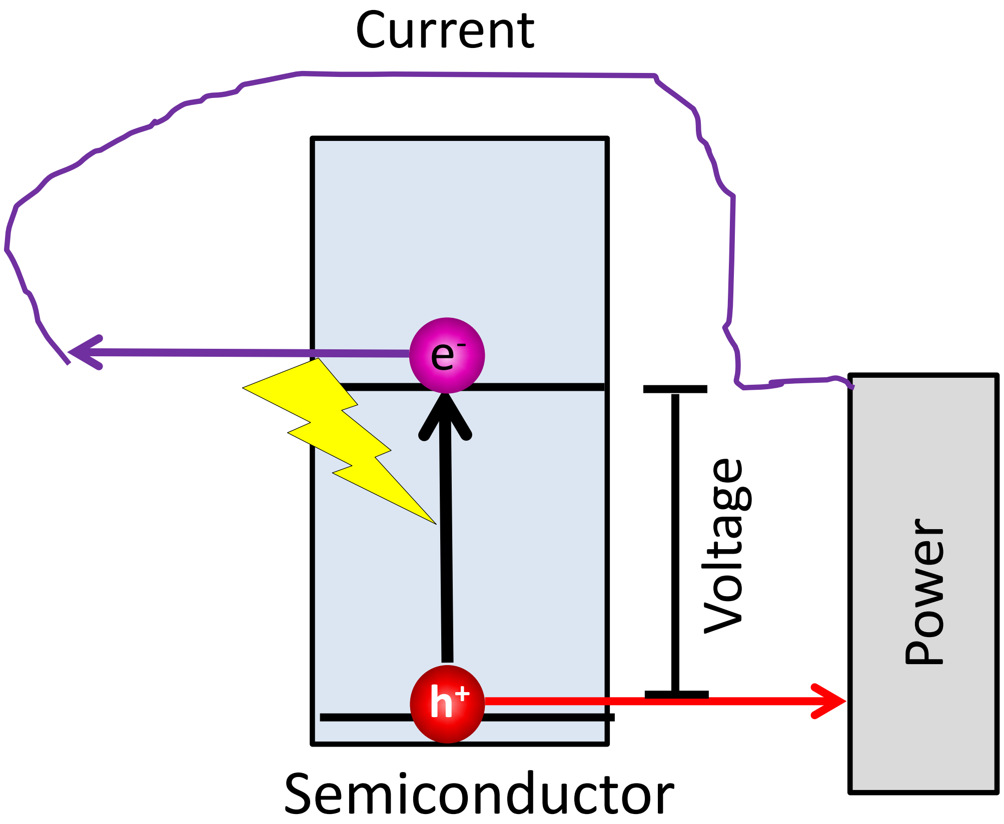
http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Jan/IRENA_2017_Power_Costs_2018.pdf

Physics of Photovoltaics

- Why is it thermodynamically impossible to get 100% efficiency photovoltaics?
- What is the maximum efficiency we can get?
- How do we get that efficiency?
- Can we make it cheap?

Solar cells explained in 2 minutes

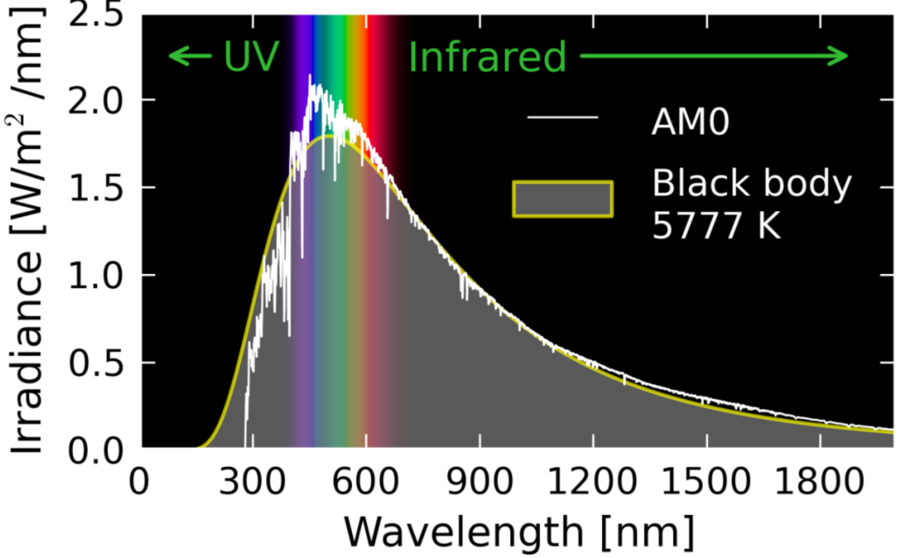
- From a first order theory we should be able to get power according to the voltage and current



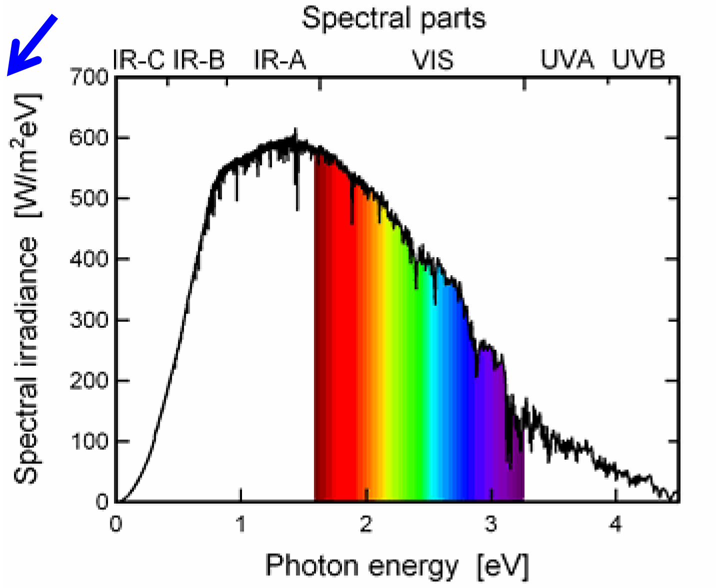
Visible Light

- 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:

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



Per nm of wavelength



Per eV of photon energy

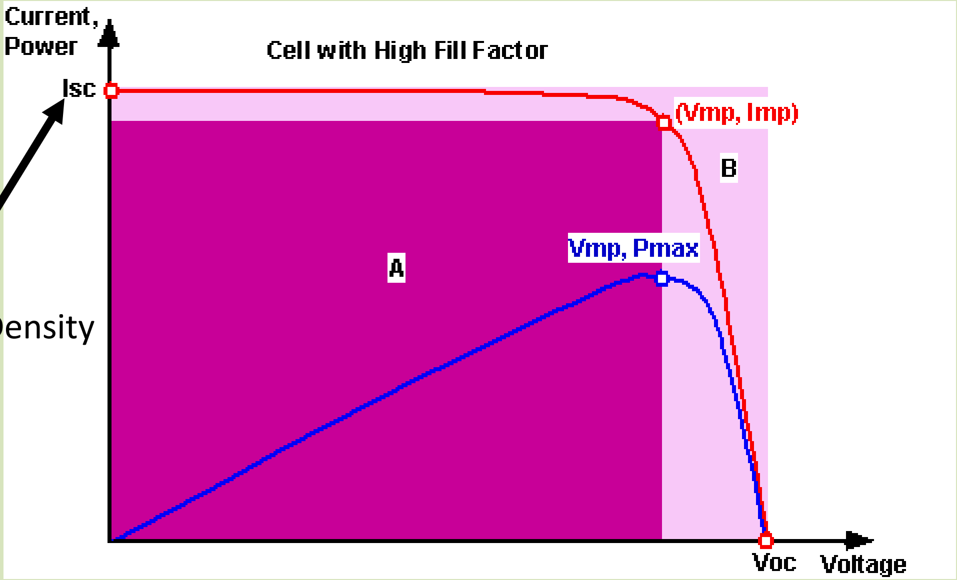
Relating voltage to current

- We want power 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

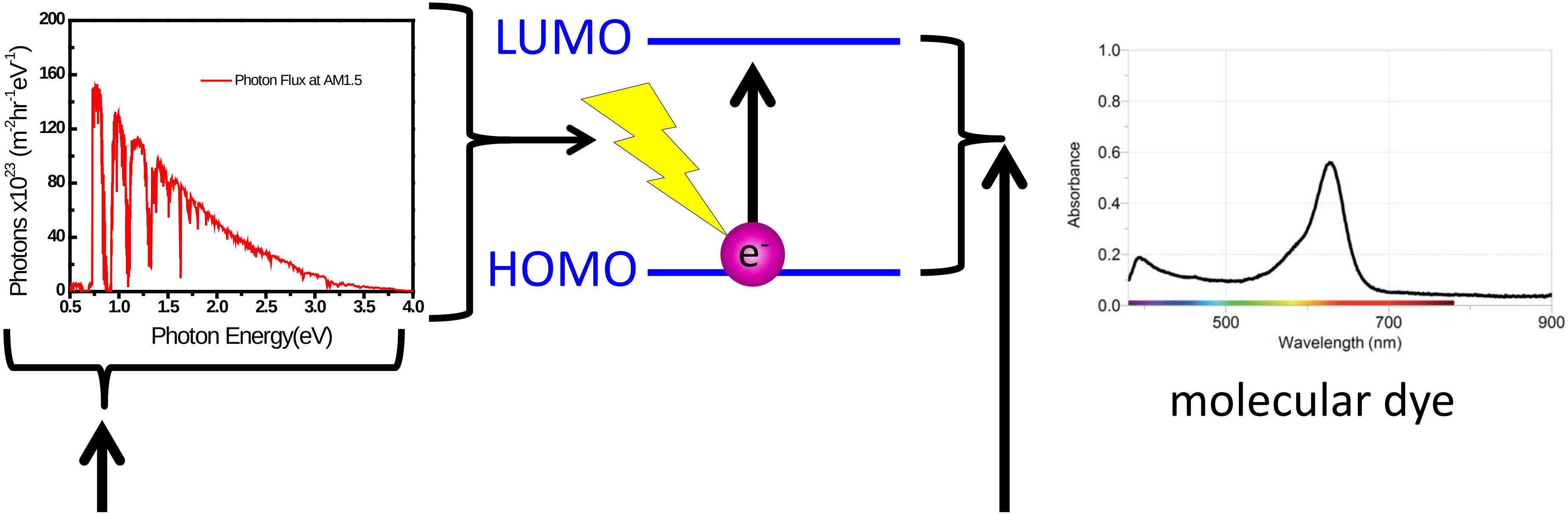
$$FF = \frac{J_{mp} V_{mp}}{J_{sc} V_{oc}}$$

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

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

Photoabsorption from Molecules

- Molecular photocatalysts have distinct energy levels.



molecular dye

This photon energy needs to match this energy gap.

- Molecular photocatalyst only absorb efficiently at one wavelength.

Size of photoabsorber molecule

- As molecules gets larger, they transition from molecular orbitals to groups of orbitals.

- For large particles, these simply become bands

- Most photoabsorbers are either:
  - molecular photocatalysts
    (mw < 300 g/mol)
  - semiconductors
    (mw > 10,000 g/mol)

- It is possible to make some intermediate range catalysts due to quantization.

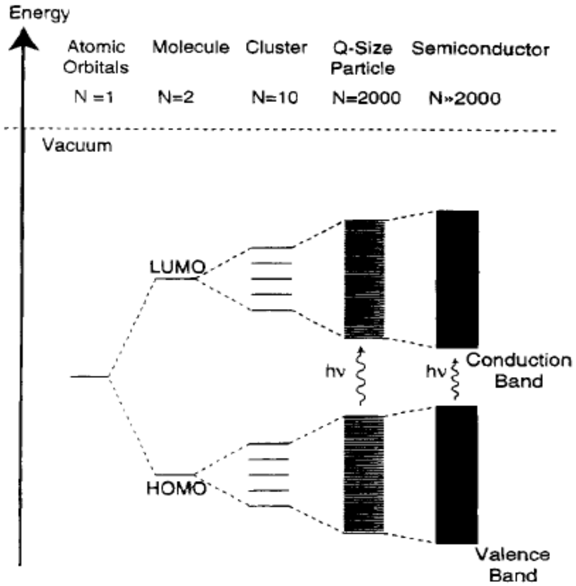
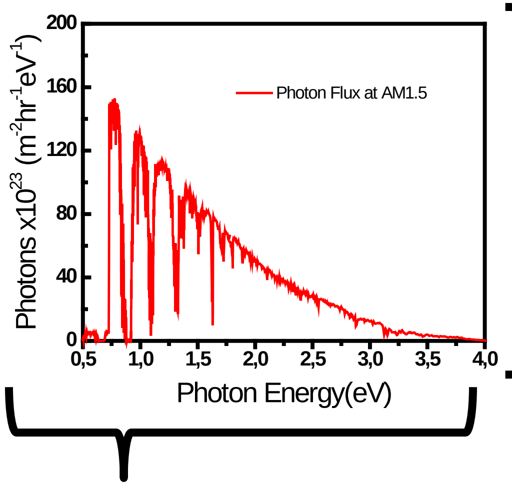


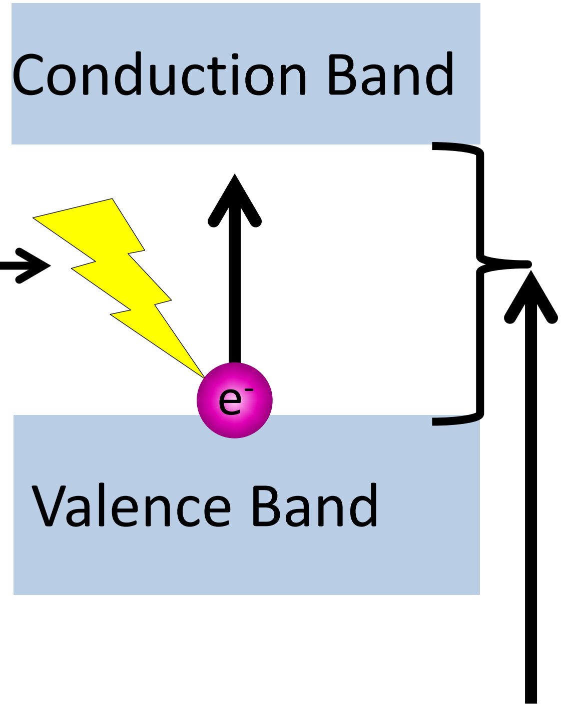
Figure 6. MO model for particle growth for N monomeric units. The spacing of the energy levels (i.e., density states) varies among systems.

Hoffmann, Chem. Rev. 1995

Semiconductor photocatalysts

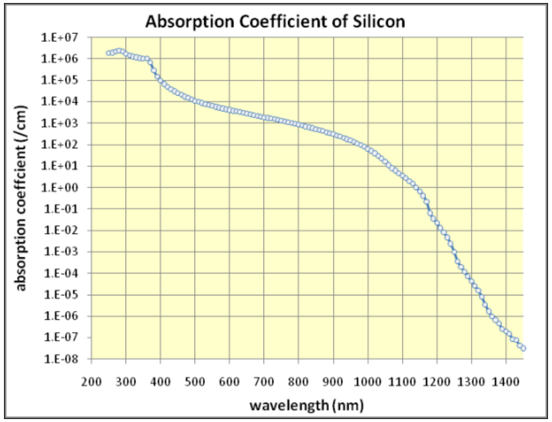
- Semiconductors have bands rather than distinct levels





Conduction Band

Valence Band

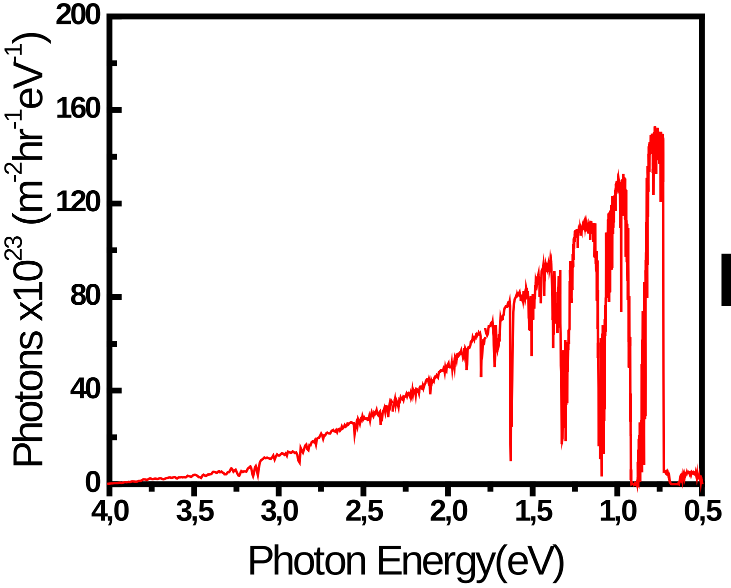


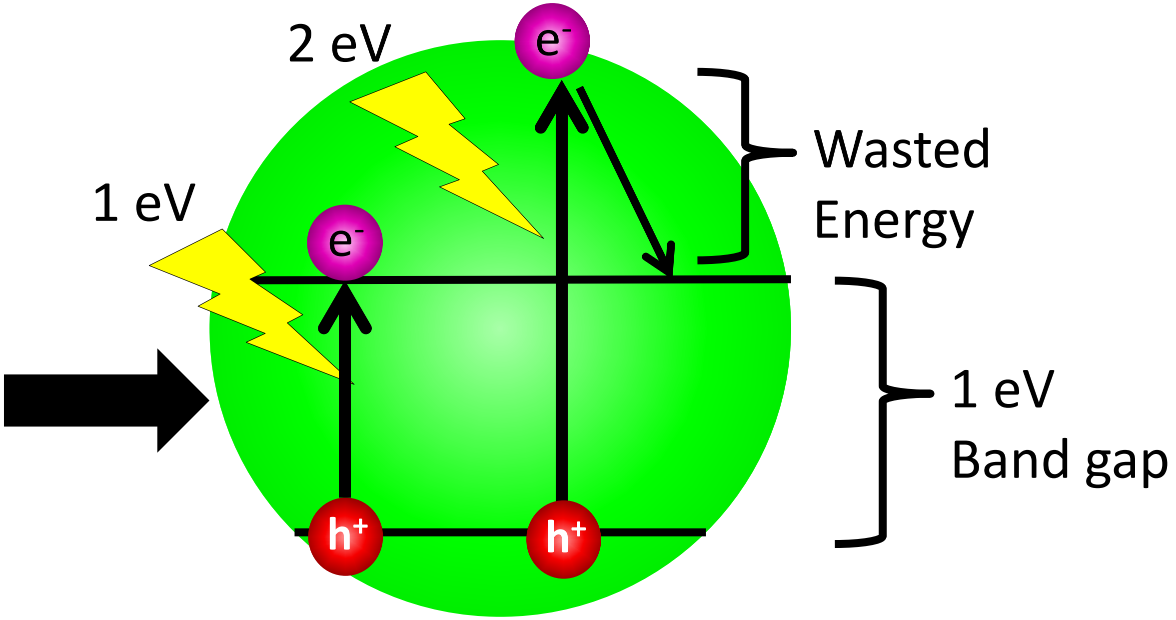
This photon energy needs to roughly match this energy gap.

- *The energy difference between the valence and conduction band is called the band gap (E_g).*
- Semiconductors can absorb a much broader range of light.

Fundamental issue with photoabsorption

- A photon with an energy higher than the bandgap will produce an electron in a very high energy level in the conduction band.
- This electron will immediately transfer to the lowest level in the conduction band.
- Thus the excess energy from the photon is lost.

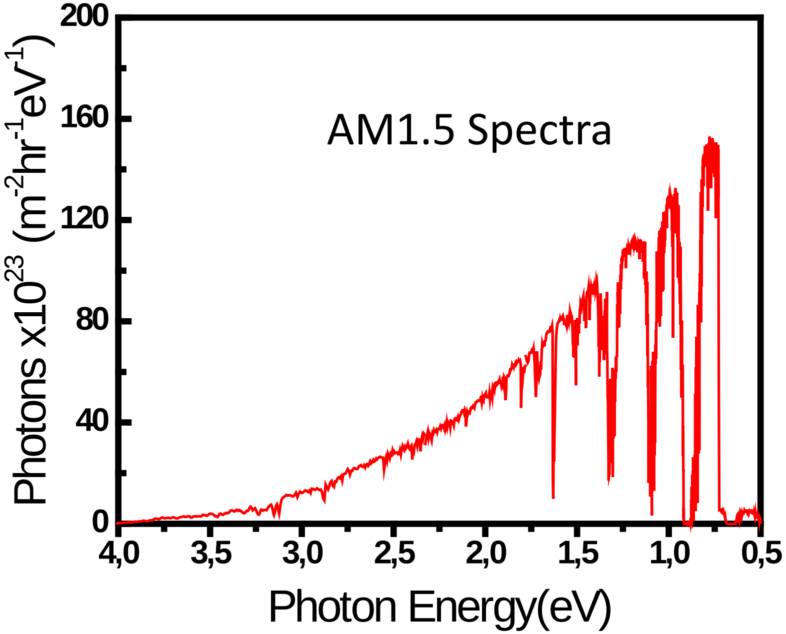




Efficiency

- The input is simply an integration of the photons multiplied by their energy.
- P_{out} is the amount of power from your solar cell.

n(E)= # of electrons at a given energy



$$Efficiency = \frac{P_{out}}{P_{in}}$$

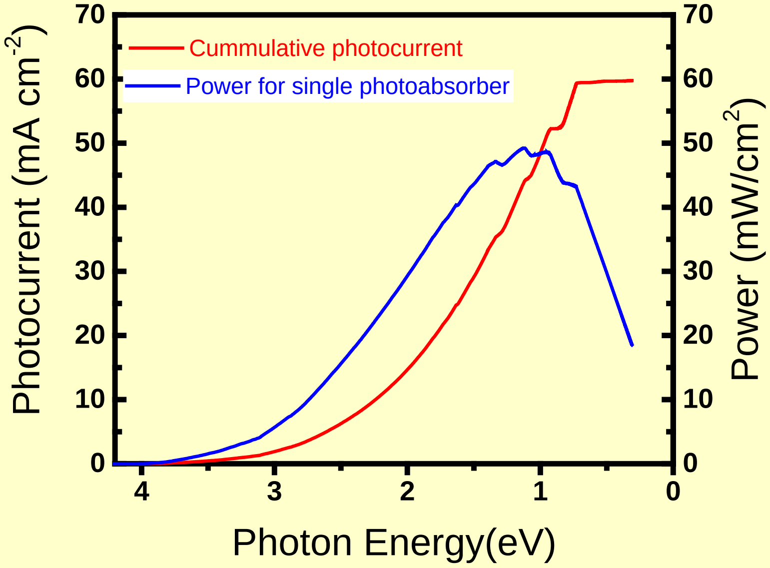
$$P_{in} = \int_0^E n(E)dE$$

$$P_{out} = iV$$

Maximum efficiency- 1 photon cell

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

Maximum P_{out}



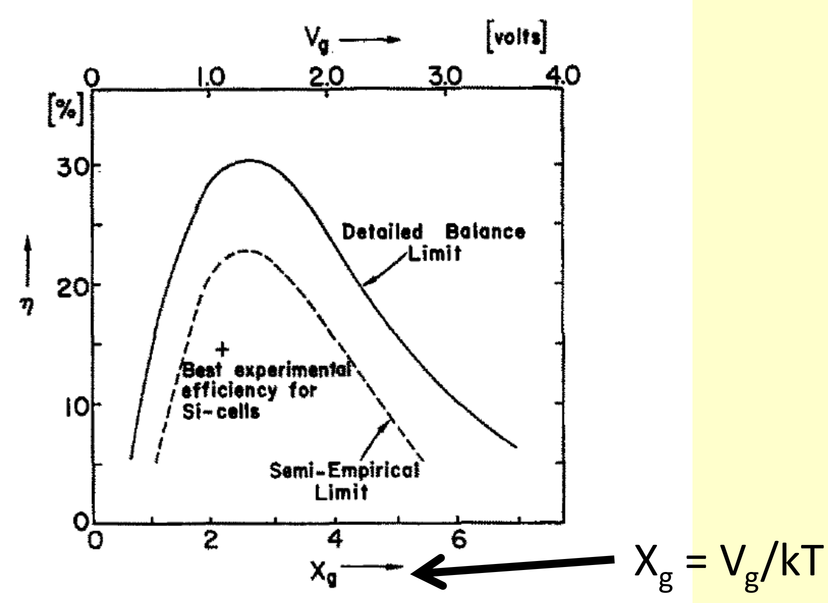


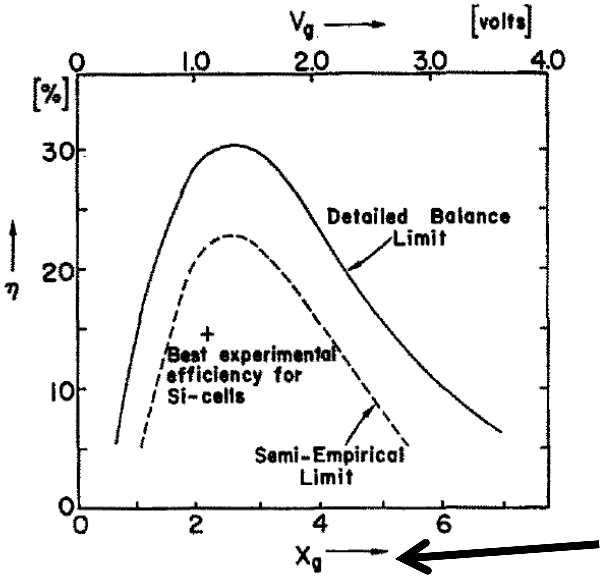
FIG. 1. Comparison of the "semiempirical limit" of efficiency of solar cells with the "detailed balance limit," derived in this paper. + represents the "best experiment efficiency to date" for silicon cells. (See footnote 6.)

Shockley and Queisser, J. Appl. Phys. 1961

What efficiency loss aren't we including?

Maximum efficiency- Shockley-Queisser

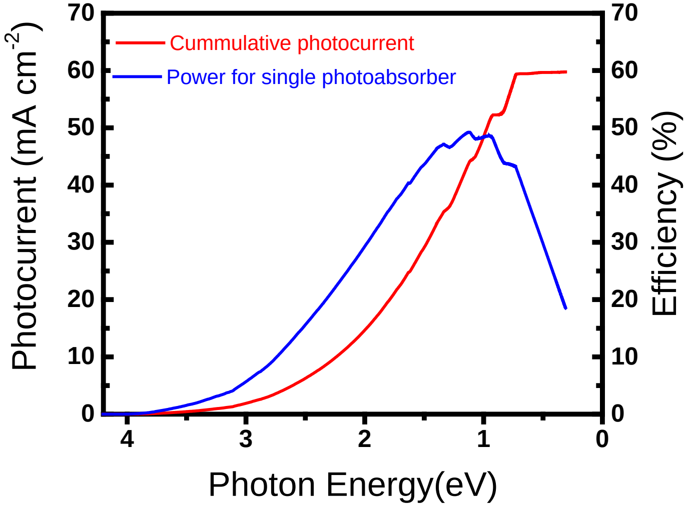
- Answer- Thermodynamics. We have losses due to both the 1st and 2nd law of thermodynamics.
- Shockley-Queisser did a much more thorough analysis to determine maximum efficiency balance.



$X_g = V_g/kT$

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



Our 1st order approximation of maximum efficiency

Blackbody radiation from Sun

- From blackbody radiation, we have

$$I_E dE = \frac{2\pi v^3}{c^2}\frac{1}{\left(e^{hv/_{kT}} - 1\right)}dE \quad \xrightarrow{\quad E = hv \quad} \quad I_E = \frac{2\pi}{h^3c^2}\frac{E^3}{\left(e^{hv/_{kT}} - 1\right)}$$

- Realize $\frac{I_E}{E} = \#\ of\ Photons/s \equiv \beta$

$$\beta_{sun}(E)\mathrm{dE} = \frac{2\pi}{h^3c^2}\left(\frac{E^2}{exp^{E/_{k_BT}} - 1}\right)\mathrm{dE}$$

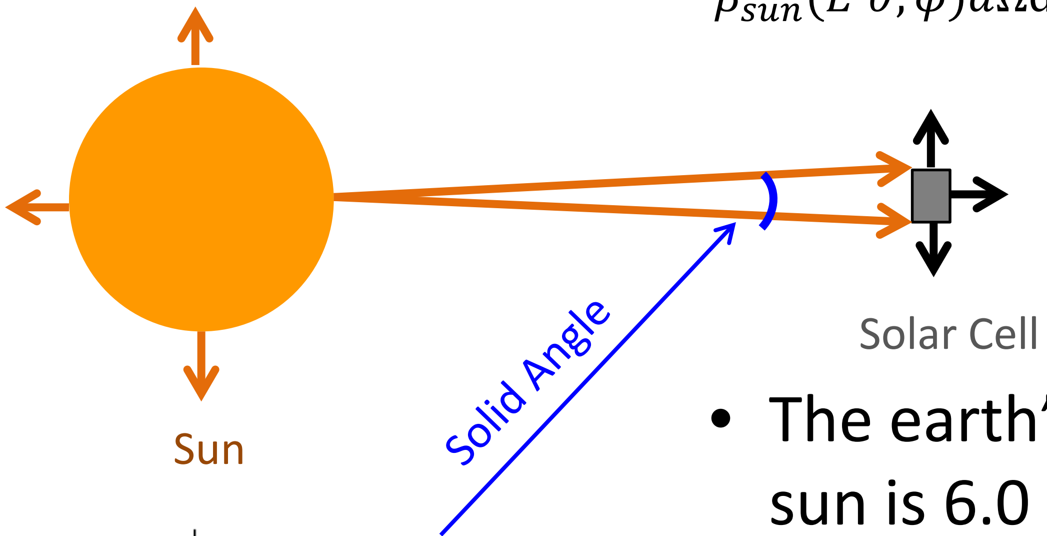
- We do need to compensate though for the fact that we are a given distance away from the sun.

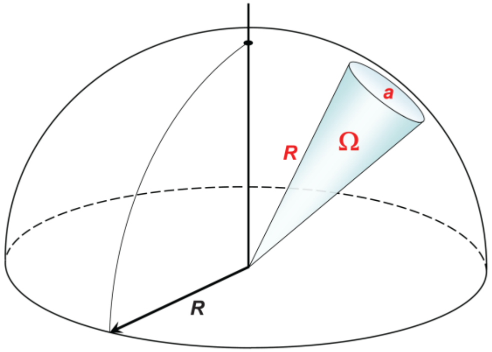
- This can be done by noting the Sun-Earth solid angle

Including solid angle into radiation

- The black-body radiation is a function of angle:

$$\beta_{sun}(E\ \theta,\phi)d\Omega\mathrm{dE} = \frac{2}{h^3c^2}\left(\frac{E^2}{exp^{E/k_BT}-1}\right)d\Omega\mathrm{dE}$$





- The earth's solid angle to the sun is 6.0 x 10^{-5} radians.

- Thus β_{sun} at earth is:

$$\beta_{sun}(E\ \theta,\phi)\ = (6\times10^{-5})\times\frac{2}{h^3c^2}\left(\frac{E^2}{exp^{E/k_BT}-1}\right)$$

where T=5760C

Blackbody radiation from solar cells

- Our solar cells can blackbody radiate just like the sun

$$b_{emit}(E,\Delta\mu) = \frac{2F_a}{h^3c^2}\left(\frac{E^2}{exp^{(E-\Delta\mu)/k_BT} - 1}\right)$$

- The emission is a function of potential (i.e. voltage) and temperature (298 K).

- The higher the voltage the more emitted radiation

- The F_a term is 2π if we emit in all directions, but will be π if we have a reflector on the backside of our solar cell.

- We don’t want our solar cell to emit radiation, we want to absorb it.

Loss due to emission

- Our loss in terms of photons / current can be denoted as followed:

$$J_{emission} = qb_{emit}\varepsilon$$

- Where ε is our emission coefficient

- We could also include a reflection term (1-R) to $J_{emission}$ if we wanted to assume that some of the emitted photons can’t get out.

Concept Check

Which will be larger:

a) absorption coefficient

b) emission coefficient

c) they will be the same

d) it is material dependent

Photocurrent during irradiation

- During irradiation, we have a net 'photocurrent' that is our absorption from the sun plus absorption from ambient (b_{amb}) minus our emission from our device.

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

where R stands for reflection and *q* is an elementary charge. This assumes 100% above band gap photon absorption

- b_{amb} is ambient radiation from the earth (i.e. dark radiation)

- Lets define a short circuit current (assuming 100% absorption and collection of charge):

- At short circuit $\Delta\mu = 0$, and the last 2 terms cancel each other out

$$J_{sc} = q \int_{E_G}^{\infty} (1 - R(E))\, b_{sun} dE$$

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:

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

$$j_0 = \left(n^2_{r,top} + n^2_{r,bottom}\right) qA\,\frac{2\pi kT}{h^3c^2} \times \left({E_g}^2 + 2kTE_g + (kT)^2\right) \times \exp\left(\frac{-E_g}{kT}\right)$$

Index of refraction issues

Diode Equation + Device Losses

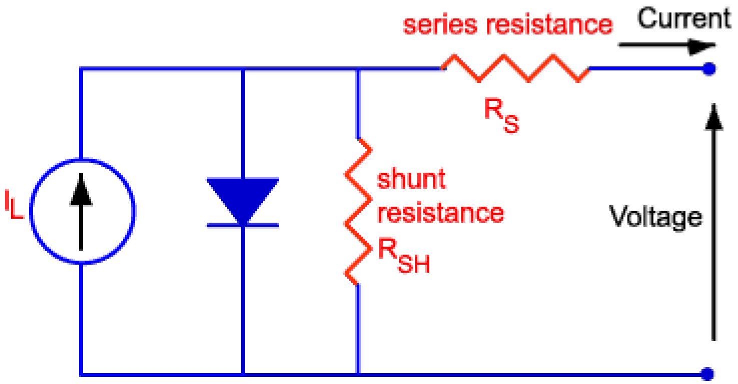
$$J_{net} = J_{sc} - J_0 \left[exp\left(\frac{qV}{kT}\right) - 1 \right]$$

- 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:

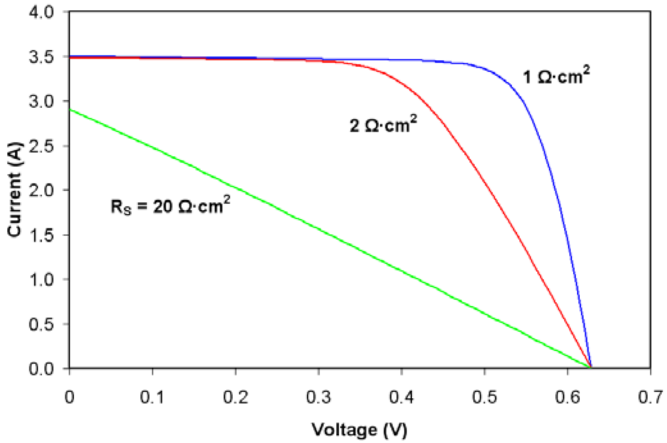
$$J_{net} = J_{sc} - J_0 \left[exp\left(\frac{q(V + J_{net}R_s)}{kT}\right) - 1 \right] + \frac{q(V + J_{net}R_s)}{R_{SH}}$$

Shunt & Series Losses

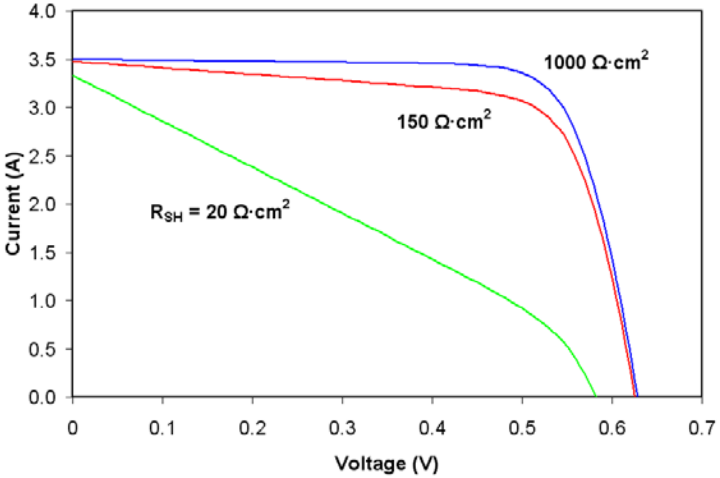
- The circuit for a shunt and series loss solar cell looks as followed:



Effects of Series Losses

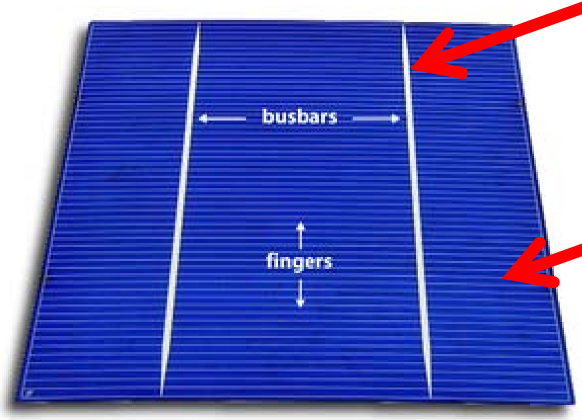


Effects of Shunt Losses



Practical Issues

- Getting electrons out without blocking light can be an annoying issue



Conductive metal (copper or silver)

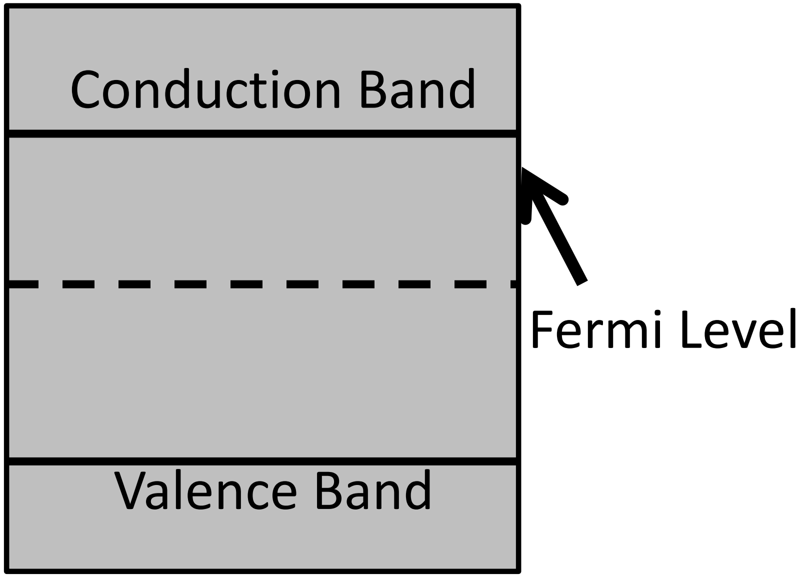
Semiconductors are conductive enough to get out of the semiconductor (10 μm), but not to a conductive contact (10 mm).

- Transparent oxides such as indium tin oxide (ITO) and fluorine doped tin oxide (FTO) were put on top of solar cells to allow good transparency and OK conductivity.
- Both ITO and FTO are slightly expensive.

Break

Semiconductor Fundamentals- quick review

- Valence band (VB) are filled energy states, conduction bands (CB) are empty states.
- The Fermi level is the chemical potential of the system.
- Semiconductor have a Fermi Level where there are no electronic states
- Thus a certain percentage of electrons must be jump into the conduction band to achieve thermodynamic equilibrium



K-space

- K-Space is basically inverse wavelength or momentum space

$$E = \frac{hc}{\lambda}$$

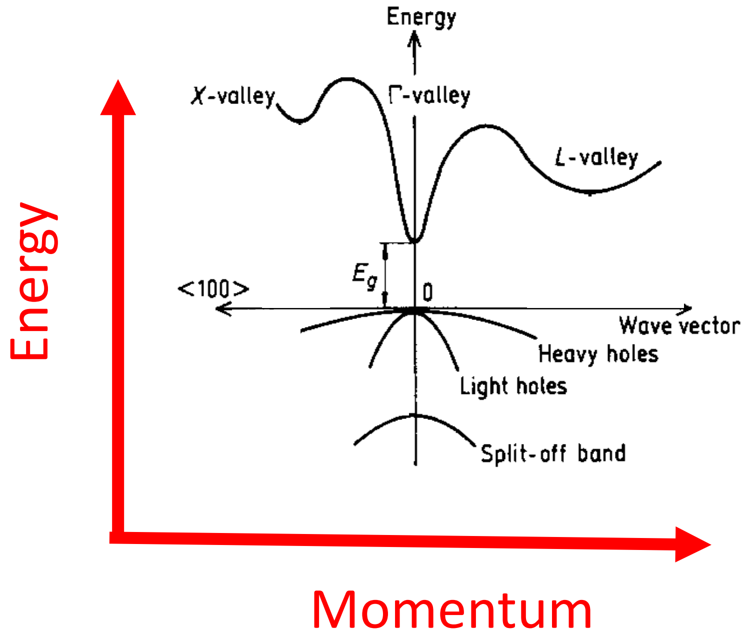
$$E^2 = (pc)^2 + (mc)^2$$ ← From Relativity

$$E^2 = (pc)^2$$ ← Mass less photon

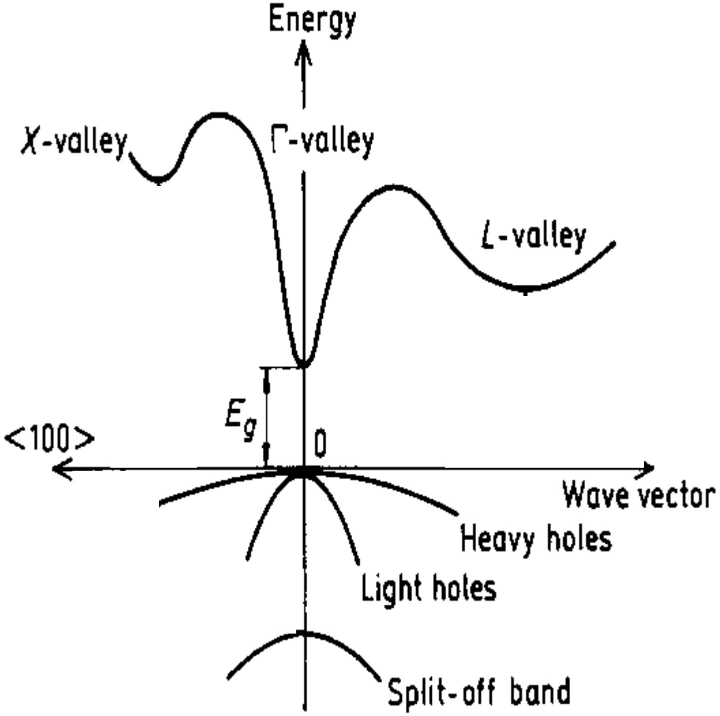
$$\lambda = \frac{h}{p} =$$

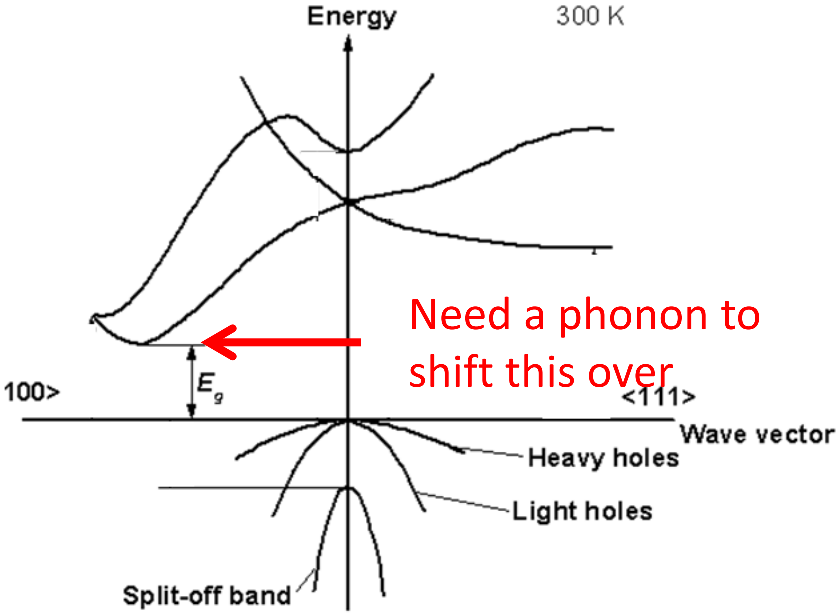
- Define k-space as:

$$k = \frac{2\pi}{\lambda} = p\,\frac{h}{2\pi}$$



Direct versus Indirect Semiconductors





Need a phonon to shift this over

Direct Band Gap

$$\alpha(h\nu) \propto A \times (E_{Photon} - E_G)^{0.5}$$

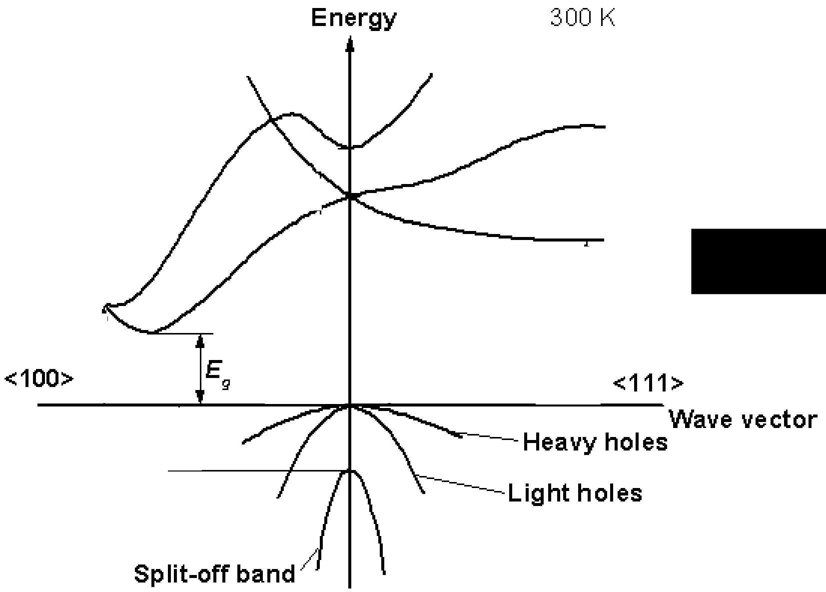
Indirect Band Gap

$$\alpha(h\nu) \propto A \times (E_{Photon} - E_G)^{2}$$

α is the absorption coefficient

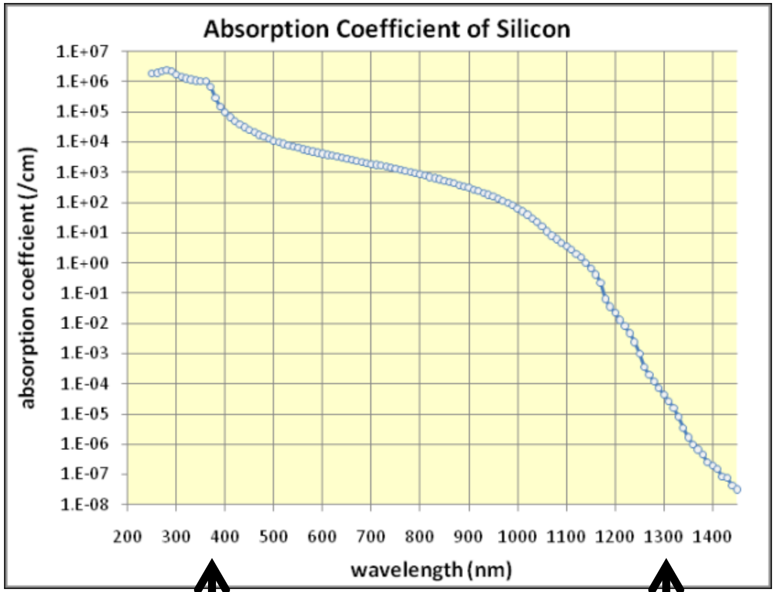
Silicon’s Band Structure

- Silicon is an indirect band gap material.
- Indirect bandgaps need phonons (i.e. vibrations) to allow for absorption.
- This results in less efficient absorption.



Actual band structure of Si

http://www.ioffe.ru/SVA/NSM/Semicond/Si/



High energy
(efficient)

Low energy
(inefficient)

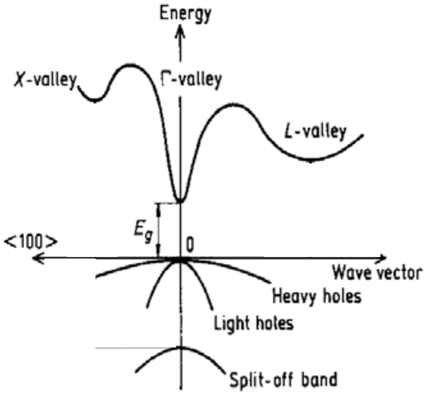
Common Semiconductors

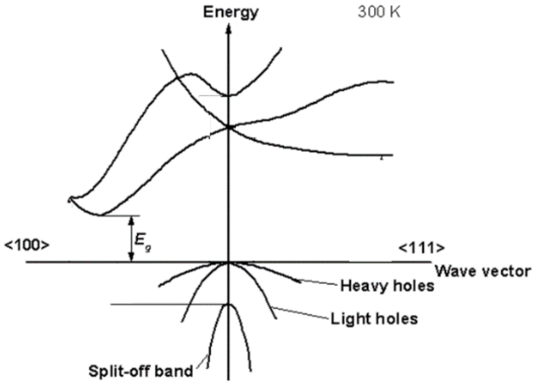
Direct

Material	Bandgap (eV)
GaAs	1.4
Amorphous Si	1.6-2.0
CdS	2.4
CdTe	1.5
$Cu(InGa)Se_2$	1.7

Indirect

Material	Bandgap (eV)
Si	1.1
TiO_2	3.0
SiC	2.3
GaP	2.3
AlP	2.45





Source: http://en.wikipedia.org/wiki/List_of_semiconductor_materials

Beer-Lambert Law

- Beer's Law allows us to determine light absorption (@ a given wavelength) as a function of semiconductor thickness.

$$I(x) = I_0 \times exp^{(-\alpha\Delta x)}$$

$$A = -ln\left(\frac{I(x)}{I_0}\right) = \alpha\Delta x$$

I= intensity
I_0= Initial Intensity
α =absorption coefficient
Δx = thickness
A = Absorbance

What is the units of Absorbance?

- When dealing with liquids in solution (such as chlorophyll in an organic medium for photosythesis) there is a slightly modified version.

$$A = -Ln\left(\frac{I(x)}{I_0}\right) = \varepsilon CL$$

ε =extinction coefficient
C = concentration (Mol/L)
L = length (cm)

$$I(x) = I_0 \times exp^{-\alpha \Delta x}$$

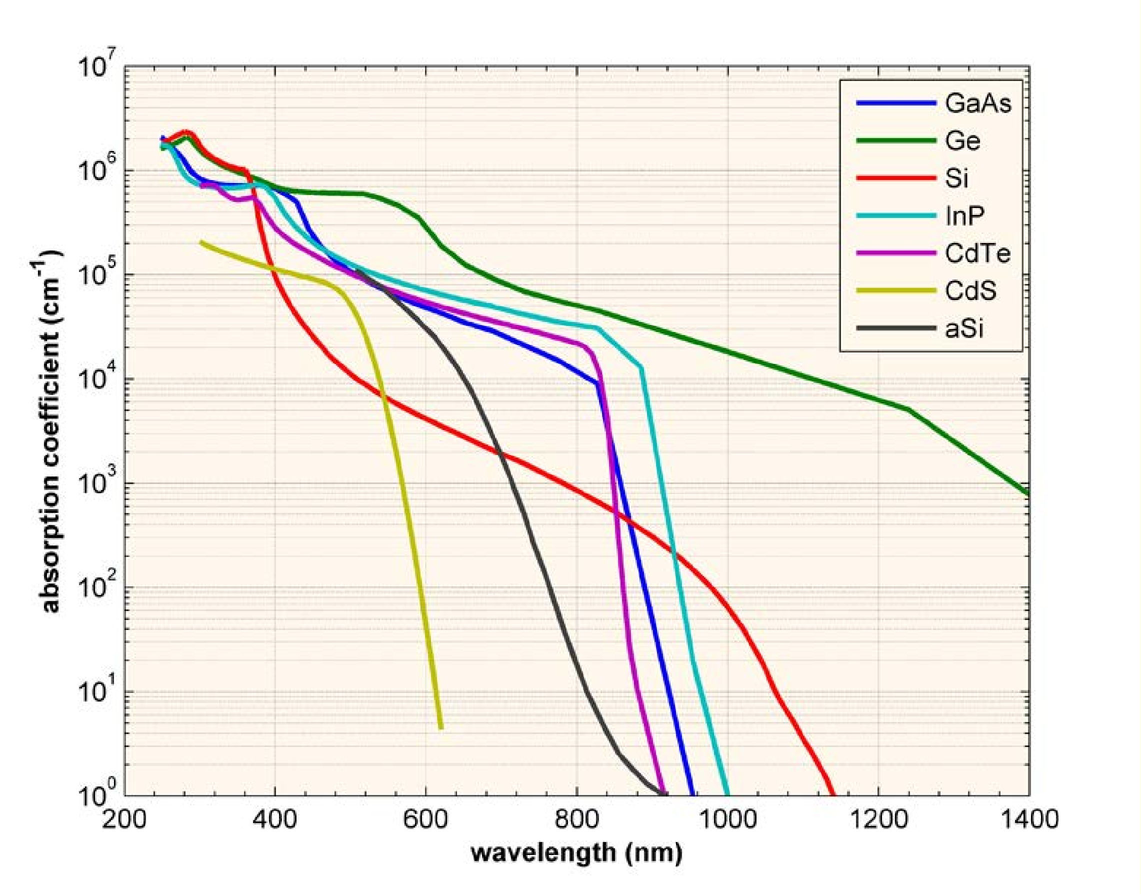


Figure from Pveducation.org

In a slab of Si, how deep into the Si do we need to go to absorb 90% of the 400 nm photons? How about the 90% of the 1000 nm photons?-

Other Information from Band Structure

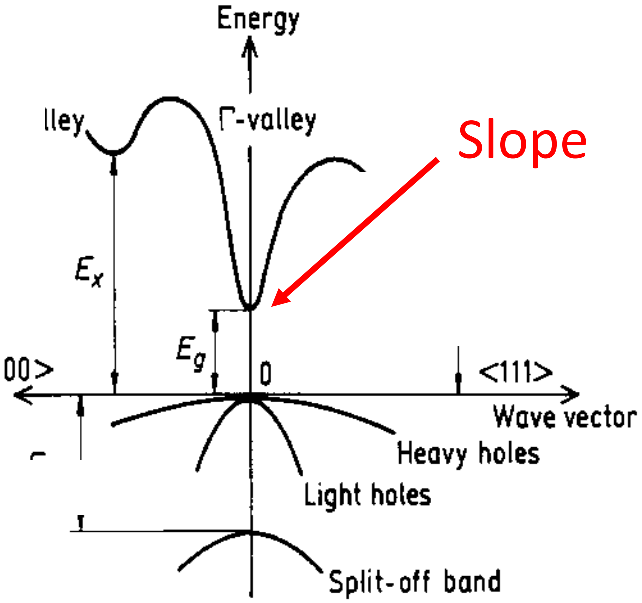
- The inverse of the second derivate (or slope) at the band gap tells us the effective mass

$$m_e^* = \frac{\hbar^2}{\left(\frac{\partial E(k)^2}{\partial k^2}\right)}$$

- The effective mass is in comparison to the mass of an electron in vacuum. This can be greater or less than 1.

- The effective mass of the electrons and holes is usually different

- The larger the effective mass, the slower the electron or hole moves.



Concept Check

An optimal photovoltaic material should have:

a) a flat band structure for both electrons and holes

b) a curvy band structure for both electrons and holes

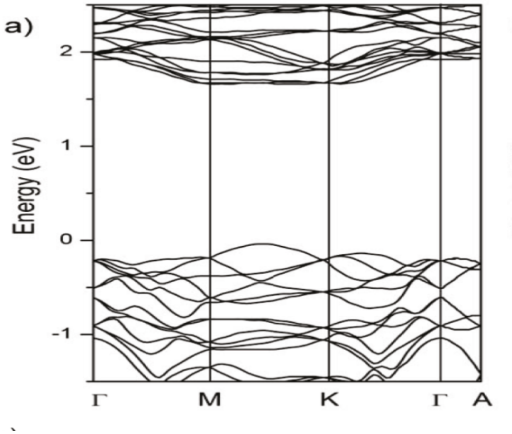
c) a flat band structure for electrons and a curvy band structure for holes

d) a curvy band structure for electrons and a flat band structure for holes

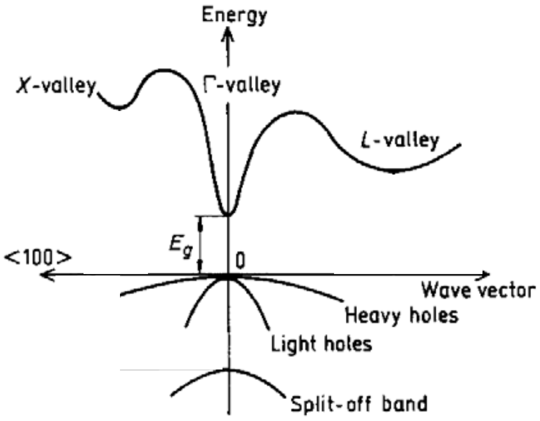
Criteria for fast electron/hole transfer

- By looking at a band structure, we can get an indication whether it is a good material
- Basically the more curvy structure, the faster electrons and holes can move, thus this is typically a better solar cell.

Fe_2O_3



GaAs



Material	**Fe_2O_3**	**GaAs**
Electron Mobility	1.1 $cm^2/V/s$	8,500 $cm^2/V/s$

--References: #1, #2, and #3

More Fundamental Understanding

- If we are going to photoexcite electrons into the conduction band, it would be nice to know how many electronic states are up there.

- The number of electronic states is

In Conduction Band

$$g_c(E) = \frac{1}{2\pi^2}\left(\frac{2m_e^*}{\hbar^2}\right)^{\frac{3}{2}}\left(E - E_{c,0}\right)$$

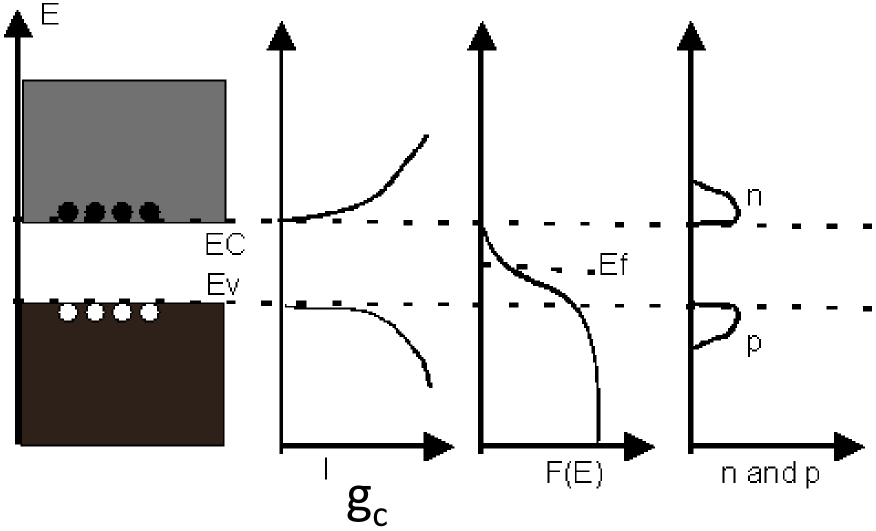
In Valence Band

$$g_c(E) = \frac{1}{2\pi^2}\left(\frac{2m_h^*}{\hbar^2}\right)^{\frac{3}{2}}\left(E_{v,0} - E\right)$$

More Fundamental Understanding

- The electrons in the conduction band or holes in the valence band is the number of states times probability of states being filled.
- The probability is given by Fermi-Dirac statistics

Number of electronic States x Probability states have electrons = Total number of electrons (at a given energy level)



e^- in Conduction Band

$$e^{-} = n = N_c exp^{\left(E_f - E_c\right)/k_bT}$$

Where N_c is:

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

h^+ in Valence Band

$$h^{+} = p = N_v exp^{\left(E_v - E_f\right)/k_bT}$$

Where N_v is:

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

- N_c and N_v are the effective density of states

Physics of a Photovoltage

- By playing around, we can multiply ‘n’ and ‘p’ together

$$np = N_c exp^{\left(E_f - E_c\right)/k_b T} N_v exp^{\left(E_v - E_f\right)/k_b T}$$

$$np = N_c N_v exp^{-\left(E_c - E_v\right)/k_b T}$$

$$np = N_c N_v exp^{-\left(E_g\right)/k_b T}$$

- Since E_g is a set value this must mean *n* x *p* will always be a set value (in the dark).

$$n_i^2 = np = N_c N_v exp^{-\left(E_g\right)/k_b T}$$

Intrinsic Doping

- n_i is referred to as intrinsic doping level.
- Since n_i is only a function of E_g, m_c*, m_v* and T it is actually a material specific property (at a given temperature)
- Below is a list of intrinsic dopant levels for a variety of semiconductors at room tempearture.

Material	**Intrinsic Dopant Density (cm^{-3})**
Si	1.1×10^{10}
Ge	2.4×10^{13}
InP	1.3×10^{7}
GaAs	2.1×10^{6}
InAs	1.0×10^{15}
InSb	2.0×10^{16}

- We can also intentionally dope our semiconductor

Concept Check

I have two materials with a band gap of 1 eV and 2 eV and the same effective mass for e^- and h^+. Which is true?

a) The 1 eV material will have a highereffective density of states and a higher intrinsic dopant density.

b) The 2 eV material will have a larger effective density of states and a higher intrinsic dopant density.

c) The 1 eV material will have the same effective density of states and a higher intrinsic dopant density.

d) The 2 eV material will have a higher effective density of states , but a higher intrinsic dopant density.

Physics of a Photovoltage

- How do we actually get a photovoltage.
- During irradiation we add electron-hole pairs (add *n* and *p*)
- This provides a splitting of the Fermi level

Conduction Band:

$$n = N_c exp^{(E_f - E_c)/k_bT}$$

$$E_{f,e-} = E_c - k_bTLn\left(\frac{n}{N_c}\right)$$

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

m_c- effective mass of electrons

Valence Band:

$$p = N_v exp^{(E_v - E_f)/k_bT}$$

$$E_{f,h+} = E_v + k_bTLn\left(\frac{p}{N_v}\right)$$

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

m_v- effective mass of holes

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

Analysis of Photovoltage

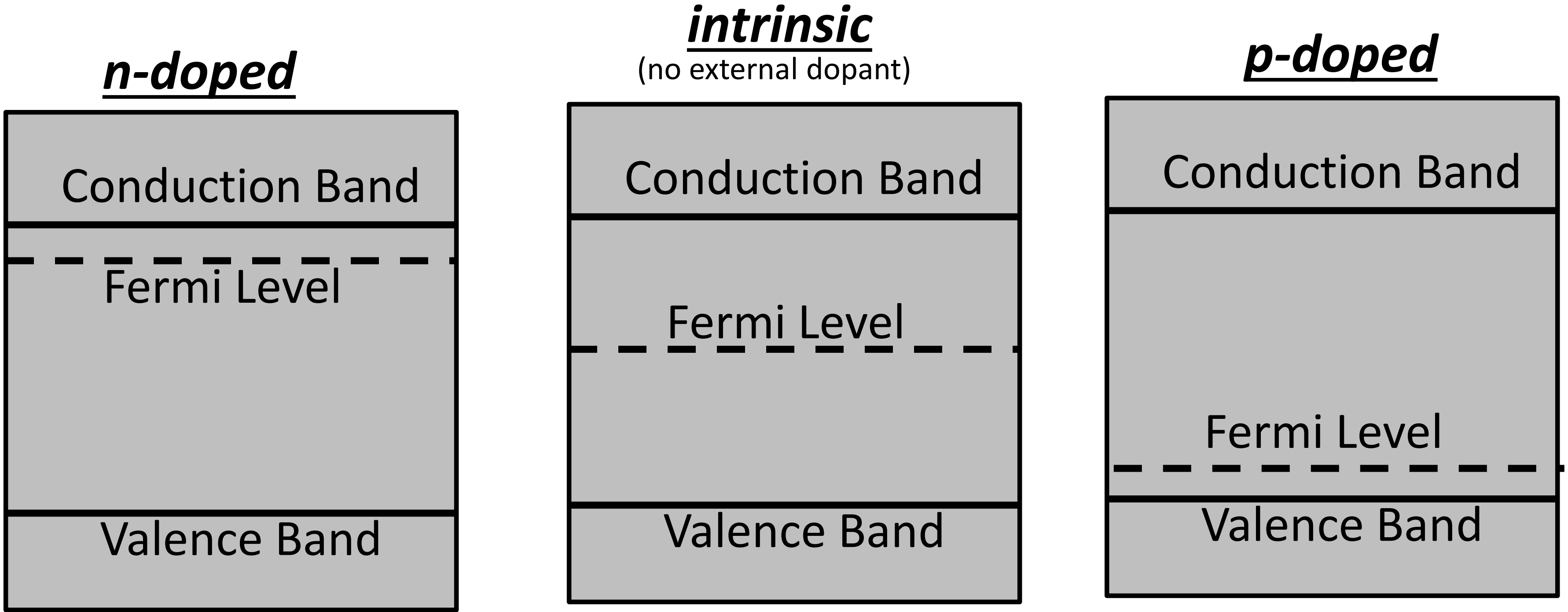
- The photovoltage is sometimes denoted at a difference in chemical potential ($\Delta\mu$)
- By rearranging the photovoltage equation we get the following

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

- This shows that increasing the electrons (n) and holes (p) we get an increased photovoltage
- N_v and N_c relate to band gap (intrinsic property) and effective mass (material specific).
- ‘pn’ can easily change by many orders of magnitude where N_c and N_v can change 1-2 orders of magnitude maximum.

Varying Semiconductor Fermi Level (in Dark)

- By doping the semiconductor with electrons or holes, we can modify the Fermi level.
- Adding a small amount of a material with extra electrons (i.e. donors) is called n-doping.
- Adding a small amount of a material with extra holes (i.e. acceptors) is called p-doping.



n-doped

Conduction Band

Fermi Level

Valence Band

intrinsic

(no external dopant)

Conduction Band

Fermi Level

Valence Band

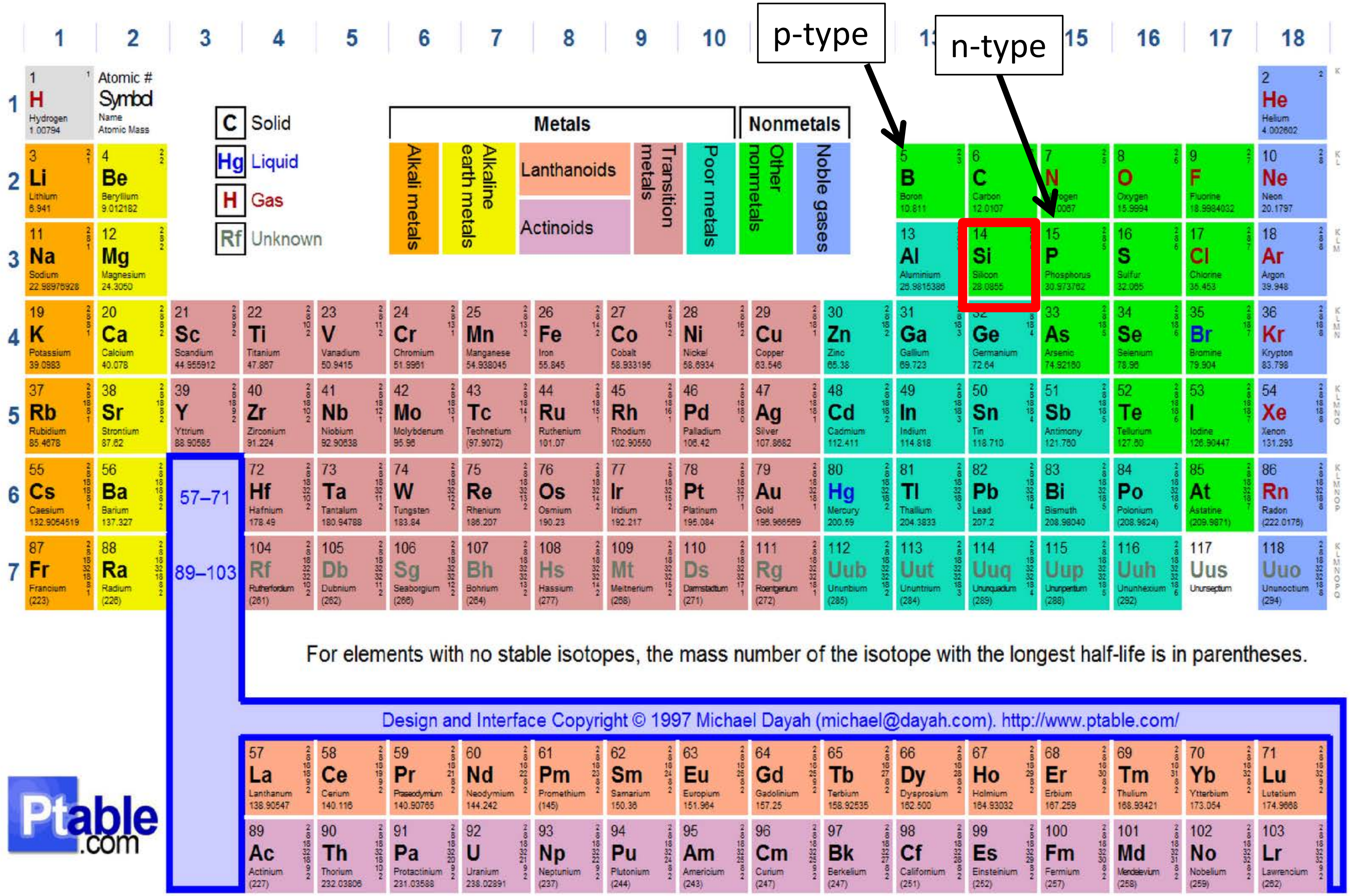
p-doped

Conduction Band

Fermi Level

Valence Band

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 1.00794	Atomic # Symbol Name Atomic Mass																2 He Helium 4.002602
2	3 Li Lithium 6.941	4 Be Beryllium 9.012182											5 B Boron 10.811	6 C Carbon 12.0107	7 N ogen .0067	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797
3	11 Na Sodium 22.98976928	12 Mg Magnesium 24.3050											13 Al Aluminium 26.9815386	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948
4	19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.955912	22 Ti Titanium 47.867	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938045	26 Fe Iron 55.845	27 Co Cobalt 58.933195	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92160	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798
5	37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.96	43 Tc Technetium (97.9072)	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60	53 I Iodine 126.90447	54 Xe Xenon 131.293
6	55 Cs Caesium 132.9054519	56 Ba Barium 137.327	57–71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.94788	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.084	79 Au Gold 196.966569	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98040	84 Po Polonium (208.9824)	85 At Astatine (209.9871)	86 Rn Radon (222.0176)
7	87 Fr Francium (223)	88 Ra Radium (226)	89–103	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (277)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (271)	111 Rg Roentgenium (272)	112 Uub Ununbium (285)	113 Uut Ununtrium (284)	114 Uuq Ununquadium (289)	115 Uup Ununpentium (288)	116 Uuh Ununhexium (292)	117 Uus Ununseptium	118 Uuo Ununoctium (294)

C Solid

Hg Liquid

H Gas

Rf Unknown

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

Nonmetals: Other nonmetals; Noble gases

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

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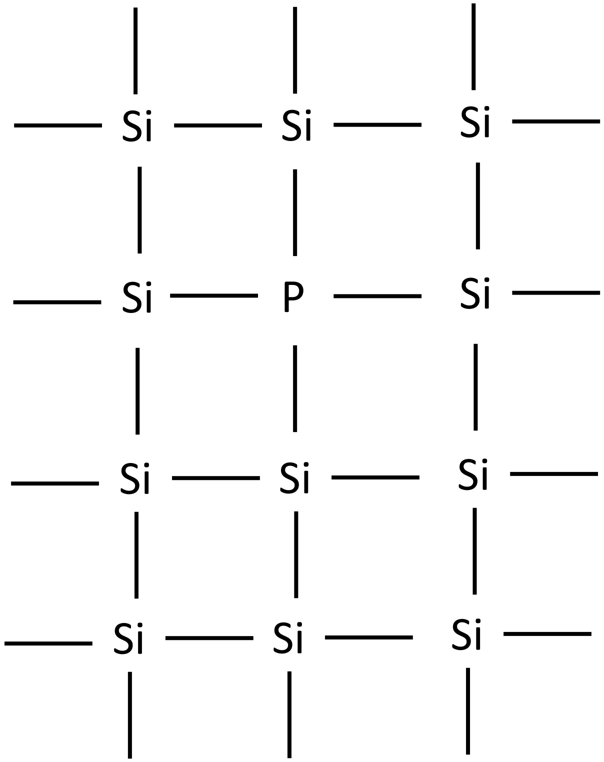
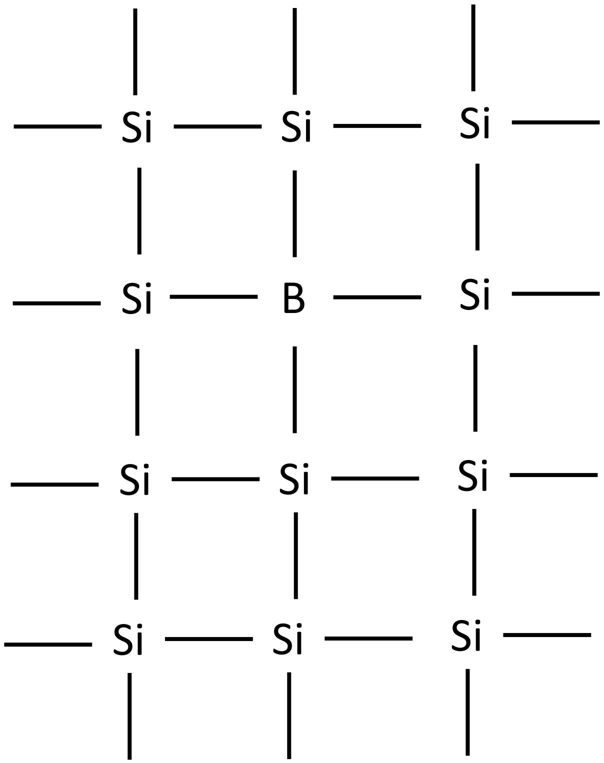
57 La Lanthanum 138.90547	58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.242	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92535	66 Dy Dysprosium 162.500	67 Ho Holmium 164.93032	68 Er Erbium 167.259	69 Tm Thulium 168.93421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

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.

Doping-orders of magnitude

- Most semiconductors have around $10^{20} – 10^{23}$ atoms/cm^3.
- The dopant densities differences between n-type and p-type are order of magnitude.
- ‘Highly doped’ is usually 0.01%-0.1%
- Too highly doped materials may put excessive strain on the crystal lattice.
- Dopant densities greater than 1% are more like alloys than dopants.

Material	**Atomic Density (cm^{-3})**
Si	5×10^{22}
Ge	2.2×10^{22}
InP	4.0×10^{22}
GaAs	4.4×10^{22}
InAs	3.6×10^{22}
InSb	2.9×10^{22}

Fermi Level with Respect to Band Locations

$$n_e n_h = {n_i}^2$$

$$\overbrace{\begin{array}{c} n_e \approx N_c exp^{\left(\frac{E_c - E_F}{k_B T}\right)} \\[2em] n_h \approx N_v exp^{\left(\frac{E_v - E_F}{k_B T}\right)} \end{array}}^{\text{Intrinsically}} \quad \begin{array}{c} \Rightarrow \\[3em] \Rightarrow \end{array} \quad \overbrace{\begin{array}{c} E_C = E_{FB} + \frac{kT}{e} \ln\left(\frac{N_D}{N_c}\right) \\[2em] E_V = E_{FB} - \frac{kT}{e} \ln\left(\frac{N_A}{N_V}\right) \end{array}}^{\text{With dopants}}$$

n_e= # of electrons/ volume
n_h= # of holes/ volume
N_i= # of intrinsic carriers
N_C= effective density of states in conduction band
(N_c = 2.8 x 10^{19} cm^{-3} in Si)
N_V= effective density of states in valence band
(N_v = 1.04 x 10^{19} cm^{-3} in Si)

N_D= # of donors/ volume
N_A= # of acceptors/ volume
N_i = # of intrinsic carriers
$N_A N_D = {n_i}^2$

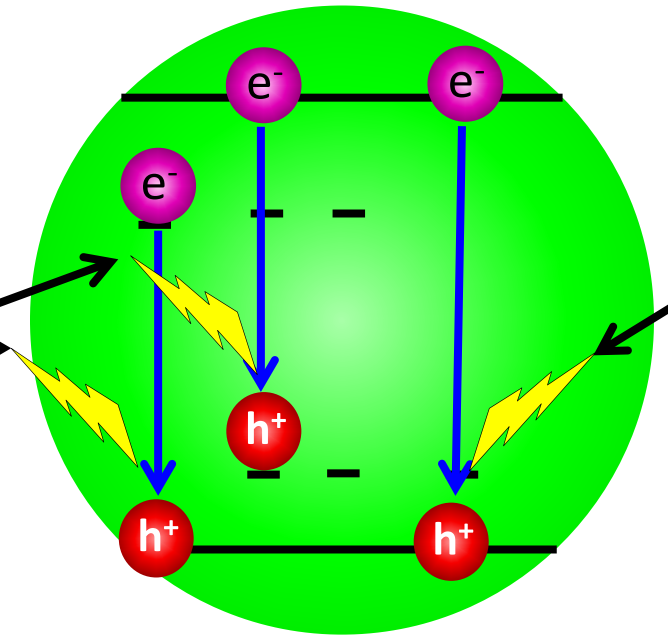
Break

Electron-hole recombination

- There are 2 major things that can happen when electron and holes recombine.
  - Radiative recombination
    - This simply means that the electron-hole produces a photon.
    - Potentially this photon could be reabsorbed by the photoabsorber.
  - Non-radiative recombination
    - This basically means the electon-hole produce heat.
    - This means the energy is wasted.
    - Non-radiative recombination
- A 3rd type of recombination, Auger recombination can happen in highly efficient cells.

Radiative recombination - Qualitative

- The energy of a radiatively recombined photon is the energy difference between the electron and hole.
- This is identical to the 'emission term' in the ideal diode equation
- Radiative photons below band gap sites can not be reabsorbed.



Photons are too small to be reabsorbed,

Photons are the right energy to be reabsorbed

Radiative Recombination- Quantitative

- The radiative recombination **in p-type materials** is:

$$U_{rad}^{net} = \frac{n - n_0}{\tau_{n,rad}} \qquad \tau_{n,rad} = \frac{1}{N_A B_{rad}}$$

U_{rad}^{net}= Net radiative emission rate
n = # of electrons
n_0 = # of electrons in dark
$\tau_{n,rad}$ = radiative lifetime of electrons
N_A= Dopant density of acceptors
B_{rad}= Intrinsic material parameter

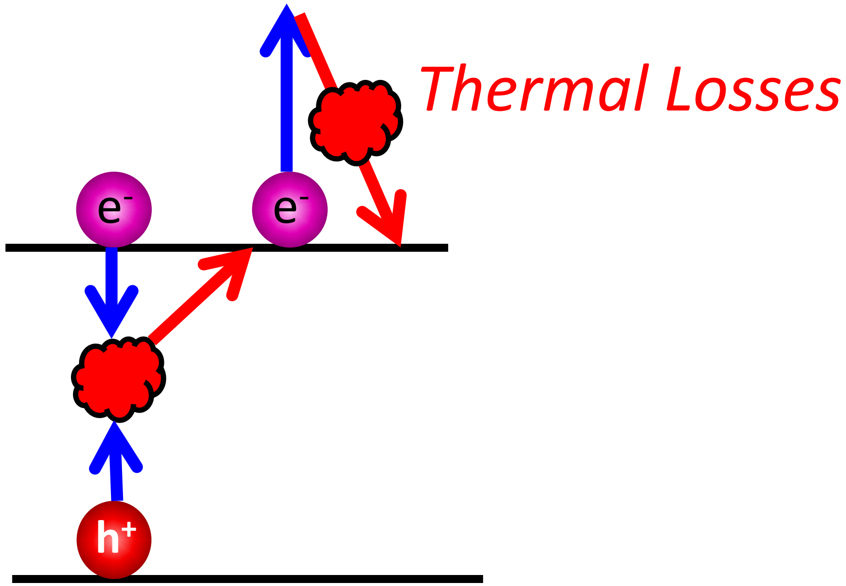
- The radiative recombination in **n-type materials** is:

$$U_{rad}^{net} = \frac{p - p_0}{\tau_{p,rad}} \qquad \tau_{p,rad} = \frac{1}{N_D B_{rad}}$$

U_{rad}^{net}= Net radiative emission rate
p = # of electrons
p_0 = # of electrons in dark
$\tau_{p,rad}$ = radiative lifetime of holes
N_D= Dopant density of donors
B_{rad}= Intrinsic material parameter

Auger Recombination- Qualitative

- 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.

Auger Recombination- Quantitative

- Auger recombination can occur with extra electron excitation or extra hole excitation

$$U_{VB,Aug} = A_{Aug}(np^2 - n_0p_0^2)$$

$$U_{CB,Aug} = A_{Aug}(n^2p - n_0^2p_0)$$

$U_{VB,Aug}$= Auger recom. in the valence band
$U_{CB,Aug}$= Auger recom. in the conduction band
A_{Aug}= Intrinsic material parameter

- Auger recombination for **p-type materials** leads to:

$$\tau_{VB,Aug} = \frac{1}{A_{Aug}N_A^2}$$

- Auger recombination for **n-type materials** leads to:

$$\tau_{CB,Aug} = \frac{1}{A_{Aug}N_D^2}$$

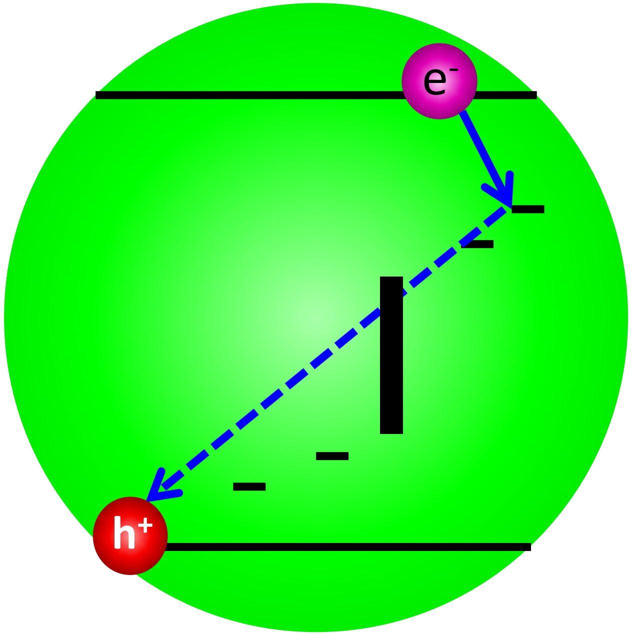
$\tau_{VB,Aug}$ = Auger lifetime of electrons in valence band

$\tau_{CB,Aug}$ = Auger lifetime of holes in conduction band

Non-radiative Recombination - Qualitative

- Basically this is radiative recombination, but the energy is so small it basically is absorbed by vibrational energy of the atoms.
- Typically if the electron-hole recombination energy will give off radiation not in the visible range, it is considered non-radiative.

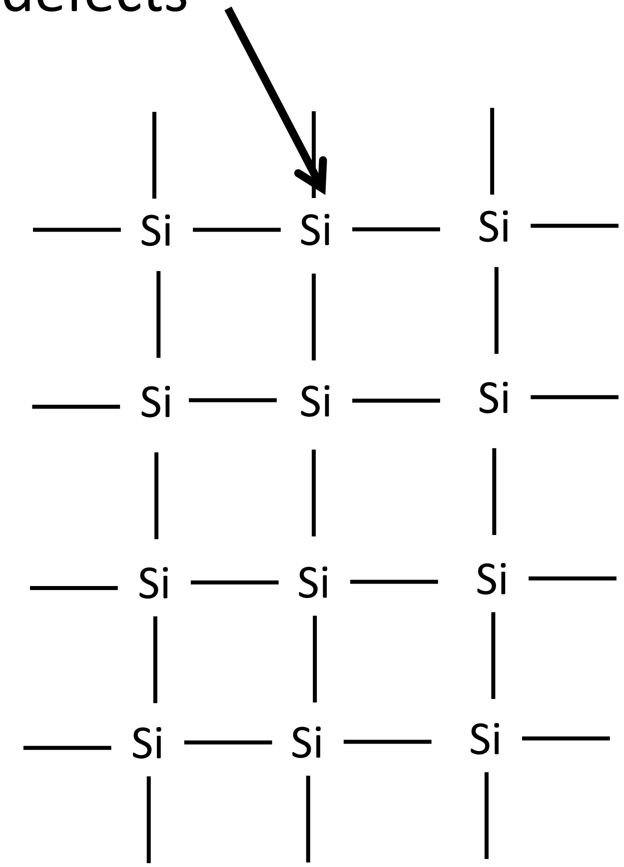
- This is also known as Shockley-Reed Hall (SRH) recombination.



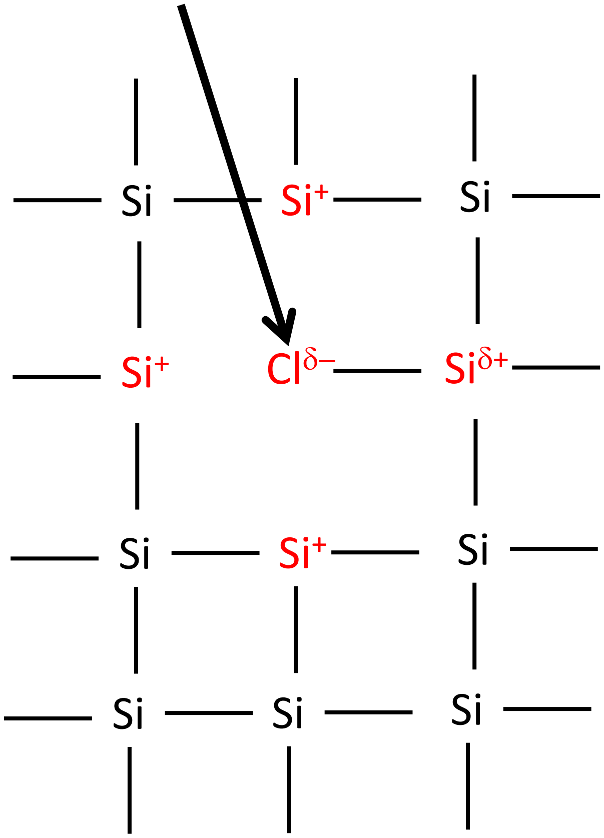
Where does non-radiative sites come from?

- One major source of defects are bulk defects- as shown below.

This is a Si lattice with no defects



This chlorine contaminant screws everything up



SRH recombination- Quantitative

- The SRH recombination **in p-type materials** is:

$$U_{SRH} = \frac{n - n_0}{\tau_{n,SRH}} \qquad \tau_{n,non-rad} = \frac{1}{\sum_{i=VB}^{i=CB} N_{t,i} B_{n,i}}$$

U_{SRH}= Net SRH rate
$\tau_{n,SRH}$ = non-radiative lifetime of e-
$N_{t,\,i}$= # of traps at energy level, i
CB = Conduction band
VB = Valence band

v_n= electron thermal velocity (~ 10^7 cm/s)

$$B_{n,i} = v_n \sigma_{t,n,i}$$

$\sigma_{t,n,\,i}$= trap cross section for electron at an Energy level i

- The SRH recombination in **n-type materials** is:

$$U_{SRH} = \frac{p - p_0}{\tau_{p,SRH}} \qquad \tau_{p,non-rad} = \frac{1}{\sum_{i=VB}^{i=CB} N_{t,i} B_{p,i}} \quad B_{p,i} = v_p \sigma_{t,p,i}$$

- *The recombination current is determined by the non-dominant carrier (i.e. electron or hole)*

General trends regarding lifetimes

- Defect states / recombination states / trap states all mean the same thing.
- An analysis of the recombination rate math shows at non-highly doped semiconductors:

$\tau_{n,SRH} \ll \tau_{p,SRH}$ → Electron trap, little recombination

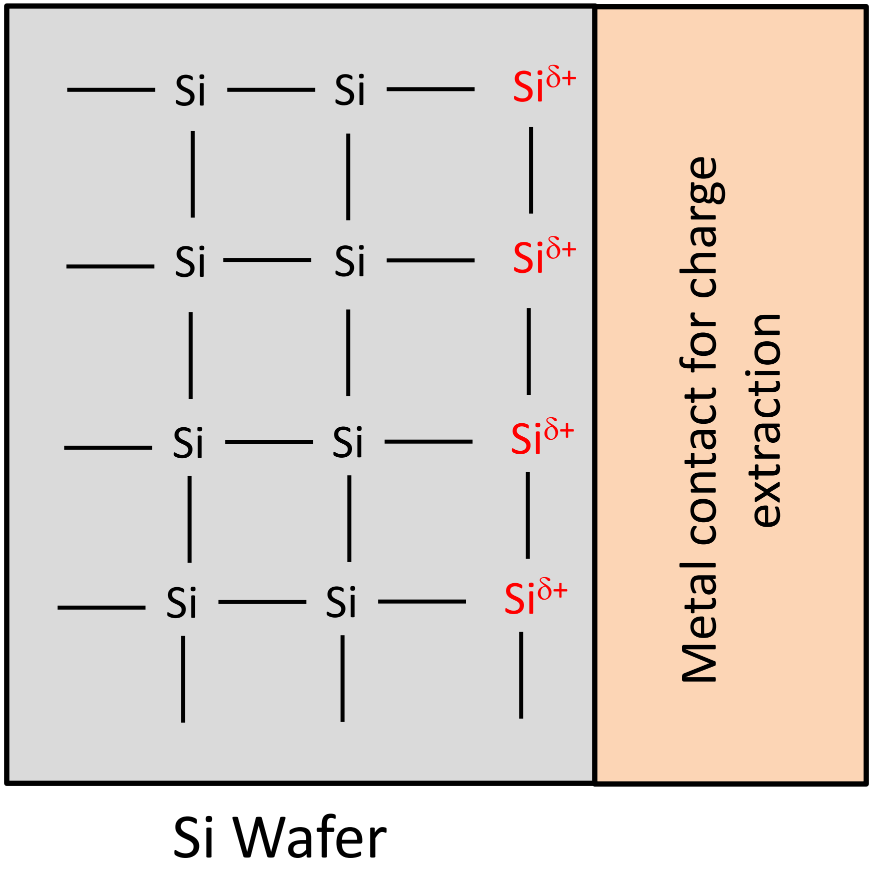
$\tau_{n,SRH} \approx \tau_{p,SRH}$ → Recombination site, a lot of recombination

$\tau_{n,SRH} \gg \tau_{p,SRH}$ → Hole trap, little recombination

- Basically a defect state near the valence of conduction band is OK, but a defect state in the middle of the band gap will create large amounts of recombination sites

Other non-radiative recombination sites

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



- 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.

Surface States- Quantitative

- It is easiest to losses from surface states as simply a current loss (i.e. J_n and J_p).
- Quantitatively this is as followed:

2-D form of SRH losses

Loss at hole collecting side

$$J_n(@x_s) = -S_n(n - n_0)$$

$$S_n = \sum_{i=VB}^{i=CB} N_{t,i} B_{n,i}$$

Loss at electron collecting side

$$J_p(@x_s) = S_p(p - p_0)$$

$$S_n = \sum_{i=VB}^{i=CB} N_{t,i} B_{n,i}$$

- This current is only a loss if the holes go to the surface where the electrons are supposed to go into the circuit or vice versa.

Recombination Losses in General

- *Non-radiative recombination (NRR)*- 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 normally a good thing.
  - RR can simply get reabsorbed again by the photocatalyst.
  - Some RR can simply escape the photocatalyst, thus leading to a loss of photons.
- *Auger recombination (AR)*- This is a minor loss
  - AR only occurs if there are lots of electron-hole pairs.
  - Thus at low light intensities (or high NRR) there are so few electrons that this rarely occurs
  - At high light intensities and/or very efficient cells, this loss becomes more and more important.

Lecture - Learning Objectives

At the end of this lecture you should be able to:

- Understand light absorption and how it applies to solar cells.
- Explain why we can not get 100% efficiency from our solar cells and denote where the losses are coming from.
- Understand what parameters makes a material a good solar cell.
- Understand where practical losses are coming from in solar cells.

Concept Check

Theoretically how does the photovoltage vary with photogenerated electron-hole pairs?

a) Logarithmically

b) Linearly

a) Exponentially

b) It is always a constant

Concept Check

The optimal band gap for a single photoabsorber solar cell is ?

a) 0.4 - 0.8 eV

b) 1.1-1.8 eV

a) 2.4 – 3.5 eV

b) 8.0-10.0 eV

Concept Check

Which of these is not a typical type or recombination?

a) Radiative Recombination

b) Shockly-Reed-Hall Recombination

a) Band bending Recombination

b) Auger Recombnіation

Concept Check

If I have a p-type material my SRH recombination is?

a) linearly proportional to the number of holes in the semiconductor

b) logarithmically proportional to the number of holes in the semiconductor

c) proportional to the number of electrons in the semiconductor

d) logarithmically proportional to the number of electrons in the semiconductor

Exercises

- A material starts absorbing at 620 nm. What is its band gap?
- Calculate the thickness of GaAs, CdTe, and Si to absorb ~90% of all above band gap photons. Use a uniform extinction coefficient (200 nm above the band gap). Assume 20% efficient cells, 1000 W/m^2 of solar irradiation that occurs only 20% of the time (the other 80% it is cloudy or dark). How much material do you need in Kg for 1TW? Compare this to Peter Vesborg's paper on materials production. How scalable is each of these technologies?